Raytheon
Engineers & Constructors

Prepared for the AIChE Clearwater Convention
American Institute of Chemical Engineers
Clearwater, Florida
May 26-27, 1995

COMPUTER MODELING METHODS
for
USE IN DESIGN AND MANAGEMENT
of
INDUSTRIAL STORM WATER SYSTEMS

Thomas Dombroski
Senior Environmental Engineer
and
Joseph W. Guida, P.E.
Environmental Supervisor

Raytheon
Environmental Services

1401 N. Westshore Boulevard
Tampa, Florida, 33607-4518

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This paper discusses the use of computer modeling in the context of generating the storm water system design basis for a major industrial complex located in the Gulf Coast region. The results are also compared to the results achieved using the conventional "rational" method typically used in the past. Since the start-up of this project, the plant had encountered a 24-Hour, 25-Year storm event. The data collected from this event are compared to the computer design basis and the performance of the storm water control system in the field.

Storm water is increasingly getting more attention in the regulatory arenas. By the CWA, NPDES permits are required from industrial facilities discharging storm water, and Storm Water Pollution Prevention Plans (SWP3) require the comprehensive management of storm water discharges. Local water management districts (SWFWMD) require water conservation plans which must detail a facilities' water management and its plans for future reductions for the use of groundwater sources.

Whether the need is for accuracy in limiting risk of permit violations, for storm water management, or for minimizing capital expenditures for storm water control equipment, computer modeling methods can be useful tool towards determining the most accurate storm water flows.

INTRODUCTION

The flow of stormwater across large land areas has traditionally been managed by installation of canals, ditches, and pumping systems designed solely to move the large quantities of water to the nearest receiving body. When these waters are contaminated or have the potential to become contaminated, it becomes necessary to manage the system in a way which will prevent its direct release. In addition to pumping, areas which may be exposed to contamination must also be designed to accommodate storage, treatment, and isolation systems.

Several computer models are currently available which can accurately predict the runoff characteristics of large, complicated watershed areas. In light of the NPDES stormwater regulations affecting most industries, this paper is intended to provide the reader with information for making stormwater management decisions which deal with predicting the intensity and quantity of stormwater. This paper will:

- Discuss when the use of a computer model can be justified, provide information on what they can do, and present information on the type of data collection necessary to get accurate results,
- Compare the traditional "rational" method to a typical computer model,
- Provide information on software which can work in conjunction with storm flow models to simulate operation of stormwater pumping systems to aid in the design of sewers, collection sumps, pumps, and controls, and
- Compare actual field data collected during a major storm event at a large gulf coast oil refinery (referenced as the case study) with a computer model prediction and the "rational" method prediction done prior to system design.

WHY SHOULD I USE A COMPUTER MODEL?

Stormwater regulations now prohibit industrial facilities from direct discharge of stormwater which may be contaminated or have the potential to be contaminated. Depending on the type of industrial storm water discharge, control and treatment systems may have to be designed to handle a volume of water equal to that which falls in 24 hours from a 25-Year storm event.

For large areas, the amount of water collected over a 24-Hour period in a 25-Year storm can be staggering. Not only is it necessary to know the volume of water produced from storms such as this, it is necessary to know the intensity of water flow so that the pumping and treatment systems can be designed to prevent flooding. Also, a system designed to handle the large storms may do a poor job on the small storms which will occur more frequently.

Since 1889, the "rational" method has been used to predict stormwater runoff. The method is simple to use and gives accurate results when there is not a high degree of complexity. However, when there are numerous hills and valleys, flow restrictions such as canals and ditches, terrain with grassed, dirt, and concrete surfaces, and large areas encompassing hundreds of acres in an industrial setting, the calculation becomes subject to gross inaccuracies which may cause serious under or over estimates.

The rational method is accepted by EPA as a means to establish the design basis for stormwater management systems. However, once the system is in operation, it is then the responsibility of the owner/operator to make sure that there is no premature release of contaminated water during storms which do not meet the 24-Hour, 25-Year criteria. If the rational method or some other method is used which yields an undersized system, contaminated water may be released prematurely. In this situation, even though EPA had previously approved the design basis, fines would be levied and the facility would then be faced with the prospect of modifying the system to handle more water.

For a large stormwater collection area, an overly conservative design will result in a very expensive system to build and operate, while an undersized unit will result in flooding, unexpected discharges, and regulatory non-compliance. The additional time and expense required to develop an accurate computer model can usually be justified given the benefits and possible repercussions stated above. A computer model can also be a powerful tool for answering what-if questions pertaining to unusual weather conditions or predict the impact from new units or changes in plant operation.

In conjunction with the modeling of storm flow, software is available to simulate sewer flow and sump operation for pumping stormwater. Because of the wide variations in flow, the pumping system is usually called upon to handle flows from just over a trickle to hundreds of thousands of gallons per minute. The size and configuration of the sewer, sump, number of pumps, pumping capacity, and control philosophy must be optimized to ensure satisfactory operation under all storm conditions, as well as to optimize the capital cost of the system.

MODELING TECHNIQUES

Modeling Options

There are many hydraulic/hydrology computer models available which can vary significantly in complexities, capabilities, and ease of operation. Computer model selection should be based on technical, functional, and operational criteria.

Technical criteria is the capability to meet the requirements of the system modeling. Functional criteria is basically the performance of the model including complexity, data requirements, and technical support. The operational criteria are related to the client's needs, like staff skill and experience with modeling, time requirements, as well as project and budget resources.

Some of the more popular water quantity models used today include:

- Advanced ICPR - Interconnected Channel and Pond Routing Model (Streamline Technologies, Inc.)
- HEC-1 (Hydrologic Engineering Center, USEPA)
- TR-20 and TR-55 (USDA; US Soil Conservation Service)
- HSPF - Hydrological Simulation Program FORTRAN (Hydrocorp, USEPA)
- STORM - Storage, Treatment, Overflow, Runoff Model (Hydrologic Engineering Center, USEPA)
- SWMM - Storm Water Management Model (Metcalf & Eddy; CDM; University of Florida; USEPA)

HSPF, STORM, and SWMM have the capabilities to perform water quality functions as well. There is also available the "FIPR Hydrologic Model" (FIPR Project No. 88-03-085, Bartow, FL, May 1991), which has many different "blocks", i.e., surface water, groundwater, etc., capable of simulating many hydrologic functions.

The approach taken in the referenced case study was to develop a computer simulation model of refinery stormwater runoff, which would generate representative and reproducible results as determined through validating flow measurements taken in the field during storm events. The computer generated simulations, when applied properly, are typically more accurate than manual calculations due to the manipulation of complex runoff and routing equations on a small time-step, iterative basis. The input variables to the model are more detailed and can be directly measured or estimated, making the model a deterministic approach to estimating the runoff. In addition, the computer simulation and output is time-based, where the rational method is an instantaneous estimate. It would be most difficult and time consuming to manually calculate the runoff and routing of an intricate sewer system of a large industrial facility. The rational method cannot directly account for the sewer routing and attenuation factors for which the computer can manipulate very easily and accurately.

The HEC-1 computer software, which was developed by the U. S. Army Corps of Engineers' Hydrologic Engineering Center, was selected in conjunction with the EXTRAN-XP transport model, which was developed by the U. S. Environmental Protection Agency (USEPA). The HEC-1 software simulates the runoff hydrographs and the EXTRAN-XP software simulates the routing of the runoff through the stormwater sewer system. These software programs were selected due to their applicability to event simulation in urban-type applications, their general acceptance in the professional and regulatory arenas, their user friendliness, and their excellent documentation and available technical support.

HEC-1 and EXTRAN-XP Computer Programs

For the case study, HEC-1 and EXTRAN-XP computer programs were calibrated by utilizing field measurements from actual storm events. Once the model was calibrated, it was run to predict the design storm conditions. In addition, simulations were conducted with varying storm conditions, to identify whether variations in the design storm conditions would result in more severe design conditions.

