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14. ABSTRACT
Six models, plus two variants of one and a variant of another, were tested with the objective of making a preliminary evaluation of their relative capabilities, accuracies, and ease of application. For four of the models, plus two variant of one of them, the primary performance criterion was the degree to which simulated values matched observed daily and monthly runoff volumes for the 5.5 square mile Castro Valley Watershed near Oakland, California. In addition, tests were performed for several individual runoff events for all six models. The results showed that each model could be calibrated on a single set of data and verified with acceptable accuracy on a different data set. The ease of application was decidedly different for all models, due to the differing level of detail in input data required. Going from the simplest to mode difficult to apply, the continuous models rank as follows: STORM, HEC-1C, SSARR, and HSP. Similar ranking of the single-event models is HEC-1, SWMM and MITCAT. Also, a recent capability added to the STORM model (i.e., SCS procedures for computing runoff and routing) produced more accurate results than the coefficient method of computing quantity of runoff incorporated in the original version of STORM. These limited tests were not intended to serve as a basis for comparison of the accuracy of the various models. However, they did show that the more complex models did not produce better results than the simple models for the Castro Valley Watershed data.

15. SUBJECT TERMS
urban runoff, model studies, California, watersheds (basins), computer models, storm runoff, routing, hydrographs, discharge (water), storm water, management, calibrations, surface runoff, hydrologic aspects, hydrology, unit hydrographs, monthly, analytical techniques, Castro Valley Watershed (CA), urban watersheds

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Mr. Jess Abbott was killed on September 8, 1978, while driving to work. He was born on April 3, 1943, in Helena, Montana, and shortly thereafter his family moved to Boise, Idaho, where he subsequently graduated from Meridian High School. He received B.S. and M.S. degrees in civil engineering at the University of Idaho at Moscow, and was recognized as an Outstanding Civil Engineering Student in his graduate studies.

After his university work, Mr. Abbott undertook his military service as an officer in the U.S. Public Health Service. He began his hydraulic engineering career with the U.S. Army Corps of Engineers after fulfilling his duties with the Public Health Service. He worked first for the Walla Walla District and from there went to the North Pacific Division in Portland, Oregon. From there in 1973 he joined the staff of the Hydrologic Engineering Center.

At the Hydrologic Engineering Center, Mr. Abbott was a Research Hydraulic Engineer, in charge of the Center's urban hydrology program. He was instrumental in furthering the development and application of the STORM computer program, and coordinated the usage of that program within the Corps of Engineers and the Environmental Protection Agency and by many private engineering firms serving local governments. He was an outstanding contributor to the public services of the ASCE Urban Water Resources Research Council through its Program.

Outside the office, Mr. Abbott took every opportunity to pursue his love of the outdoors. He was an avid pilot and was just completing his instrument rating. At the office and outside, his enthusiasm, good humor and integrity were legend. His tragic and untimely death has deprived his profession of a very promising career. He enriched the lives of all who met him and he will be sorely missed by his many friends. The Jesse W. Abbott Memorial Fund has been established at the University of Idaho, Moscow, Idaho 83843.

PREFACE

by M. B. McPherson

Background

The following Technical Memorandum is Addendum 5 of a 1977 ASCE Program report on "Urban Runoff Control Planning".[1] Addendum 1, "Metropolitan Inventories," and Addendum 2, "The Design Storm Concept," were appended to the latter report. Addendum 3[2] and Addendum 4[3] were the first of several additional, individual Addenda to be released over the period 1977-1979.

The principal intended audience of the ASCE Program's June, 1977, report was the agencies and their agents that are participating in the preparation of areawide plans for water pollution abatement management pursuant to Section 208 of the Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500). While the presentation which follows is also directed to areawide agencies and their agents, it is expected that it will be of interest and use to many others, particularly local governments.

ASCE Program

The ASCE Council on Urban Water Resources Research initiated and developed its ASCE Program of the same name. The basic purposes of the Council and its Program are to help advance the state-of-the-art by identifying and promoting needed research and by facilitating the transfer of the findings from research to users.

Abstracts of the twenty-eight reports and technical memoranda of the Program for the 1967-1974 period are included in a readily available paper.[4] The two reports and the six technical memoranda of the regular series completed since are identified in a recent publication.[5] Also included in the latter is a listing of all but one of the twelve national reports in the special technical memorandum series for the International Hydrological Programme; and the last national report[6] and an international summary[7] have been released since.

A Steering Committee designated by the ASCE Council gives general direction to the Program: S. W. Jens (Chairman); W. C. Ackermann; J. C. Geyer; C. F. Izzard; D. E. Jones, Jr.; and L. S. Tucker. M. B. McPherson is Program Director (23 Watson Street, Marblehead, Mass. 01945). Administrative support is provided by ASCE Headquarters in New York City.

The Model Tests

The Hydrologic Engineering Center of the Corps of Engineers has provided, in cooperation with others, two previous ASCE Program Technical Memoranda, a documentation of the planning model STORM[8] and a set of lectures on urban stormwater management.[9] One of the functions of the Center is to provide basic technical information in support of urban projects of the Corps of Engineers, such as for the many Urban Studies that have been undertaken. Thus, for example, the latest versions of STORM have been developed at the HEC, where the computer program is continually upgraded and made available to Corps of Engineers' offices and other public agencies including local governments.

In the U.S. national report on urban hydrological modeling and catchment research for the International Hydrological Programme,[10] we referred to two studies in progress at the HEC, one on the use of STORM applied to four California urban catchments (quantity and quality) and the other on the use of several models (quantity only) on a single catchment. The report which follows is for the second study. We expect to issue the other report subsequently.

STORM apparently enjoys the most extensive use nationally of the various models used in planning applications, particularly for total jurisdictions or entire metropolitan areas. It was the primary tool used for the most recent national assessment of urban runoff pollution,[11,12] and we know or have heard of a number of instances where it has been or is being employed in connection with areawide planning under Section 208 of PL 92-500 and in several urban studies of the Corps of Engineers. The only detailed validation of STORM that has been widely disseminated has been in the report noted earlier[8] and in the users' guide.[13] Subsequent validations have been mostly inferential or incompletely reported. The purposes of the following report were: to compare the performance of the newer versions of STORM with the original version, and for the longer record of field data that has since accumulated; to test the reliability of STORM, a relatively simplistic model, against another simple model and more complicated and comprehensive models; and to test the relative ease and cost of using a wide range of models to expand the repertoire of the Corps of Engineers at large.

The test results reported enhance the credibility of the use of STORM, once calibrated against field data. However, one catchment does not constitute a very good sample of urban America. Further, this study was not a contest, pitting one model against the other. The intention was to make a reasonable effort in the calibration of each model, giving equable attention to each, but not to engage in elaborate fine tuning such as to maximize the agreement between observed and calculated runoff. Therefore, the report should be read in terms of the relative performance of simple versus more complicated models and the results for the wide variety of models used should not be judged as being typical of any of them. To reiterate, this was an exploratory or probing study. However, despite the fact that water quality was not included, it appears to be the most extensive instance of the use of a variety of models on a U.S. urban catchment.