The HEC-1 Flood Hydrograph Package simulates surface runoff characteristics and generates discharge hydrographs. Model input data may originate from historical, theoretical, or design rainfall events. Several methods are available for the calculation of the overland flow and routing components of the model. Due to the urbanized nature and relatively small size of the subbasins within a large watershed, the kinematic wave equations for both overland flow and channel routing were appropriate for use in the refinery case referenced in this study. The HEC-1 program generates total excess rainfall volume, infiltration, peak flow, time to peak, maximum celerity (wave velocity for overland flow), as well as other interim time variable results.

The kinematic wave method is based on physical parameters of the catchment such as Manning's Roughness Coefficients, slope, hydraulic length, channel shape, and land use type (pervious or impervious). These can be physically measured or estimated from site conditions, and when applied in HEC-1, a time based discharge hydrograph is generated. The resultant discharge hydrographs were generated for each unit or area, and were input as data for the EXTRAN-XP program.

The Extended Transport (EXTRAN) Block of the EPA Stormwater Management Model (SWMM) was used to simulate the conveyance through the sewer system from the input hydrographs from the HEC-1 output. EXTRAN-XP is a dynamic flow routing model that routes inflow hydrographs through either an open channel or a closed conduit system and computes the time history of flows and hydraulic heads throughout the system. The program is based on solving the full dynamic St. Venant equations for the conservation of momentum and continuity, using an enhanced-explicit solution technique to step forward in time. The solution time-steps are governed by the celerity in the conduit systems. In the case study, time-steps of approximately 1-to-5 seconds were necessary to meet the conveyance criteria for the program as well as to generate smooth discharge hydrographs.

The input data to the EXRAN-XP program included parameters which define the sewer system, including all the catch basins, actual conduit sizes and elevations, and discharge conditions (weirs, tanks, etc.). EXTRAN-XP proved to be a powerful tool in both the hydrologic analyses and in the design of the new outflow conditions, i.e., the main sump with stormwater pumps. Information can be generated at any point in the system, which includes the hydrograph, peak flow, peak velocity, and elevation profile. The program was also used to estimate the available surge volume in the sewer system.

Rational Method

This method was developed in 1889 by Emil Kuichling, City Engineer of Rochester, New York. While used extensively in the United States, there have been few investigations and little changes made to this technique since it was first introduced. The rational method equation is

$$q_p = k_c C i A$$

where q_p = peak flow (cfs),
C = runoff coefficient,
k_c = 1.008 conversion factor for acre-in/hr,
i = rainfall intensity (in/hr),
A = catchment area (acre).

The following assumptions are made for this method:

1. Runoff volume is proportional to imperviousness. This effect is accounted for by the runoff coefficient in the rational method formula. (Where a value of 1.0 reflects a surface with no absorption/retention characteristics, i.e. wet pavement.)

2. Maximum discharge occurs when the rainfall lasts long enough for the entire tributary area to contribute flow. This is the basis for defining the time-of-concentration, t_c, and using it to determine the average rainfall intensity. In determining t_c, an estimate must be made of the time required for a wave to move from the farthest point in a watershed area to the outlet. For a given storm, the flow of water exiting the watershed would continue to rise until the time-of-concentration is reached. The flow at the time-of-concentration will therefore be the peak discharge flow.

3. Peak discharge is proportional to rainfall intensity. This is the basis for including intensity in the rational method equation.

   The intensity, i, is determined from a rainfall Intensity-Duration-Frequency (IDF) curve. The interception of the time equal to the time-of-concentration and the frequency of the storm will yield the intensity.

4. Ground saturation (antecedent moisture condition) will have a significant effect on peak flows. Dry ground will allow some percolation and absorption during the beginning of a storm while wet ground will result in immediate runoff. There is no means to account for this effect in the rational method.

A "Modified Rational Method" (MRM) has also been developed which will produce a hydrograph depicting flow versus time. This requires an additional parameter, d, the average rainfall duration. This method assumes that there is a linear relationship between storm flow and time from the beginning of a storm to the time of concentration and from the time of peak intensity to the end of a storm.

If the storm duration is less than the time of concentration, peak flow calculated from the rational method will not be reached. If the storm duration is equal to t_c, peak flow will be reached but then immediately fall off (in a linear fashion). If storm duration is greater than t_c, peak flow is reached and is maintained until storm intensity falls off.

The rational methods are very good for quick estimates. Accuracy can be improved by dividing the watershed area into multiple sub-basins. This method can also be used to estimate the storage volume required by calculating the area under the curve. However, it has been documented (Walesh, 1989) that the MRM will generally underestimate the required volume of storage. This is because there is not usually a linear relationship between storm flow and time of concentration.

METHODOLOGY AND RESULTS

System Description

The case study oil refinery in southwest Louisiana covers an area of over 300 acres and, being located along the gulf coast, is subject to large storms, with severe intensities. A new wastewater treatment system for this facility was recently designed, constructed, and commissioned by Raytheon Engineers & Constructors, in April 1994. In addition to treating normal process wastewater, stormwater also reports to the process sewers and becomes contaminated, requiring treatment.

Process water is normally pumped to an advanced secondary wastewater treatment system designed to treat 10,000 GPM through removal of remove oil, grease, and dissolved COD prior to being released. The introduction of peak stormwater flow brings the instantaneous flow to 219,000 GPM. This system consists of two large gravity sewer systems which converge into one pumping station to transfer the contaminated water to treatment and storage. Storage of contaminated stormwater for the design storm required a volume of over 27 million gallons. (Refer to Figure 1 for a basic flow diagram of the system.)

Because of the large flow of stormwater, the potential to flood the refinery, and the possible premature release of contaminated water to a nearby river, the plant decided to undertake a stormwater simulation model to produce the most accurate design basis. Manual calculations, including the rational and Soil Conservation Service (SCS) methods, were used to provide a "sanity" check on the computer model results.

Field Survey and Monitoring

An initial task was to perform a detailed field survey of the drainage area. Existing drawings were reviewed and actual surveys were performed, from which detailed composite drawings were developed for each unit within the refinery. This was necessary to develop a complete understanding of the watershed and drainage delineations.

Concurrent with the field survey, stormwater monitoring equipment, consisting of Stevens' continuous water level gages and a tipping bucket rain gage with a continuous data logger were installed. The level gages were installed at the discharges of the subbasins within the watershed discharge. The rain gage provided a record of the storm event at 15-minute intervals. A Marsh-McBirney Flow Meter was used to measure discharge velocities during a storm event, so stage-discharge relationships (rating curve) could be developed to determine the estimated flow rates.

The composite drawings of the units that were generated from the field survey were summarized for the specific surface-types, and were utilized as the basis for the model calibration and in the manual calculations. The "C" values are per the ranges provided by Viessman et al., 1989, and the curve numbers are from ranges suggested by McCuen, 1989.

The monitoring was in operation for 48 days and was discontinued on December 9, 1992. There were only five and three discharge recordings for the offsite and process areas, respectively. All of these events were of similar depth (1" to 2"), duration, and antecedent moisture condition. Since the measured storm events were all similar, the December 9, 1992 event was chosen for utilization in the model calibration. The rainfall hyetograph (bar chart of measured rainfall from the rain gage), along with the respective discharge hydrographs are shown on Figure 2 (process area) and Figure 3 (offsite area).

Model Calibration

Computer simulations were performed for both wet and average antecedent moisture conditions. As part of the field measurements, the model was calibrated based on wet conditions which represents the worst case scenario. Published literature values of runoff coefficients and curve numbers were also reviewed to support the field observations, the model calibration, and the manual calculations. The objective was to input into the model the actual storm distribution of the calibration event, and apply the proper parameters in the model to reproduce the discharge of the actual event.