Lastly, readers are advised that the HEC has recently issued guidelines for the calibration and application of STORM;[14] and has described the capabilities of STORM and two other computer packages in a symposium paper.[15]

Acknowledgments

The ASCE Urban Water Resources Research Council is indebted to Mr. Abbott and The Hydrologic Engineering Center for their generous contribution of this report as a public service.

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SECTION 1

INTRODUCTION AND SUMMARY

Introduction

For several decades the Rational Formula had been the almost exclusive method used for planning and designing urban stormwater facilities. With the advent of high-speed digital computers more comprehensive and more conceptually realistic techniques have been developed for the study and design of urban water resource systems. In particular, there is now a multitude of urban runoff mathematical models, but these differ widely in their intended application, scope, reliability, data requirements and output, yet often have certain capabilities or features in common. To complicate matters, all such models are continuously subjected to modification and further verification.

Unceasing efforts to develop model refinements and the large number and kind of models have hindered development of acceptable criteria for systematic evaluation of model performance. However, several attempts have been made to categorize and compare their capabilities. Examples are an assessment of mathematical models for storm and combined sewer management,[1] a review of models and methods applicable to Corps of Engineers' Urban Studies,[2] and a comparison of the performance of five watershed models.[3]

Six models, plus two variants of one and a variant of another, were tested in the study reported here, with the objective of making a preliminary evaluation of their relative capabilities, accuracies and ease of application. A detailed comparison of the many capabilities and features of these models was beyond the scope of the study. For four of the models, plus two variants of one of them, the primary performance criterion was the degree to which simulated values matched observed daily and monthly runoff volumes for the 5.5-square mile Castro Valley Watershed near Oakland, California. In addition, tests were performed for several individual runoff events for all six models.

Procedure

Urban runoff models are often classified in terms of their application or the type of procedures used in computations with them. Principal usage categories are planning, design and operations. In order to categorize the models used in this study, four computational attributes are distinguished:

- Single-event simulation models, which generate a runoff hydrograph from a discrete storm event, usually over a duration of a few hours or days. Soil moisture processes reflect the accumulated wetting from precipitation but not the dry-weather periods between storms.

- Continuous simulation models, which generate a runoff hydrograph from a continuous series of storm events. The period of record for which continuous runoff hydrographs may be calculated varies from a few months to many years. A continuous history of precipitation data is normally the primary type of input, and soil-moisture conditions are continually simulated by the model as a function of precipitation, length of antecedent dry periods, evapotranspiration, etc.

- Hydraulic routing techniques, which approximate in varying degrees the basic equations describing unsteady flow in open channels or on land surfaces.

- Hydrologic computation techniques, which employ empirical relationships to estimate indirectly the effects of physical processes.

Four continuous simulation models were tested: Storage Treatment Overflow Runoff Model (STORM);(4) Hydrocomp Simulation Program (HSP);(5) Streamflow Synthesis and Reservoir Regulation (SSARR);(6) and Continuous Flood Hydrographs (HEC-1C).(7) Comparisons for several single-storm events were made using STORM, HSP, SSARR, Storm Water Management Model (SWMM),(8) Flood Hydrograph Package (HEC-1)(7) and Massachusetts Institute of Technology Catchment Model (MITCAT).(9) In Table 1 are listed the salient features of each model. A description of each model is presented in Section 2.

The Castro Valley Watershed (5.5-square miles) near Oakland, California, was chosen to assess the performance of the models because of availability of pertinent data. The basin consists of approximately 80% single-family residential areas and schools, 5% is strip-commercial development and the remaining 15% is undeveloped. The data base consisted of 42 months of continuous rainfall and runoff data. Data collection was funded by the San Francisco District of the Corps of Engineers as part of a study to provide data to assess the quantity and quality of storm runoff entering the San Francisco Bay. The U.S. Geological Survey at Menlo Park, California, conducted the field data collection in cooperation with The Hydrologic Engineering Center. The HEC published the annual data reports.(10)

While the performance criterion for the four continuous simulation models was the degree of correlation between observed and simulated daily and monthly runoff volumes, single-event tests were restricted to seven individual runoff events from the 42-month record.

A split-record test was used to evaluate each of the four continuous simulation models. Each model was calibrated with the first two-fifths of the 42-month record and the resultant set of coefficients were used in simulating the runoff for the remaining three-fifths of the record. The single-event models were calibrated with three individual events from the first part of the record and applied to four events from the second part. The same seven single events from the STORM simulations were extracted for comparison, with no attempt to recalibrate that model for individual events. SSARR and HSP were also not recalibrated for the individual events; however, because of available channel routing options they were rerun for the individual events using shorter time-steps.

Results and Conclusions

The results showed that each model could be calibrated on a single set of data and verified with acceptable accuracy on a different data set. The ease of application was decidedly different for all models, due to the differing level of detail in input data required. Going from the simplest to the most difficult to apply, the continuous models rank as follows: STORM, HEC-1C, SSARR, and HSP. Similar ranking of the single-event models is: HEC-1, SWMM and MITCAT. Also, a recent capability added to the STORM model (i.e., SCS procedures for computing runoff and routing) produced more accurate results than the coefficient method of computing quantity of runoff incorporated in the original version of STORM.

TABLE 1

MODEL CAPABILITIES

CONTINUOUS MODELS

	Infiltration	Basin Routing	Channel Routing	Time Step	Relative Complexity	Runoff Quality
STORM	Coefficient; SCS; Snowmelt	Triangular Unit Hydrograph	Modified Puls Muskingum	1 Hour	Low	Empirical Equations
HEC-1C	Simple nonlinear function of precipitation and losses; snowmelt	Unit Hydrograph	Modified Puls Muskingum	Variable	Low	No
HSP	Complex accounting of basin moisture	Kinematic Wave	Kinematic Wave	Variable	High	Empirical Equations
SSARR	Variable runoff coefficient is a function of soil moisture	Multiple Reservoir	Multiple Reservoir	Variable	Moderate	No

SINGLE-EVENT MODELS

	Infiltration	Basin Routing	Channel Routing	Time Step	Relative Complexity	Runoff Quality
SWMM	Horton's Equation	Kinematic Wave	Kinematic Wave	Variable	Moderate	Empirical Equations
HEC-1	Simple nonlinear function of precipitation and losses; snowmelt	Unit Hydrograph	Modified Puls Muskingum	Variable	Low	No
MITCAT	Horton; Holtan; SCS; Coefficient	Kinematic Wave	Kinematic Wave	Variable	Moderate	No

These limited tests were not intended to serve as a basis for comparison of the accuracy of the various models. However, they did show that the more complex models did not produce better results than the simple models for the Castro Valley Watershed data.