The primary model parameters that were adjusted were the curve number, Manning's values for overland flow, and the Manning's value for conduit flow. In general, the curve numbers were used to adjust the peak flow and Manning's values were adjusted to bring the discharge duration in line. Due to less confidence in velocity measurements, the model was judged to be calibrated when the model results matched the measured peak flow and the measured discharge duration. The calibration results are summarized in Table 1 for the measured storm event. As can be noted, the model simulation output closely matches the peak flow, the peak velocity, and the maximum discharge elevation. Figures 4 and 5 show the comparison of the modeled and measured results for the process and offsite areas respectively.

Table 1

SUMMARY OF CALIBRATION RESULTS

COMPARISON DESCRIPTION	OFFSITE AREAS	PROCESS AREAS
MEASURED Q_{peak}	41.4 CFS	12.0 CFS
MODELED Q_{peak}	36.2 CFS	12.3 CFS
MEASURED v_{peak}	1.0 FPS	0.9 FPS
MODELED v_{peak}	0.8 FPS	0.7 FPS
MEASURED EL_{peak}	6.5 FT	9.4 FT
MODELED EL_{peak}	6.3 FT	9.3 FT

After the model was calibrated, it was run to reflect the design storm conditions. The design storm basis used the "average" curve number value for the respective "wet" curve number value obtained from the calibration, per the recommendation in McCuen (1989). Once the hydrograph information was set in the HEC-1 program, the EXTRAN-XP program was used to develop the design basis for the new sump and the pumping system.

Manual Calculations

The manual calculation methods used here are consistent with industry standards and regulatory guidelines. The SCS TR-55 method was utilized for calculating the maximum storage volume. This method, which is a function of the total precipitation, the subbasin storage, and curve number is also part of the results generated by the HEC-1 program. The curve number is a dimensionless coefficient index that represents the combination of a hydrologic soil group, land-use, and treatment class. The model uses the SCS loss rate method which is based on the following equations,

$$Q=\frac{(P-0.2S)^2}{P+0.8S}$$

where
Q = rainfall excess (inches),
P = total precipitation (inches),
S = subbasin storage (inches).

Also,

$$S=\frac{1000}{CN}-10$$

where CN = curve number.

These are empirical relationships developed by the SCS, and when calculating for total rainfall excess, Q, the volume can be determined by multiplying by the respective catchment area. This method is a function of land type, antecedent soil moisture, and other factors that affect runoff and retention, and is directly dependent on the selection of proper curve numbers.

The rational method was used to check the peak flows generated by the HEC-1/EXTRAN-XP simulations. Due to the rational method's inherent simplicity and required assumptions, and the model using the different deterministic equations, the rational method results are not directly comparable to the model results.

The results of this equation are a function of two parameters, the runoff coefficient "C" and the storm intensity "i". The storm intensity is determined from an Intensity-Duration-Frequency (IDF) curve for the given design storm, return period, and estimated storm duration, which is set equal to the basin time-of-concentration. The rational method also assumes the "C" value is constant with storm intensity, which is usually not the case.

In addition, calculations were made to estimate the watershed "C" value for both the main subbasins, based on the known acreage, the measured rainfall intensity, and the measured peak flow. However, these represented attenuated "C" values due to the backwater conditions of the outfalls and were not applicable for comparison during the model calibration. These values are much lower than would have been measured under "free flow" conditions at the outfalls. The rational method is usually applied based on a "free flow" discharge condition, which refers to the concept of peak flow being a direct effect of the runoff and its unobstructed discharge from the outlet of the drainage basin. Backwater conditions and interior routing need to be considered for determining an accurate peak flow estimate.

Table 2

COMPARISON OF PEAK FLOW CALCULATIONS

CALCULATION METHOD	C or CN VALUE	General Area Q_{peak} (GPM)	Process Area Q_{peak} (GPM)
"Rational" method modified for a 25-YR storm	C (MAX)	169,700	27,000
Model run based on the design pumping system	CN (AVG)	173,000	30,000
Model run based on the design pumping system	CN (WET)	195,000	30,000
Model run based on "free flow" conditions (no pumps)	CN (AVG)	194,000	34,000
Model run based on "free flow" conditions (no pumps)	CN (WET)	219,000	34,000

Required Storage Volume

Table 3 compares the design storm volume calculations using the SCS TR-55 method and the HEC-1/EXTRAN-XP model. The work-off rates represent the processing capacity of the WWTP, which can be increased to help offset the peak inflow. The runoff volume resulting from the average and wet conditions can be used to optimize the storage tank sizes.

Table 3

RESULTS OF STORAGE TANK VOLUME CALCULATIONS

CALCULATION	CN	Runoff Volume (Mgal)	Work-Off Rate (MGD)	WWTP Runoff Volume (Mgal)	Req'd Storage Volume (Mgal)
Manual calculation based on the SCS TR-55 method	AVG	23.7	(6.5)	1.1	18.3
	WET	26.2	(6.5)	1.1	20.8
Model results from HEC1/XTRAN	AVG	23.0	(6.5)	1.1	17.6
	WET	26.1	(6.5)	1.1	20.7

CASE STUDY: ACTUAL STORM ENCOUNTERED AUGUST 23, 1994

Since the start-up of the new wastewater treatment plant for this case study refinery, the site had encountered an equivalent 25-Year storm event on August 23, 1994. Complete data on the rainfall event is not available since the plant does not routinely monitor for these parameters. However, total rainfall was available, and due to the severity of the storm, the duration was noted in the plant logs.

The new WWTP, including the pumping station utilizes a distributed control system (DCS) where the sump water levels are recorded in the plant computer. Also recorded by the DCS is level rise in the large storm water storage tanks. The level changes during the August 23rd storm were recorded, from which a total volume of runoff could be estimated.

Actual peak flows are not measured and hence, are not available for comparison with the computer model. But as previously mentioned, the model not only generates the predicted flow, but it also generates a predicted water elevation in the sump as the runoff enters the system during a storm. These sump water elevations are used as the comparative mechanism to determine the quality of the system design.

Table 4 summarizes the design storm rainfall parameters used in the computer model runs. In the case study, the U.S. Soil Conservation Service (SCS) Type III, 24-Hour, 25-Year rainfall distribution for the design storm was used. The SCS developed this distribution based on the rainfall frequency atlases generated by the National Weather Bureau. The design storm depth is estimated to be 10.3 inches over a 24 hour duration and a 25 year return period. The Type III distribution is typical for the region, and is characterized by the sharp peak of the distribution function which peaks at the midpoint of the storm duration (see Figure 6).

Table 4

DESIGN STORM RAINFALL PARAMETERS

Time-of-Concentration (MIN)	Intensity (IN/HR)	Rainfall Depth (IN)
30	6.9	3.45
45	5.1	3.82
60	4.8	4.20

The measured rainfall at the plant for the August 23rd storm was 3.8 inches over a 45-minute period. This is equivalent to a 5.1 IN/HR intensity and a 25-Year storm as shown in Table 4. The total volume increase recorded in the storm water storage tanks was 10.1 million gallons.

The performance of the storm water system was excellent as can be seen from the comparisons made in Table 5. The computer model for this case study accurately predicted the offsite sump water level and total volume. The process sump water level was conservative since the actual level fell well short of the predicted level. This means that the runoff coefficients and surface storage factors were conservative estimates in this instance.

Table 5

COMPUTER MODEL VS. ACTUAL STORM PERFORMANCE

PARAMETER	COMPUTER MODEL	ACTUAL PERFORMANCE
Offsite Sump: Peak Water Elevation	20.25 FT	19.5 FT
Process Sump: Peak Water Elevation	15.0 FT	9.0 FT
Peak Discharge Duration (est. from rising to recession limb)	2 HR	2 HR
Runoff Volume	10.1 MGal	10.1 MGal

SUMMARY AND CONCLUSIONS

The approach was to develop a computer simulation model of refinery stormwater runoff, which would generate representative and reproducible results as validated through flow measurements taken in the field during storm events. The HEC-1 and EXTRAN-XP programs, when applied properly, can yield more accurate results than prior methods, because it is based on measurable parameters and the physically based kinematic wave equations. These computer methods are typically more accurate than manual calculations due to the manipulation of complex runoff and routing equations on a small time-step, iterative basis. In addition, the computer simulation and output is time-based, where the "rational" method is a instantaneous estimate of peak flow.

The model was utilized to optimize the design for the most efficient and cost effective option. This results in the effective utilization of the available storage capacity within the sewer system, which significantly decreased the required size of the new sump.

The results obtained from this study were used to determine the design basis for the stormwater management system. The calibrated model produced the peak flow, flow velocity, and flow elevations within five percent of the measured values. In general, the "rational" method calculations yielded lower peak flows than the model results. Depending on the assumptions made in using the "rational" method, the peak flows were as much as 20 percent different than those generated by the calibrated model.

Due to the size and cost of the new stormwater management facility for this case study, utilizing more sophisticated computer models is warranted to obtain a more accurate determination of the required flows to be handled. The additional costs to develop a more detailed hydrologic analysis for the design basis can be easily justified due to proper sizing of the large equipment involved and the reduced risk of flooding stemming from the increased accuracy. In addition, since the stormwater sewers are combined with some of the process wastewater streams, an overflow can lead to a hazardous waste violation (per the Toxicity Characteristics rules) and require subsequent hazardous waste clean-up.

The results obtained in this study are site specific, and where it was prudent to do so, appropriately conservative values were selected for use in the model. It should be emphasized that the use of the computer model does not suspend the need for good engineering judgement and experience. The use of the available modeling techniques, however, provides a greater opportunity for these attributes to be effectively applied to achieve greater accuracy in predicting peak flow rates and runoff volumes for the design storm event. These accuracy improvements can be the basis for cost effective equipment sizing and for reducing risk.

BIBLIOGRAPHY

Bedient, P. B. and Huber, W. C., _Hydrology and Floodplain Analysis_, Addison-Wesley Publishing Co., Reading, MA, 1992.

Chow, V. T., _Applied Hydrology_, McGraw-Hill, New York, 1988.

French, R. H., _Open-Channel Hydraulics_, McGraw-Hill, New York, 1985.

Grant, D. M., _Isco Open Channel Flow Measurement Handbook_, Isco, Lincoln, NE, 991.

Hydrologic Engineering Center, _HEC-1 Flood Hydrograph User's Manual Version 4_, U.S. Army Corps of Engineers, Davis, CA, 1990.

Mao, Kent, _How to Select a Computer Model for Storm Water Management_, Pollution Engineering, October 1, 1992.

McCuen, R. H., _Hydrologic Analysis and Design_, Prentice-Hall, Inc., Englewood Cliffs, 1989.

Parmley, R. O., _Hydraulics Field Manual_, McGraw-Hill, New York, 1992.

Schweitzer, Jeff, _Interoffice Letter to R. Boutte: "Storm Event at CITGO Refinery"_, CITGO Petroleum Corporation, August 26, 1994.

Southwest Florida Water Management District (SWFWMD), _Management and Storage of Surface Waters: Permit Information Manual, Volume I_, Resource Management Department, Brooksville , FL, 1988.

U.S. Department of Commerce, _Technical Paper No. 40: Rainfall Frequency Atlas of the United States_, National Climatic Data Center, Ashville, NC, 1986.

U. S. Environmental Protection Agency, _Guidance Manual For The Preparation Of NPDES Permit Applications For Storm Water Discharges Associated With Industrial Activity_, U.S.E.P.A., Office of Wastewater Enforcement and Compliance, Washington, D.C., April 1991.

U.S.E.P.A. Environmental Research Laboratory, _Storm Water Management Model (SWMM) User's Manual Version 4: EXTRAN Addendum_, U.S. Environmental Protection Agency, Athens, GA, 1989.

Viessman, W., Jr., Lewis, G. L., and Knapp, J. W., _Introduction to Hydrology_, Harper & Row, Publishers, New York, 1989.

Walesh, S.G., _Urban Surface Water Management_, John Wiley & Sons, Inc., New York, 1989.