General conclusions regarding the applicability and accuracy of the several models cannot be made on the basis of this study, and that was not the intent. However, some general impressions surfaced as a result of attempts to apply each model to the same data set.

The continuous models were calibrated on daily and monthly volumes for the first 17 months of the record. Therefore, these models may not adequately represent the peak flows for the single events, especially for such a small drainage area. Their response could have been improved by recalibrating them against discrete events.

The models which utilize hydrologic computation techniques (STORM, HEC-1, and SSARR) produced results for the Castro Valley Watershed that were of an equal acceptability to those which use hydraulic techniques (SWMM, MITCAT, and HSP). A possible explanation is that, at least for the data set used in this study, the lumped-parameter hydrologic models required less judgment in assigning magnitudes to the various model parameters. Because the data available were limited, the exercise of having to estimate the magnitudes of a larger number of parameters for the more complex models may have introduced errors. Therefore, while the models which use hydraulic techniques may produce more accurate results where adequate data are available, the results of this study suggest that the simpler models can definitely be used effectively in planning or screening type applications.

The relationship between the time step used in the models and the basin time of concentration may have introduced errors. Each continuous model was operated on a 1-hour time step, which is approximately equal to the time of concentration for the Castro Valley Watershed. One would normally restrict the time step to something less than the time of concentration of the basin in order to define hydrographs adequately.

A disadvantage of STORM and HEC-1C is that neither simulate base flow, Therefore, the base flow had to be estimated and added to the appropriate values for use in comparison with observed data. SSARR and HSP results include base flow, making direct comparison with observed flow data more straightforward.

SECTION 2

DESCRIPTIONS OF WATERSHED AND MODELS

Watershed

The Castro Valley Watershed was chosen for this simulation study primarily because of availability of precipitation and runoff data. At the present time there are four recording rain gages in the basin and one recording flow gage at the outlet of the basin. The flow gage, operated by the U.S. Geological Survey, and one rain gage, operated by the Castro Valley Fire Department, were placed in operation in November, 1971. Three other recording rain gages, two funded by The Hydrologic Engineering Center and one by the Alameda County Flood Control and Water Conservation District, were put in operation in the fall of 1975. The purpose of these additional rain gages was to provide data on the spatial variation of rainfall across the basin and thus to allow better computation of basin average precipitation. However, two successive and unusually dry years have precluded collection of a significant amount of data. Runoff quality for several selected storms each year was collected during the 71-72, 72-73, and 74-75 water years. The storm runoff quality measurements and the flow gage were funded by the San Francisco District, Corps of Engineers, and the equipment was operated by the Menlo Park office of the U.S. Geological Survey with guidance from The Hydrologic Engineering Center.(10)

Figure 1 is a topographic map of the Castro Valley Watershed. The drainage area above the flow gage is 5.5-square miles. The basin is primarily residential (80%) with a small amount of strip-commercial development (5%), and the remainder is in the undeveloped, hilly, brush-covered headwaters of Castro Valley Creek. The central portion of the valley is relatively flat while the perimeter of the basin is quite steep and hilly. The minimum elevation in the basin is 100-feet MSL while the maximum is 1110-feet MSL.

The climate of the area is characterized by warm, dry, summer-fall seasons and relatively humid winter seasons. The average annual precipitation is approximately 23-inches, almost all of which occurs during the period of November through March. Temperatures below freezing are extremely rare.

Because little change in land use occurred over the 42-month period for which data were used, the runoff record was considered to be statistically homogeneous.

Continuous Models

STORM

The Storage, Treatment, Overflow, Runoff Model is a continuous simulation model designed to be used primarily in planning studies for evaluating storage and treatment capacity required to reduce pollution from stormwater runoff or combined sewer system overflows.(4) Pollutograph (variations in pollutant mass-emission rates with time) loadings can also be computed for use in a receiving water assessment model. STORM uses a one-hour computation interval.

Because STORM was intended for use in metropolitan planning or total jurisdiction master planning for screening alternatives, some of its analytical techniques are necessarily simplified. For example, the two procedures used to compute the quantity of runoff in STORM are the coefficient method and the Soil

FIGURE 1

CASTRO VALLEY WATERSHED

Conservation Service (SCS) method. In the coefficient method, a single runoff coefficient weighted according to land-use is applied to each hour of rainfall in excess of depression storage to compute runoff. Therefore, the runoff coefficient is a function of only the relative amounts of pervious and impervious areas in the watershed. Antecedent conditions and rainfall intensity are not taken into account.

The SCS runoff-curve-number technique is considered to be more conceptually correct than the coefficient method. The SCS curve consists of a nonlinear relationship between accumulated rainfall and accumulated runoff.[11] The procedure, as developed by the SCS, was intended to be used on single events. Three antecedent moisture conditions were available to adjust the curve number for prior precipitation. Because STORM is fundamentally a continuous model, HEC developed a procedure that computes the curve number for each event based on the number of dry hours since the previous runoff event and the interevent evapotranspiration and percolation. A third method used is a combination, with the coefficient method applied to impervious areas and the SCS method applied to pervious areas of the watershed.

STORM possesses many other capabilities which were not used in this study. These include quality of storm runoff as defined by six parameters, snow accumulation and melt, land-surface erosion, quantity and quality of dry-weather flow, and analysis of storage volumes and treatment rates.

HEC-1C

HEC-1C is an adaptation of The Hydrologic Engineering Center's computer program, Flood Hydrograph Package (HEC-1).[7] It performs a simple continuous synthesis of basin moisture. Basin moisture is expressed as a function of precipitation, losses, and an evapotranspiration recovery factor. Basin moisture, in turn, controls the loss rate function, which governs how much of the precipitation is divided between losses and runoff excess. Runoff excess is transformed by a unit hydrograph into sub-basin outflows. Outflows may then be combined and routed to obtain a continuous watershed response. Various computation time increments may be used, depending on watershed size and precipitation data available. Output includes event hydrographs as well as daily, monthly, and annual runoff summaries.

SSARR

The Streamflow Synthesis and Reservoir Regulation (SSARR) Model is a continuous simulation model designed to be used for operation of a river basin system. Its development began in 1956 as an operational tool for the Columbia River System.[6] However, in recent years it has been used successfully in many locations in the U.S. and abroad. Its functional use is for large non-urban watersheds, but in this study it was successfully applied to a small urbanized watershed.

The model consists of watershed, river system, and reservoir regulation modules for comprehensive analyses and day-to-day operational use. Obviously, the river system and reservoir regulation modules were not used in this study.

In the SSARR model, runoff in any given time period is a function of an empirically derived relationship between runoff and the soil moisture index (SMI). The SMI is then increased by the moisture input not contributing to runoff and reduced by an adjusted evapotranspiration index. Computations are made for each incremental time period. The SMI is a relative soil wetness used to determine runoff. When the soil moisture is depleted (by evapotranspiration) to a value approximately equivalent to the permanent wilting point, the value of the SMI is considered to be zero. When rain and/or snowmelt recharges soil moisture, the value of the SMI increases until it reaches a maximum value considered to represent its field capacity. The computed runoff, which is a percentage of total moisture input, based on the SMI, is divided into surface, subsurface, and baseflow components; and each of these components are routed separately through basin storage and combined to develop basin outflow.

Hydrocomp Simulation Program

The Hydrocomp Simulation Program (HSP) is an improved version of the Stanford Watershed Model and is one of the most comprehensive continuous models available for analysis of runoff quantity. The program is organized into subprograms for: (1) data management; (2) modeling the rainfall-runoff process on the land surface; and (3) routing land surface runoff through a stream network of open channels and closed conduits to produce continuous hydrographs at a series of locations within the watershed.

The "Lands" subprogram is the principal component in the determination of the total stream flow timing and runoff. "Lands" is intended to represent the hydrologic cycle for a unit area using observed precipitation to simulate either rain or snowfall, and accounts for interception storage, infiltration (based upon the equation for infiltration developed by Phillips) to two soil moisture storages, routing of surface runoff over an overland flow plain from pervious surfaces, impervious runoff, interflow runoff, and groundwater runoff. Estimated continuous potential evapotranspiration is determined from observed evaporation and used in the model to estimate the actual evaporation from each storage. Watersheds with different land-use characteristics can be represented by a series of subwatersheds with specific parameters assigned to them for unique hydrologic characteristics. The channel network is represented by a series of channel lengths where each length has a tributary area. The description of the channel network is entered as the physical characteristics of the individual channel length. The upstream and downstream elevations, bottom and top width, channel depth, overbank flood plain slope, and Manning's n for the channel and overbank flood plain are specified for each open channel reach. Closed conduit channel lengths are represented by invert slope, diameter, and Manning's n. A good physical representation of the channel network is necessary for evaluating the impact of proposed changes to the channel system.

The HSP routing algorithm is based upon the kinematic wave approach. Other capabilities of HSP include the simulation of stream water quality and reservoir routing.

Single-Event Models

HEC-1

The Flood Hydrograph Package (HEC-1) is suitable for most rainfall-runoff computations for a complex, multi-basin, multi-channel river basin.[7] Precipitation must be input as a single hypothetical or recorded event because there are no computations for loss-rate recovery during periods without precipitation, as opposed to HEC-1C, described earlier. HEC-1 has a user-specified computation interval.

Five major types of flood hydrograph analyses can be performed using HEC-1:

- Rainfall-runoff routing to simulate the hydrologic response of a watershed.
- Stream system computations for a watershed using precipitation depth-area relationships.
- Optimization of unit hydrograph and loss rate parameters.
- Optimization of routing parameters.
- Simulation of multiple-basin development plans using multiple floods and economic analysis of flood damages.

The model may be used to optimize loss rate and routing parameters to achieve a best-fit reconstitution of an observed hydrograph using known precipitation. This option was used in the calibration phase of this study to develop a set of parameters for several observed events.

Several techniques are provided to process and distribute precipitation data, compute precipitation or snow accumulation, compute precipitation or snow-melt excesses, define sub-basin outflows by using unit hydrographs, and to route hydrographs using hydrologic methods. Different techniques for each process may be combined in the same project if appropriate. Graphical display of precipitation excess and runoff hydrographs can be provided.

Storm Water Management Model

The Environmental Protection Agency's Storm Water Management Model (SWMM) was designed specifically for analysis of urban storm water runoff and is one of the most comprehensive of such tools available.(8) Storm runoff and sanitary sewage flows from several subcatchments can be computed using data from several precipitation stations. Flow and quality are routed in a converging or "tree-like" network of pipes or open channels. Diversion features can be modeled and either on-line or off-line storage can be simulated. Off-line treatment can be modeled. The program also contains a module to assess the impact of pollutant loadings on a receiving water body.

The only portion used in this study was the runoff module. Techniques used in this module are hydraulic in nature, i.e., explicit calculations are made of the depth of water in overland flow and in channels. This technique requires detailed subcatchment data, including subcatchment characteristics and channel geometry. Rainfall excess is computed using Horton's infiltration equation, a simple time-decay of infiltration rate. Rainfall intensity is not considered. The model has the capability of using data from a different raingage (a single hyetograph) for each subcatchment. The kinematic wave method is used for overland flow and channel flow routing in the version of SWMM employed in this study.

Massachusetts Institute of Technology Catchment Model

The Massachusetts Institute of Technology Catchment Model (MITCAT)(9) is a comprehensive mathematical model used for the study of stormwater runoff. It has many similarities to the SWMM model except that MITCAT has no runoff quality computation capability and does not possess computational elements for treatment and receiving waters.

Runoff volume is calculated by one of four infiltration equations: Horton's method, Holtan's method, SCS method and the coefficient method. A catchment is discretized into a series of overland flow planes, stream segments and pipe segments. Runoff excesses are routed over the watershed surface and in conveyance elements by the kinematic wave method. The model also possesses a reservoir routing module.

SECTION 3

SIMULATION RESULTS, CONTINUOUS MODELS

Procedure

A split-record test was devised to demonstrate the application of each continuous simulation model. The available runoff record was divided into two subsets. The first subset consisted of the records for the 17 months beginning in November 1971 and continuing through March 1973. The second subset consisted of the records for the 25 months beginning in April 1973 and ending in April 1975. For several of the months in each subset there was no measurable precipitation (four months in the first subset and 12 in the second subset). STORM and HEC-1C did not generate any simulated runoff for these months because they do not simulate base flow.

The first data subset was used as the calibration period. Appropriate coefficients regulating the runoff quantity in each model were adjusted so that computed total period runoff volumes, monthly volumes and daily volumes most nearly matched observed values for the data subset. Each model was considered calibrated when further adjustment of certain coefficients did not produce significantly closer agreement. One cannot guarantee that the final sets of parameters are unique since there are more parameters requiring adjustment in each model than the number that are measurable or can be easily defined.

The following routing methods were used in the continuous model applications, with a one-hour time step employed in each instance:

	STORM	HEC-1C	HSP	SSARR
Land Surface:	unit hydrograph	unit hydrograph	kinematic wave	multiple reservoir
Channels:	none	none	kinematic wave	multiple reservoir

Results

Table 2 presents the computed and observed monthly runoff volumes for the calibration period. Table 3 presents the computed and observed daily runoff volumes for the calibration period.