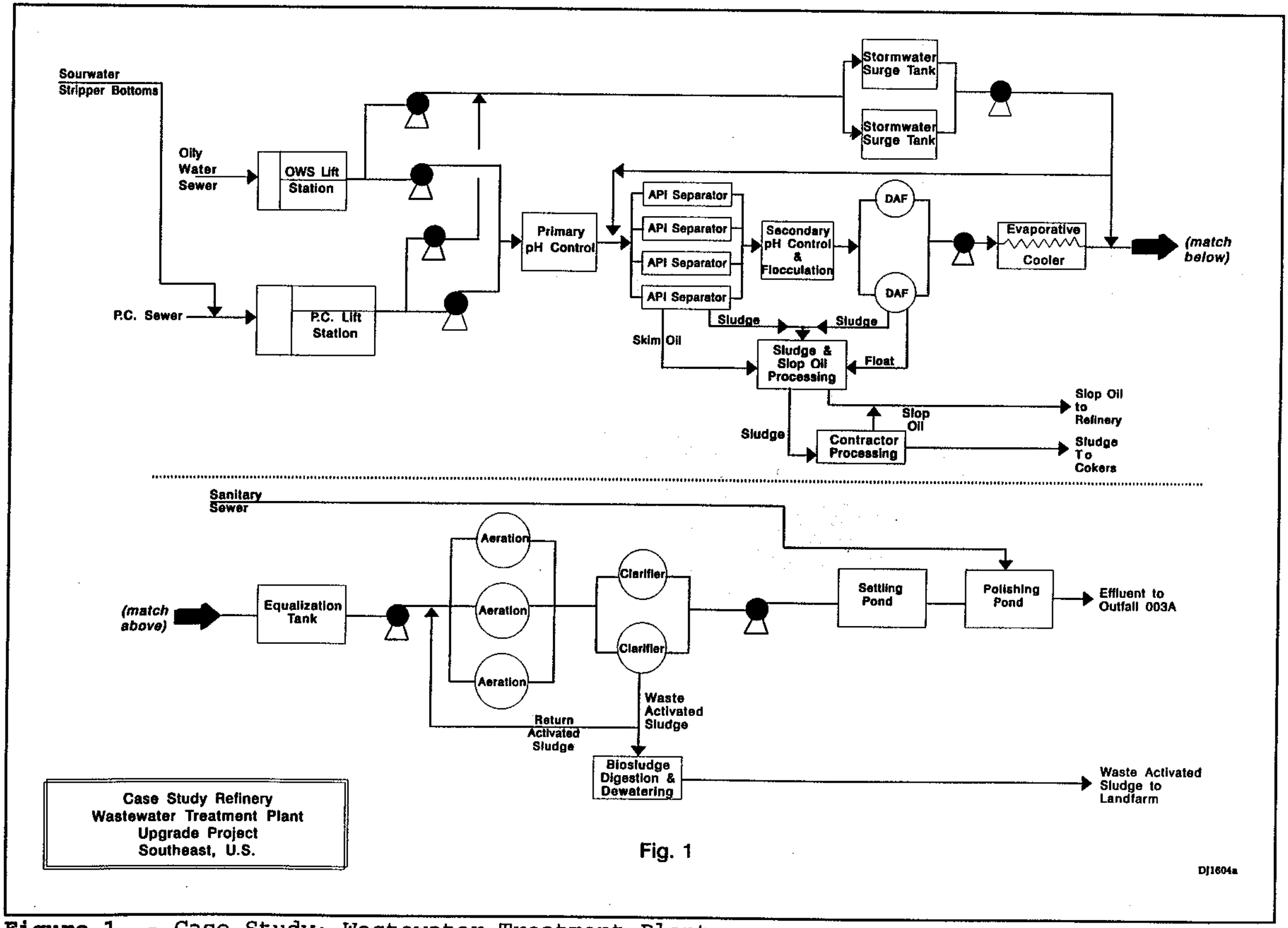

Fig. 1

Figure 1. - Case Study: Wastewater Treatment Plant

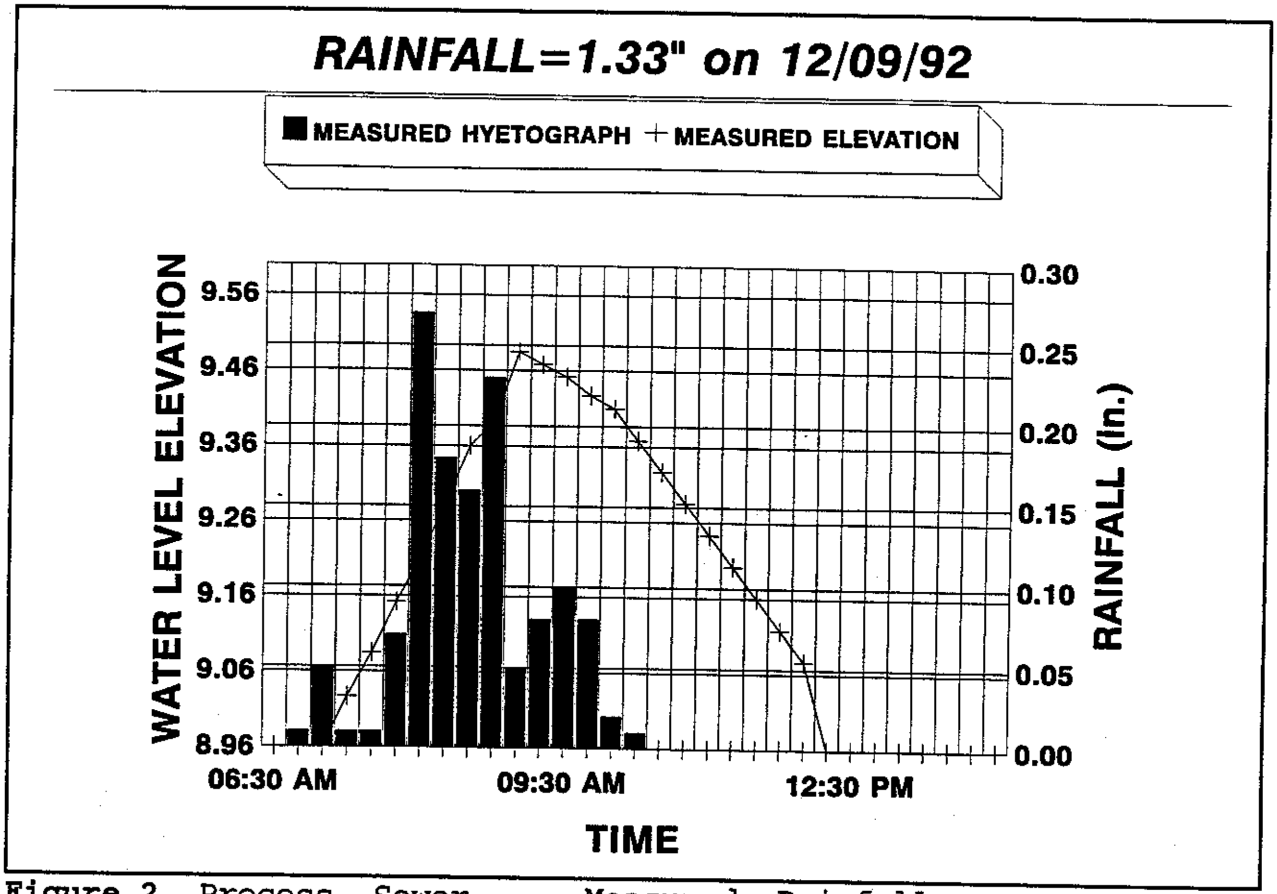

Figure 2. Process Sewer -- Measured Rainfall Hyetograph and Measured Discharge Stages

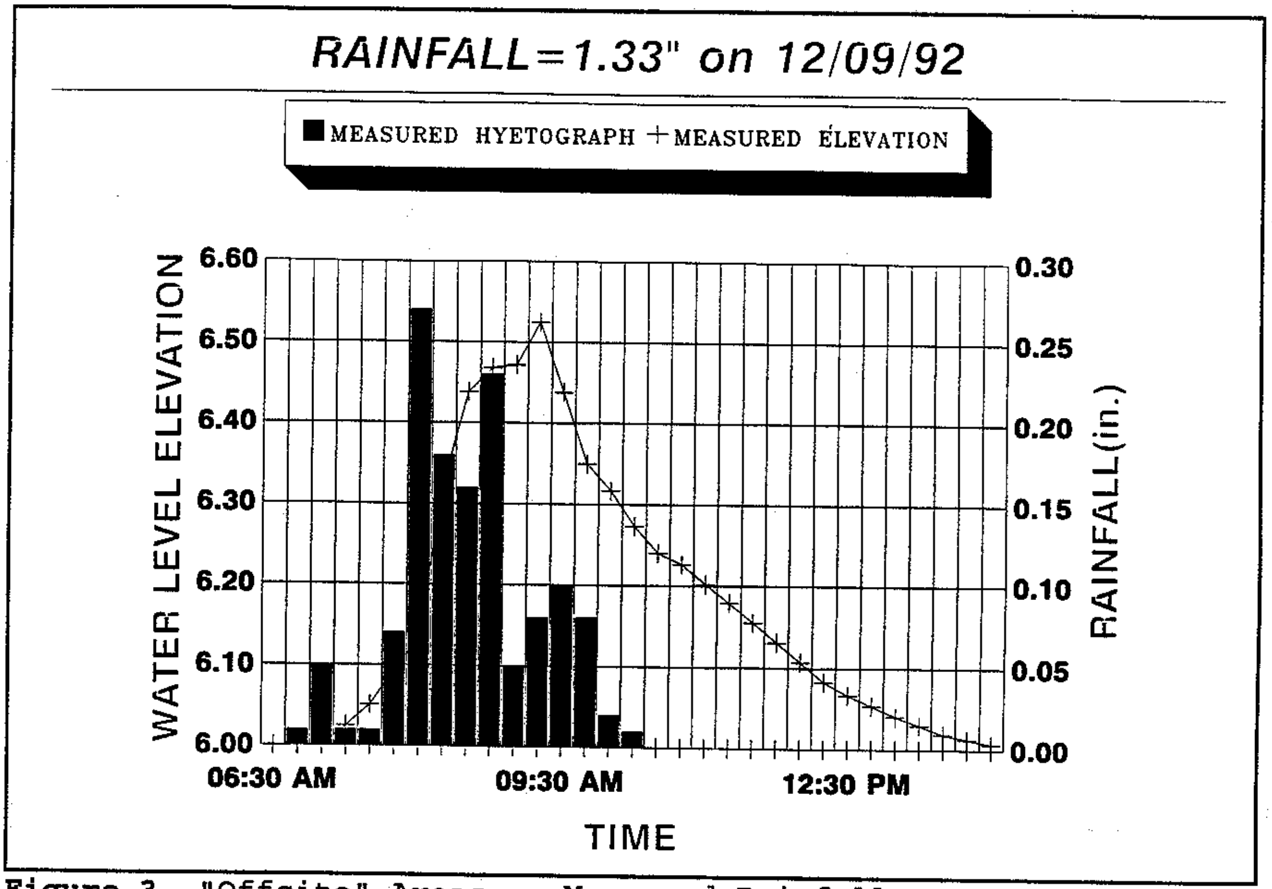

Figure 3. "Offsite" Areas -- Measured Rainfall Hyetograph and Measured Discharge Stages