Conclusions with respect to the accuracies of each model for the Castro Valley application should be made on the basis of agreement between computed and observed results from the second data subset or verification period. All results for the verification period were obtained by using the coefficients developed during the calibration phase for each model. Table 4 presents the computed and observed monthly runoff volumes for the verification period. Table 5 presents the computed and observed daily runoff volumes for the verification period.

Interpretation of Results

A statistical analysis was performed using the HEC Multiple Linear Regression program(12) in order to quantify the degree of agreement between computed and observed results. The results of that analysis are presented in Table 6, page 19.

(Continued on Page 20)

TABLE 2

RESULTS FOR CONTINUOUS MODELS
FOR THE CALIBRATION PERIOD,
CASTRO VALLEY MONTHLY VOLUMES (INCHES)

Year	Month	Observed Runoff	Estimated Base Flow*	STORM** LEQ-1	STORM** LEQ-2	STORM** LEQ-3	HEC-1C	HSP	SSARR
71	11	.31	.04	.35	.40	.37	.48	.20	.29
	12	1.33	.08	1.21	1.86	1.60	1.68	1.56	1.87
72	1	.45	.12	.38	.40	.37	.48	.29	.62
	2	.53	.14	.40	.47	.44	.56	.32	.62
	4	.30	.09	.23	.23	.28	.36	.13	.21
	6	.15	.09	.15	.16	.16	.18	.07	.15
	9	.19	.05	.27	.12	.17	.21	.27	.22
	10	.90	.06	.77	1.31	1.01	1.28	2.73	.91
	11	2.53	.13	1.39	2.30	2.16	2.80	2.65	2.62
	12	.81	.17	.73	.76	.78	1.16	.79	1.22
73	1	5.13	.68	2.80	4.71	5.00	5.36	5.59	6.00
	2	3.84	.66	2.17	2.95	3.03	3.82	3.24	4.21
	3	1.81	.52	1.31	1.58	1.46	2.33	1.70	2.28
	SUM	18.28	2.83	12.16	17.25	16.83	20.70	19.54	21.22
	MEAN	1.41	.22	.94	1.33	1.29	1.59	1.50	1.63
STANDARD DEVIATION		1.56		.82	1.36	1.41	1.59	1.66	1.78

*: Baseflow estimations have been added to values for STORM and HEC-1C. (Baseflow is included in values computed by HSP and SSARR).

**: LEQ-1 = Loss Equation No. 1 (Coefficient Method)
LEQ-2 = Loss Equation No. 2 (SCS Method)
LEQ-3 = Loss Equation No. 3 (Combination of both methods)

TABLE 3

RESULTS FOR CONTINUOUS MODELS
FOR THE CALIBRATION PERIOD,
CASTRO VALLEY DAILY RUNOFF VOLUMES (INCHES)

DATE	OBSERVED RUNOFF	STORM LEQ-1	STORM LEQ-2	STORM LEQ-3	HEC-1C	HSP	SSARR
711111	.007	.000	0.000	.010	0.000	0.000	.008
711112	.020	0.000	0.000	.010	0.000	.008	0.000
711113	.060	.148	.128	.190	.073	.106	.139
711126	.039	.045	.037	.070	.046	.038	.054
711128	.139	.165	.145	.150	.106	.114	.127
711202	.146	.242	.168	.240	.146	.144	.174
711203	.030	.010	.024	.030	.020	.030	.020
711213	.093	.076	0.000	0.000	.086	.068	0.000
711221	.113	.167	.109	.160	.106	.068	.125
711222	.126	.166	.135	.260	.106	.213	.124
711223	.023	.019	.034	.040	.026	.053	.027
711224	.252	.559	.279	.360	.246	.380	.415
711225	.272	.488	.182	.200	.756	.440	.446
711226	.021	.005	.010	.050	.010	.068	.011
711227	.120	.042	.061	.070	.011	.152	.049
711228	.009	.000	.007	.010	.033	.023	.006
711229	.021	.003	.014	.020	.027	.053	.011
720124	.004	.020	.011	.040	.033	.061	.033
720125	.065	.058	.093	.100	.080	.121	.076
720126	.028	.007	.037	.040	.033	.091	.030
720127	.153	.192	.124	.150	.106	.213	.112
720204	.040	.007	.006	.060	.027	.061	.030
720205	.240	.257	.176	.240	.160	.273	.180
720206	.015	0.000	0.000	0.000	.013	.030	0.000
720221	.013	.005	.004	.050	.028	.030	.024
720222	.067	.057	.060	.060	.040	.091	.052
720223	.022	.004	.015	.010	.013	.030	.012
720405	.080	.054	.056	.100	.047	.046	.070
720406	.064	.008	.038	.030	.027	.030	.030
720424	.056	.061	.046	.080	.060	.053	.062
720609	.062	0.000	0.000	0.000	.047	.061	.074
721009	.073	.076	.071	.110	.073	.068	.082
721011	.418	.952	.409	.750	.458	.334	.645
721012	.021	.001	0.000	.010	.047	.038	0.000
721013	.004	0.000	0.000	0.000	.002	.008	0.000
721014	.100	.102	.078	.140	1.567	.121	.088
721015	.059	.015	.042	.040	.146	.091	.034
721016	.126	.101	.082	.150	.153	.137	.087
721017	.030	.005	.014	.020	.070	.076	.012
721018	.005	0.000	0.000	0.000	.027	.008	0.000
721019	.003	0.000	0.000	0.000	.013	0.000	0.000
721103	.140	.136	.153	.400	.166	.114	.157
721104	.299	.222	.103	.080	.060	.114	.149
721105	.013	0.000	0.000	0.000	.013	.008	0.000
721106	.010	0.000	0.000	0.000	.007	0.000	0.000
721107	.166	.106	.088	.170	.100	.114	.096
721108	.005	0.000	0.000	0.000	.013	.008	0.000

(Continued)

TABLE 3 (Continued)

RESULTS FOR CONTINUOUS MODELS
FOR THE CALIBRATION PERIOD,
CASTRO VALLEY DAILY RUNOFF VOLUMES (INCHES)

DATE	OBSERVED RUNOFF	STORM LEQ-1	STORM LEQ-2	STORM LEQ-3	HEC-1C	HSP	SSARR
721109	.013	.003	0.000	.030	.020	.008	.006
721110	.312	.383	.216	.380	.279	.250	.300
721111	.093	.081	.064	.130	.146	.121	.067
721112	.008	0.000	0.000	0.000	.033	.008	0.000
721113	.200	.157	.134	.170	.146	.167	.174
721114	.246	.006	.002	0.000	.219	.288	.005
721115	.656	.994	.414	1.030	.876	.615	.982
721116	.146	.027	.036	.110	.166	.281	.038
721117	.021	0.000	0.000	0.000	.113	.114	0.000
721118	.012	0.000	0.000	.010	.046	.030	0.000
721119	.080	.057	.053	.170	.146	.167	.059
721206	.153	.146	.153	.240	.140	.228	.142
721207	.062	.006	.056	.050	.060	.137	.046
721208	.010	0.000	0.000	0.000	.013	.015	0.000
721209	.009	0.000	0.000	0.000	.013	0.000	0.000
721216	.023	.015	.013	.060	.040	.053	.034
721217	.160	.084	.150	.120	.053	.121	.122
721218	.023	.203	.143	.380	.179	.129	.142
721219	.120	.127	.046	.020	.086	.220	.084
721220	.017	0.000	0.000	0.000	.033	.023	0.000
721222	.044	.001	0.000	.040	.026	.046	.012
721227	.028	.005	0.000	.030	.013	.038	.012
730108	.272	.329	.254	.500	.310	.387	.310
730109	.671	.690	.308	.450	.548	.653	.561
730110	.046	0.000	0.000	0.000	.132	.091	0.000
730111	.472	.472	.246	.480	.515	.493	.418
730112	.558	.252	.148	.290	.429	.425	.345
730113	.047	0.000	0.000	0.000	.105	.030	0.000
730114	.032	0.000	0.000	0.000	.052	.008	0.000
730115	.023	0.000	0.000	0.000	.033	0.000	0.000
730116	.967	.897	.425	1.150	1.010	.956	.914
730117	.362	.276	.190	.480	.522	.417	.424
730118	1.003	.942	.373	.900	1.040	1.154	1.140
730119	.073	0.000	0.000	0.000	.159	.061	0.000
730120	.036	0.000	0.000	0.000	.079	.008	0.000
730121	.100	.045	.034	.080	.126	.167	.045
730125	.061	.014	.026	.030	.066	.129	.030
730129	.133	.108	.100	.240	.159	.266	.105
730203	.080	.022	.035	.080	.066	.137	.048
730205	.048	.010	.018	.050	.039	.030	.018
730206	.675	.733	.363	.800	.727	.812	.620
730207	.060	0.000	0.000	0.000	.106	.137	0.000
730208	.030	0.000	0.000	0.000	.059	.023	0.000
730209	.259	.209	.161	.420	.337	.250	.222
730210	.166	.037	.054	.070	.145	.296	.050
730211	.146	.034	.078	.100	.165	.213	.082
730212	.186	.088	.106	.130	.205	.243	.181

(Continued)

TABLE 3 (Continued)

RESULTS FOR CONTINUOUS MODELS
FOR THE CALIBRATION PERIOD,
CASTRO VALLEY DAILY RUNOFF VOLUMES (INCHES)

DATE	OBSERVED RUNOFF	STORM LEQ-1	STORM LEQ-2	STORM LEQ-3	HEC-1C	HSP	SSARR
730213	.146	.099	.043	.040	.185	.220	.126
730214	.239	.099	.110	.230	.284	.296	.187
730215	.045	0.000	0.000	0.000	.085	.023	0.000
730226	.326	.348	.206	.400	.013	0.000	.262
730227	.996	.595	.324	.750	.443	.562	.543
730228	.139	.000	.005	0.000	.072	.205	.005
730303	.259	.188	.129	.320	.218	.334	.161
730306	.232	.171	.099	.310	.231	.281	.126
730307	.086	.033	.034	.090	.092	.091	.037
730308	.056	.004	.015	.010	.072	.121	.012
730310	.073	.043	.024	.110	.046	.114	.045
730319	.232	.271	.181	.410	.178	.273	.220
730320	.052	.001	.006	.010	..039	.197	.005
730321	.099	.079	.091	.180	.145	.228	.074
730330	.232	.270	.209	.370	.212	.372	.264
SUM	16.02	8.93	14.24	13.67	17.15	17.72	18.15
MEAN	.147	.082	.131	.125	.157	.163	.167
STANDARD DEVIATION	.200	.104	.220	.206	.226	.242	.197

TABLE 4

RESULTS FOR CONTINUOUS MODELS
FOR THE VERIFICATION PERIOD,
CASTRO VALLEY MONTHLY VOLUMES (INCHES)

Year	Month	Observed Runoff	Estimated Base Flow*	STORM** LEQ-1	STORM** LEQ-2	STORM** LEQ-3	HEC-1C	HSP	SSARR
73	10	.39	.09	.39	.42	.41	.59	.27	.25
	11	3.84	.15	2.46	4.69	4.50	5.20	4.08	3.65
	12	2.63	.25	1.10	2.38	2.11	2.34	1.99	1.88
74	1	1.68	.48	1.60	1.55	1.60	1.97	3.13	3.35
	2	.69	.25	.44	.64	.60	.91	.43	.65
	3	2.04	.44	1.38	1.85	1.64	2.07	1.43	1.84
	4	2.49	.51	1.43	2.56	2.53	2.77	2.24	1.98
	11	.27	.05	.23	.36	.29	.55	.17	.12
	12	.57	.09	.59	.60	.57	.86	.34	.37
75	1	1.02	.10	.85	1.39	1.15	1.58	.74	.65
	2	1.56	.38	1.36	1.46	1.59	1.94	1.68	1.49
	3	2.68	.46	1.90	2.97	2.62	3.84	2.88	3.07
	4	.99	.37	.79	.95	.88	1.34	.62	1.06
	SUM	20.85	3.60	14.52	21.82	20.49	25.96	20.00	20.36
	MEAN	1.60	.28	1.12	1.68	1.58	2.00	1.54	1.57
STANDARD DEVIATION		1.08		.65	1.23	1.17	1.34	1.26	1.20

*: Baseflow estimations have been added to values for STORM and HEC-1C. (Baseflow is included in values computed by HSP and SSARR).

**: LEQ-1 = Loss Equation No. 1 (Coefficient Method)
LEQ-2 = Loss Equation No. 2 (SCS Method)
LEQ-3 = Loss Equation No. 3 (Combination of both methods)

TABLE 5

RESULTS FOR CONTINUOUS MODELS
FOR THE VERIFICATION PERIOD,
CASTRO VALLEY DAILY RUNOFF VOLUMES (INCHES)