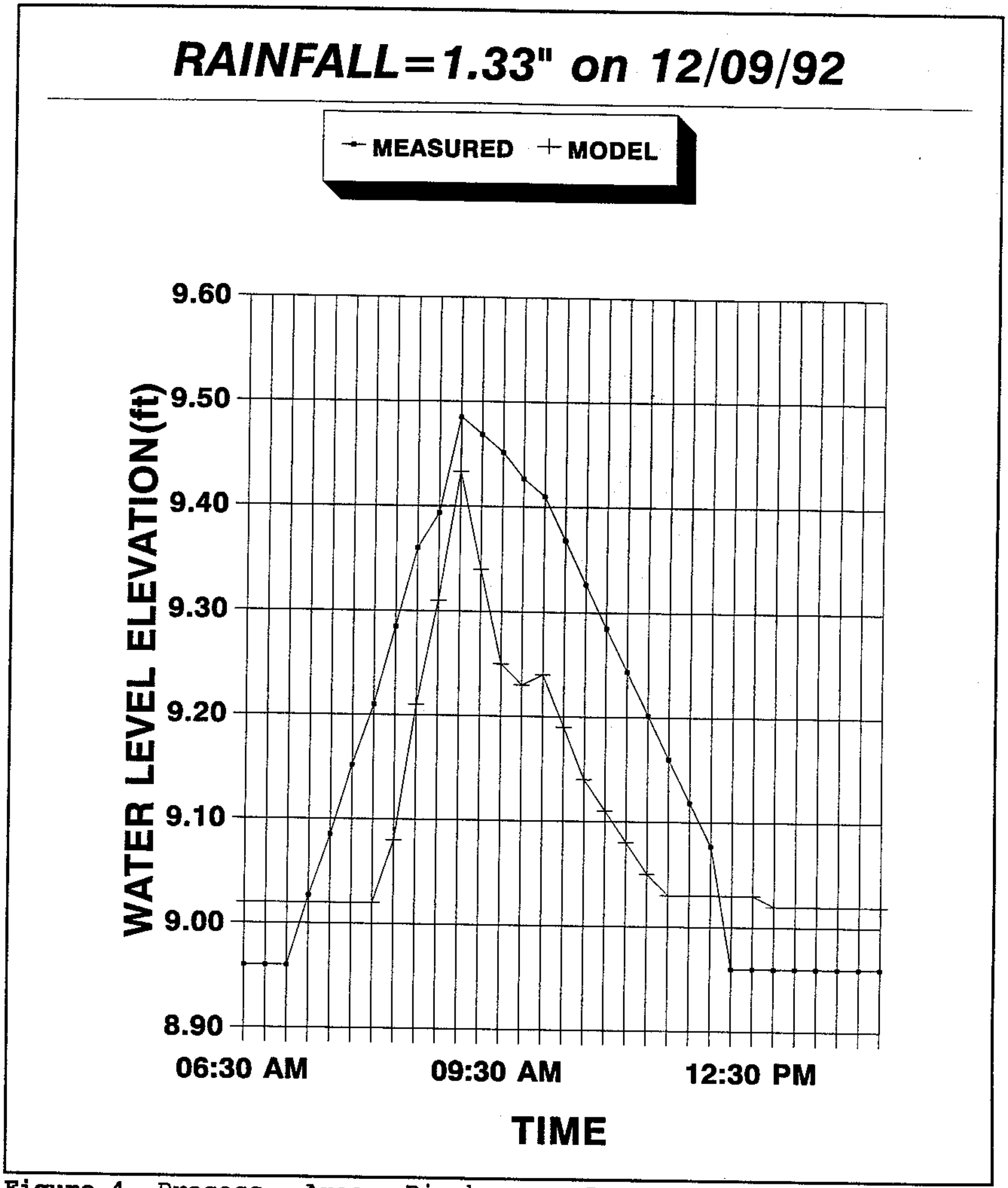

Figure 4. Process Area Discharge Stages -- Measured vs. Modeled

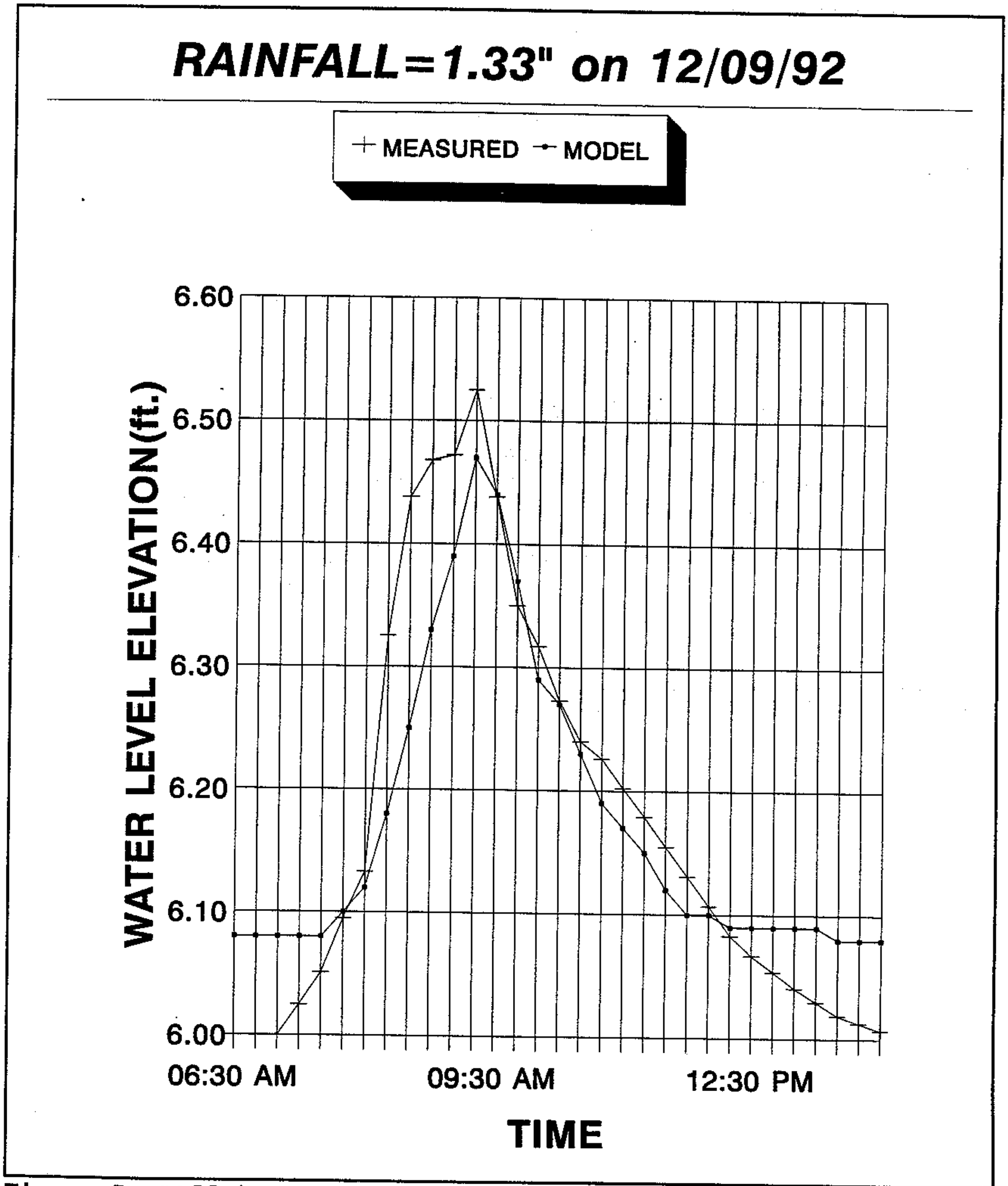

Figure 5. "Offsite" Area Discharge Stages -- Measured vs. Modeled