DATE	OBSERVED RUNOFF	STORM LEQ-1	STORM LEQ-2	STORM LEQ-3	HEC-1C	HSP	SSARR
731006	.013	.004	0.000	.030	.013	.137	.012
731007	.133	.180	.189	.170	.139	.008	.174
731008	.033	0.000	0.000	0.000	0.000	0.000	0.000
731009	.013	0.000	0.000	0.000	0.000	.030	0.000
731022	.099	.126	.095	.240	.085	.053	.104
731105	.996	1.347	.574	1.030	.549	.342	1.071
731106	.532	.373	.185	.240	.304	.410	.289
731107	.066	0.000	0.000	0.000	.072	.038	0.000
731108	.027	0.000	0.000	0.000	.033	.008	0.000
731109	.133	.014	.006	.050	.039	.053	.029
731110	.266	.148	.167	.210	.165	.266	.155
731111	.398	.394	.270	.640	.423	.478	.498
731112	.066	.385	.144	.250	.364	.402	.430
731113	.023	.003	.003	.030	.079	.083	.007
731116	.246	.387	.242	.620	.463	.516	.369
731117	.186	.229	.149	.330	.278	.380	.302
731130	.617	1.207	.529	1.460	1.020	.713	1.113
731201	.272	.380	.103	.120	.297	.653	.304
731211	.093	.095	.067	.200	.092	.197	.080
731213	.093	.099	.085	.130	.119	.213	.075
731221	.133	.100	.103	.180	.112	.220	.107
740103	.412	.626	.315	.690	.740	.721	.566
740104	.173	.144	.050	.070	.238	.243	.141
740105	.080	.019	.056	.090	.198	.182	.025
740106	.052	.002	.032	.040	.099	.091	.026
740107	.073	.002	.027	.020	.079	.091	.022
740116	.246	.201	.189	.400	.258	.395	.216
740117	.073	.025	.028	.020	.126	.213	.032
740118	.067	.000	0.000	.010	.052	.046	0.000
740119	.080	.010	.032	.050	.079	.106	.029
740131	.046	.039	.028	.060	.052	.114	.047
740201	.052	.019	.042	.060	.052	.129	.034
740212	.064	.029	.018	.110	.039	.091	.039
740216	.040	.029	0.000	.060	.019	.053	.037
740219	.153	.216	.126	.290	.145	.288	.149
740228	.173	.092	0.000	.110	.006	0.000	.082
740301	.415	.465	.204	.450	.231	.243	.320
740302	.166	.022	.078	.090	.152	.304	.065
740303	.173	.129	.081	.080	.178	.205	.126
740307	.120	.123	.076	.130	.112	.197	.092
740325	.093	.102	.106	.130	.099	.175	.115
740327	.252	.301	.220	.550	.337	.220	.251
740328	.212	.193	.105	.070	.066	.334	.153
740330	.133	.062	.054	.050	.046	.121	.044
740401	1.508	1.800	.695	1.660	1.560	1.442	1.760
740402	.120	0.000	0.000	0.000	.172	.167	0.000
740409	.146	.126	.107	.280	.106	.266	.117
740423	.113	.113	.084	.200	.079	.106	.096

(Continued)

TABLE 5 (Continued)

RESULTS FOR CONTINUOUS MODELS
FOR THE VERIFICATION PERIOD,
CASTRO VALLEY DAILY RUNOFF VOLUMES (INCHES)

DATE	OBSERVED RUNOFF	STORM			HEC-1C	HSP	SSARR
		LEQ-1	LEQ-2	LEQ-3			
740708	.113	.152	.124	.160	.092	0.000	.133
741027	.092	.031	.028	.070	.046	.053	.047
741028	.055	.061	.048	.040	.033	0.000	.041
741029	.001	0.000	0.000	0.000	0.000	0.000	0.000
741107	.139	.280	.162	.390	.139	.121	.191
741121	.050	.028	.015	.080	0.000	.030	.037
741202	.119	.074	.105	.150	.113	.076	.110
741203	.165	.277	.194	.360	.133	.152	.175
741227	.119	.142	.151	.210	.133	.091	.153
741228	.041	.009	.029	.030	.027	.046	.024
750106	.403	.799	.367	.780	.412	.334	.623
750107	.046	.003	.010	.040	.053	.038	.009
750108	.192	.204	.168	.240	.080	.137	.147
750131	.198	.268	.202	.380	.173	.152	.246
750201	.099	.026	.071	.080	.080	.182	.057
750202	.139	.076	.113	.170	.126	.182	.091
750203	.085	.067	.075	.060	.093	.167	.062
750204	.099	.037	.066	.120	.120	.152	.055
750208	.139	.066	.102	.180	.100	.083	.081
750209	.238	.282	.180	.260	.226	.296	.254
750210	.048	.000	.010	.010	.106	.197	.007
750212	.145	.239	.152	.340	.206	.167	.209
750213	.225	.208	.124	.150	.252	.417	.281
750219	.092	.075	.079	.130	.093	.197	.091
750305	.043	.043	.031	.070	.040	.038	.049
750307	.383	.439	.301	.590	.325	.463	.362
750308	.159	.118	.102	.110	.179	.281	.100
750309	.019	0.000	0.000	0.000	.053	.030	0.000
750310	.132	.126	.086	.120	.146	.213	.086
750313	.377	.643	.290	.890	.624	.577	.576
750314	.035	0.000	0.000	0.000	.053	.099	0.000
750315	.198	.178	.107	.280	.186	.152	.141
750316	.126	.057	.021	0.000	.093	.213	.044
750321	.483	.648	.321	.840	.511	.440	.577
750322	.126	.002	.010	.010	.113	.334	.009
750325	.251	.256	.153	.380	.319	.357	.202
750404	.239	.294	.239	.540	0.000	.334	.253
750405	.192	.070	.079	.100	0.000	.342	.076
750407	.119	.178	.102	.280	0.000	.099	.128
SUM	15.60	10.08	16.82	15.43	20.34	15.44	18.98
MEAN	.179	.116	.193	.177	.234	.178	.218
STANDARD DEVIATION	.209	.127	.296	.267	.303	.229	.211

TABLE 6

STATISTICAL ANALYSIS OF RESULTS
FOR THE CONTINUOUS MODELS

	STORM LEQ-1	STORM LEQ-2	STORM LEQ-3	HEC-1C	HSP	SSARR
	MONTHLY CALIBRATION PERIOD					
$\overline{R}^2$	.97	.96	.97	.97	.97	.99
Standard Error (in.)	.27	.32	.25	.18	.56	.17
	MONTHLY VERIFICATION PERIOD					
$\overline{R}^2$	.84	.95	.94	.91	.81	.75
Standard Error (in.)	.43	.24	.26	.33	.47	.55
	DAILY CALIBRATION PERIOD					
$\overline{R}^2$	.76	.79	.85	.79	.52	.84
Standard Error (in.)	.10	.09	.08	.09	.14	.08
	DAILY VERIFICATION PERIOD					
$\overline{R}^2$	.82	.89	.88	.75	.77	.67
Standard Error (in.)	.09	.07	.07	.10	.10	.12

The results presented in Table 6 show that the SCS Runoff-Curve-Number Technique in STORM (combined with the HEC-developed simple moisture-accounting procedure) produced better results than the coefficient method. One would expect this to be the case since the HEC-developed method attempts to account for antecedent conditions (although crudely) and the SCS method attempts to account for the nonlinearity between rainfall and runoff during a rainfall sequence. The coefficient method uses a land-use weighted runoff coefficient computed from runoff coefficients for the pervious and impervious portions of the watershed. The basis of weighting is the relative per cent of imperviousness of each land use. The composite runoff coefficient is held constant throughout an entire simulation regardless of rainfall amounts or antecedent conditions.