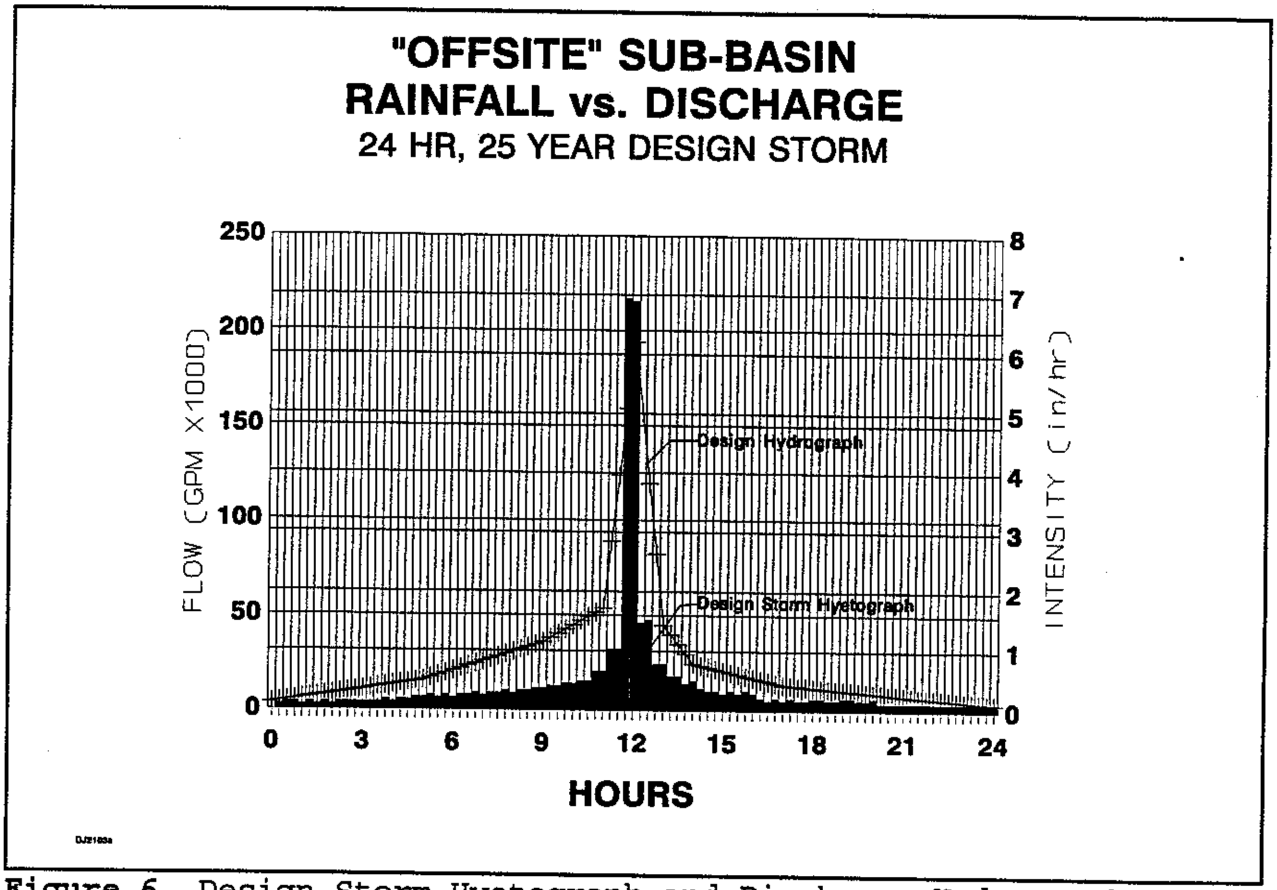

Figure 6. Design Storm Hyetograph and Discharge Hydrograph

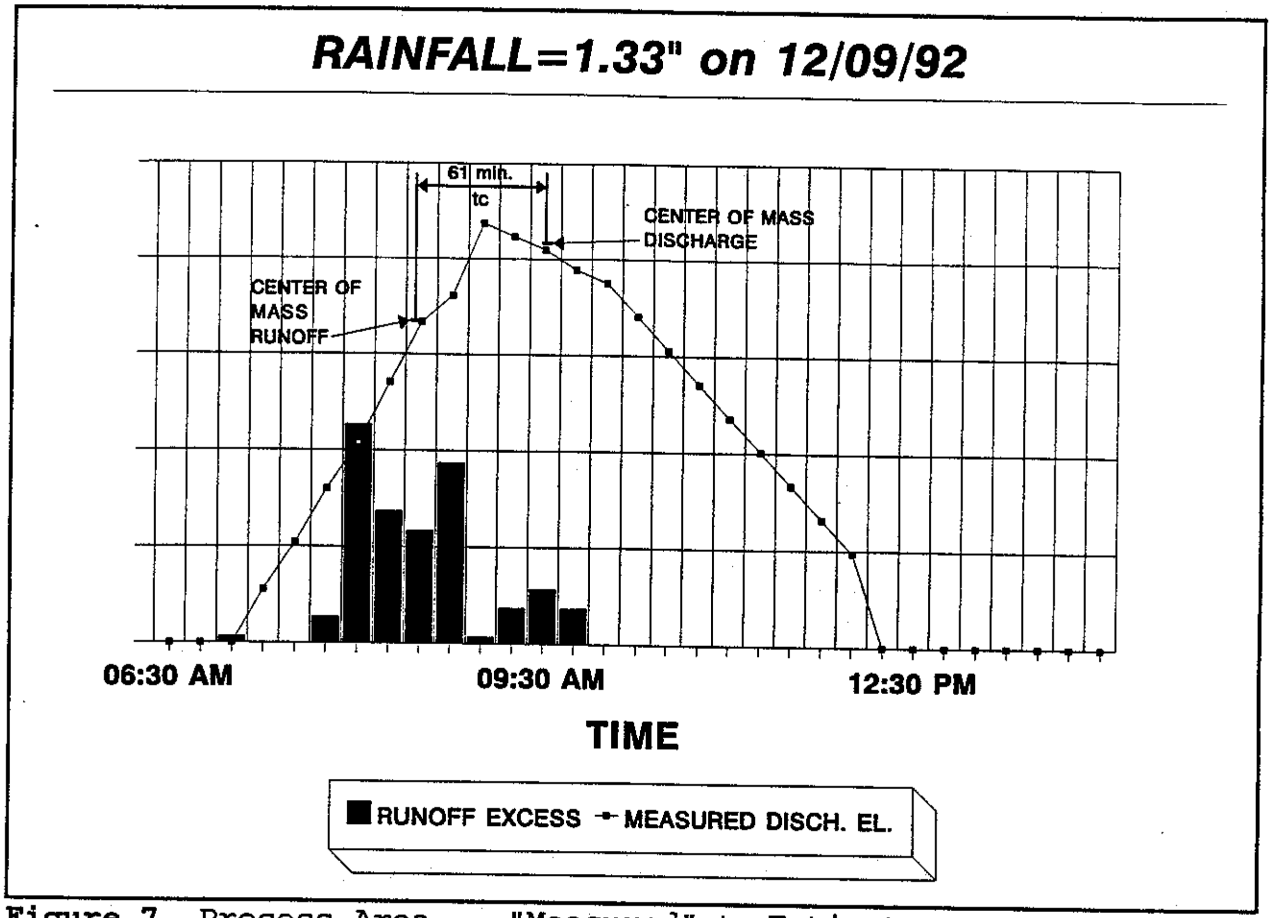

Figure 7. Process Area -- "Measured" t_c Estimate

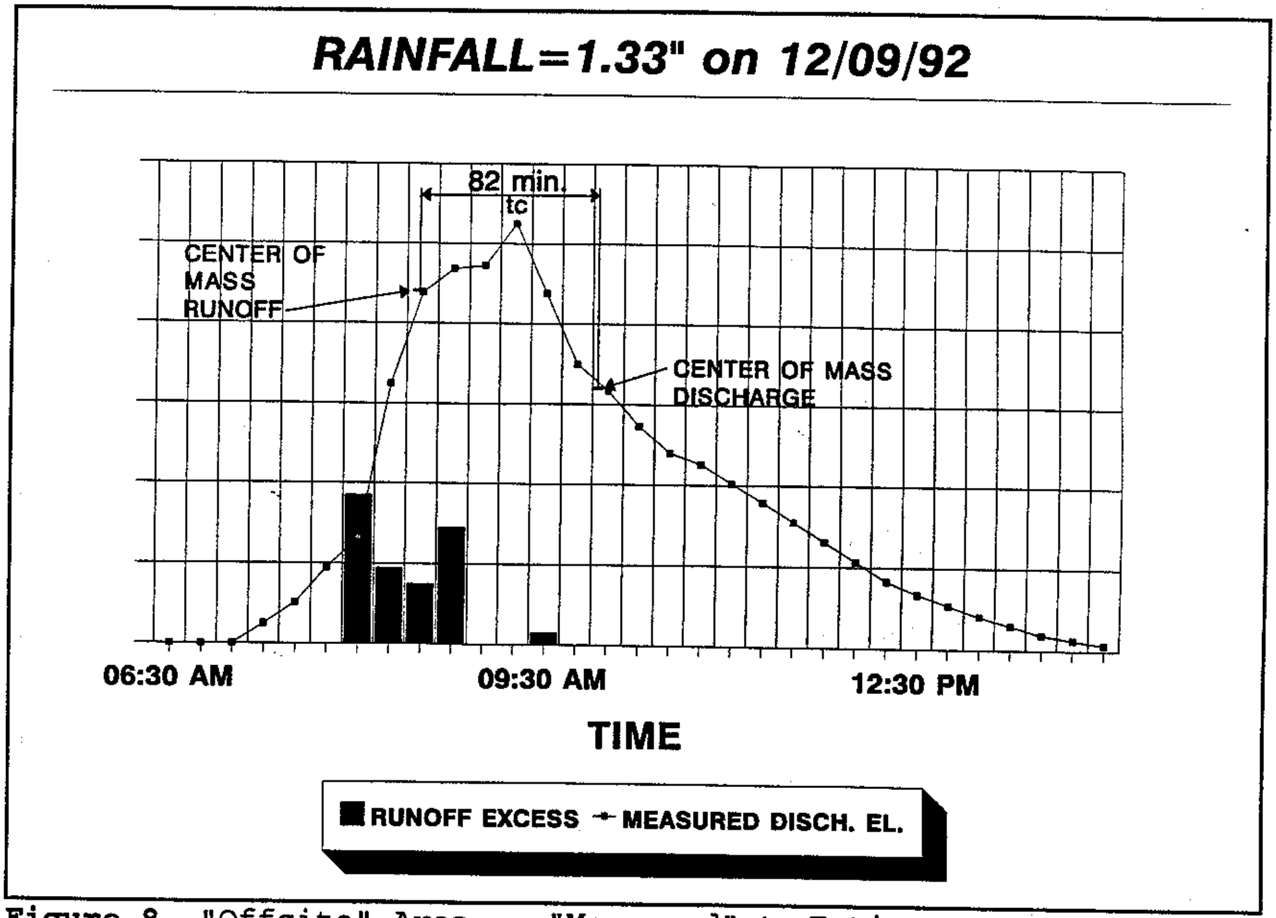

Figure 8. "Offsite" Area -- "Measured" t_c Estimate

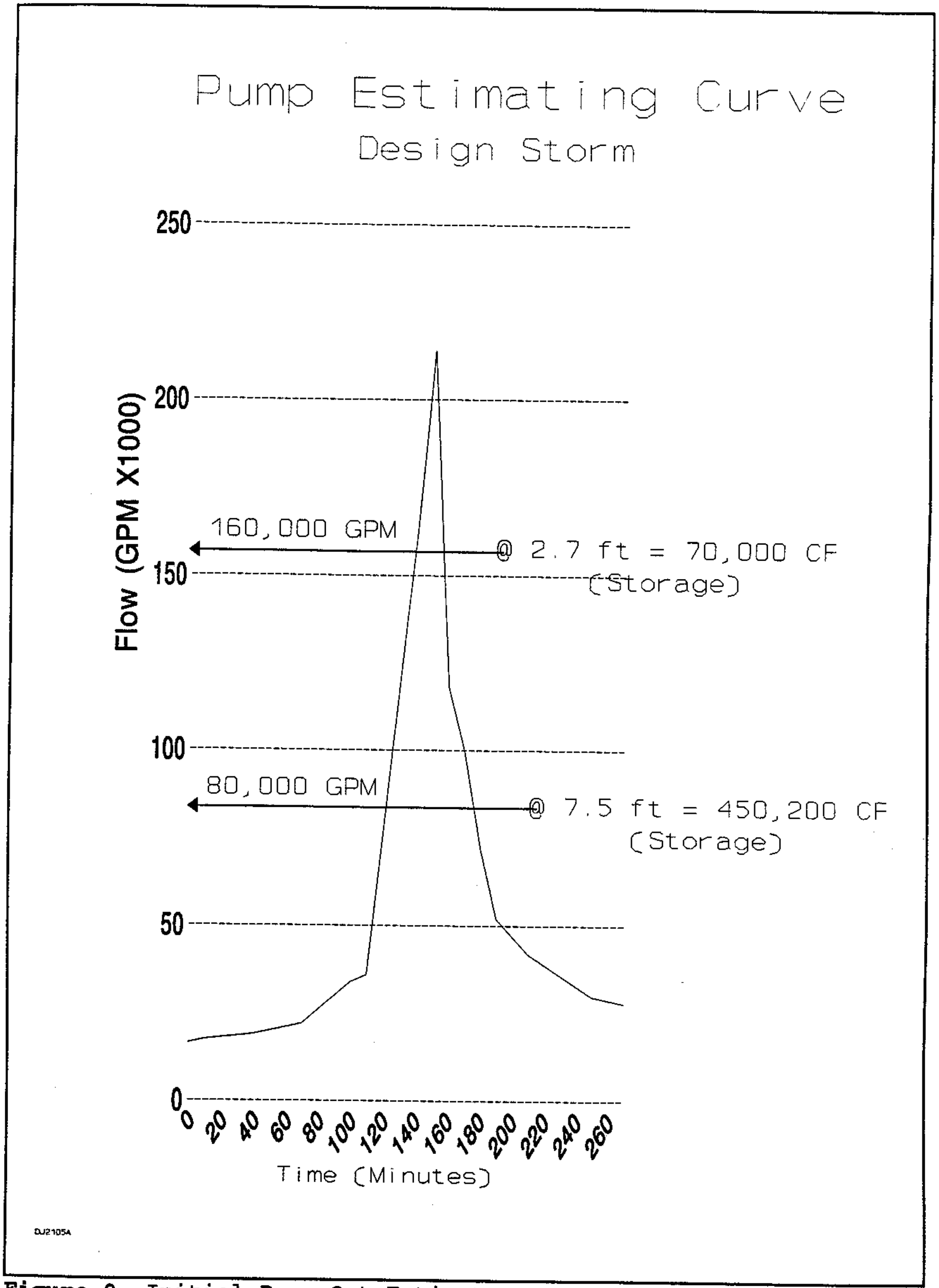

Figure 9. Initial Pump-Out Estimate