The degree of complexity of data preparation and rainfall-runoff calculations had less effect on results than expected. While rainfall-runoff procedures in HSP and SSARR are quite involved, they did not produce better results than STORM or HEC-1C when comparing daily and monthly volumes. It should be pointed out that SSARR was developed to model rather large nonurban basins in the Columbia River System, while STORM and HEC-1C were developed to be used as generalized planning tools for smaller urban or urbanizing basins. Despite this difference in original purpose, SSARR was successfully adapted to an urban watershed.

SECTION 4

SIMULATION RESULTS, SINGLE-EVENT MODELS

Procedure

Comparisons of results from STORM, HSP, SSARR, HEC-1, SWMM and MITCAT were made for several individual runoff events. Three events were taken from the calibration period and four from the verification period. For the continuous simulation model STORM, the corresponding single-event hydrographs were simply extracted from the results previously obtained during the calibration and verification of monthly and daily runoff volumes (i.e., no special attempt was made to recalibrate for the single events). For the continuous simulation models SSARR and HSP, no special attempt was made to recalibrate them for single events; however, because of available channel routing options they were rerun for the individual events using shorter time steps (6-min. for SSARR and 15-min. for HSP).

The following routing methods were used in the single-event model applications:

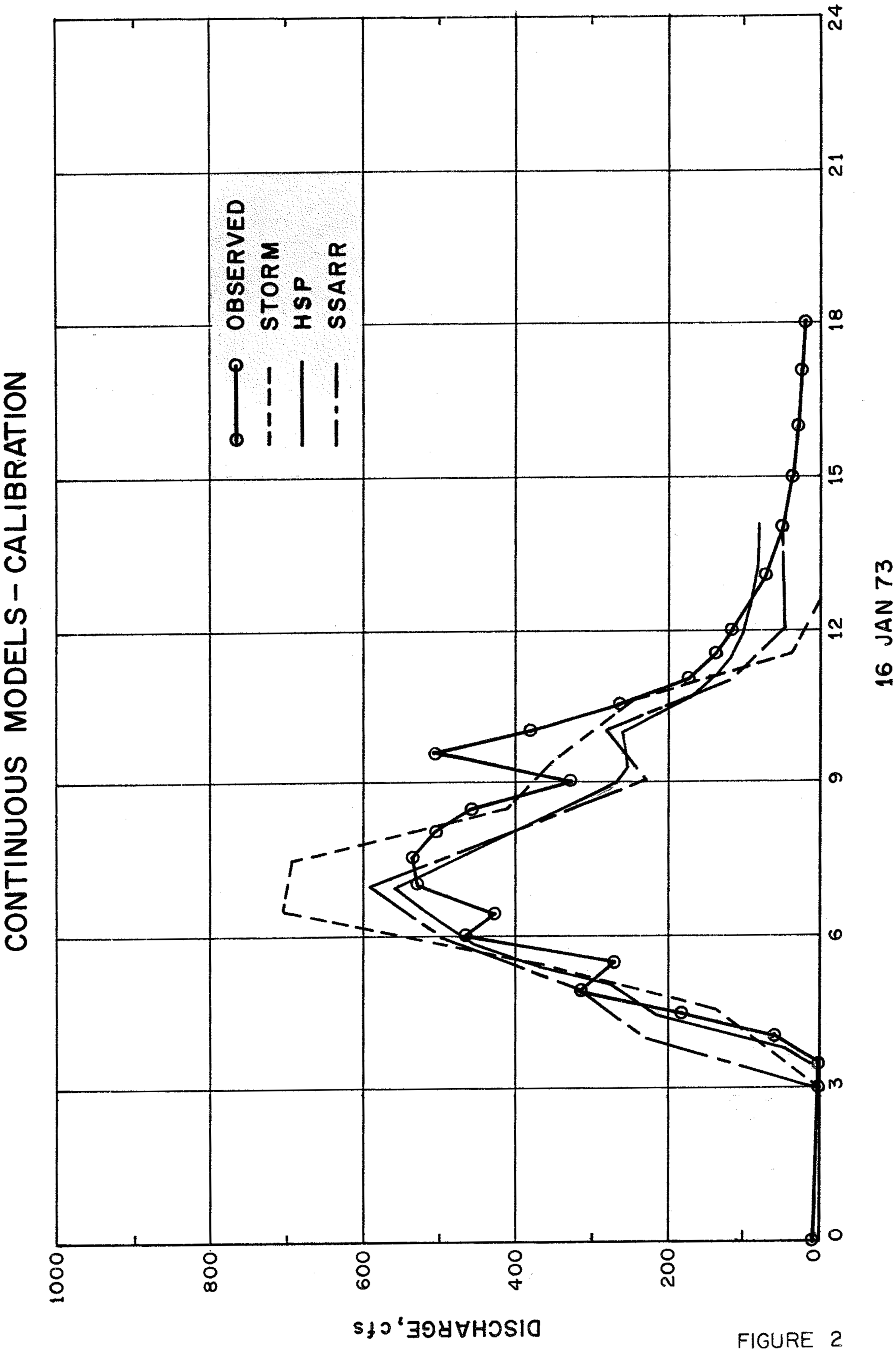
	HEC-1	SWMM	MITCAT
Land Surface:	unit hydrograph	kinematic wave	kinematic wave
Channels:	none	kinematic wave	kinematic wave

Results

The observed versus the computed results for the three events in the calibration period are shown in Figures 2 through 7, and Figures 8 through 15 show the results for the four events in the verification period:

Calibration		
16 Jan 73		
	Continuous Models:	Figure 2, page 22
	Single Event Models:	Figure 3, page 23
17-18 Jan 73		
	Continuous Models:	Figure 4, page 24
	Single Event Models:	Figure 5, page 25
6 Feb 73		
	Continuous Models:	Figure 6, page 26
	Single Event Models:	Figure 7, page 27
Verification		
3-4 Jan 74		
	Continuous Models:	Figure 8, page 28
	Single Event Models:	Figure 9, page 29
5 Jan 74		
	Continuous Models:	Figure 10, page 30
	Single Event Models:	Figure 11, page 31
16-17 Jan 74		
	Continuous Models:	Figure 12, page 32
	Single Event Models:	Figure 13, page 33
1 Apr 74		
	Continuous Models:	Figure 14, page 34
	Single Event Models:	Figure 15, page 35

(Continued on Page 36)



CONTINUOUS MODELS - CALIBRATION
OBSERVED
STORM
HSP
SSARR
DISCHARGE, cfs
0
200
400
600
800
1000
0
3
6
9
12
15
18
21
24
16 JAN 73

FIGURE 2

SINGLE EVENT MODELS - CALIBRATION

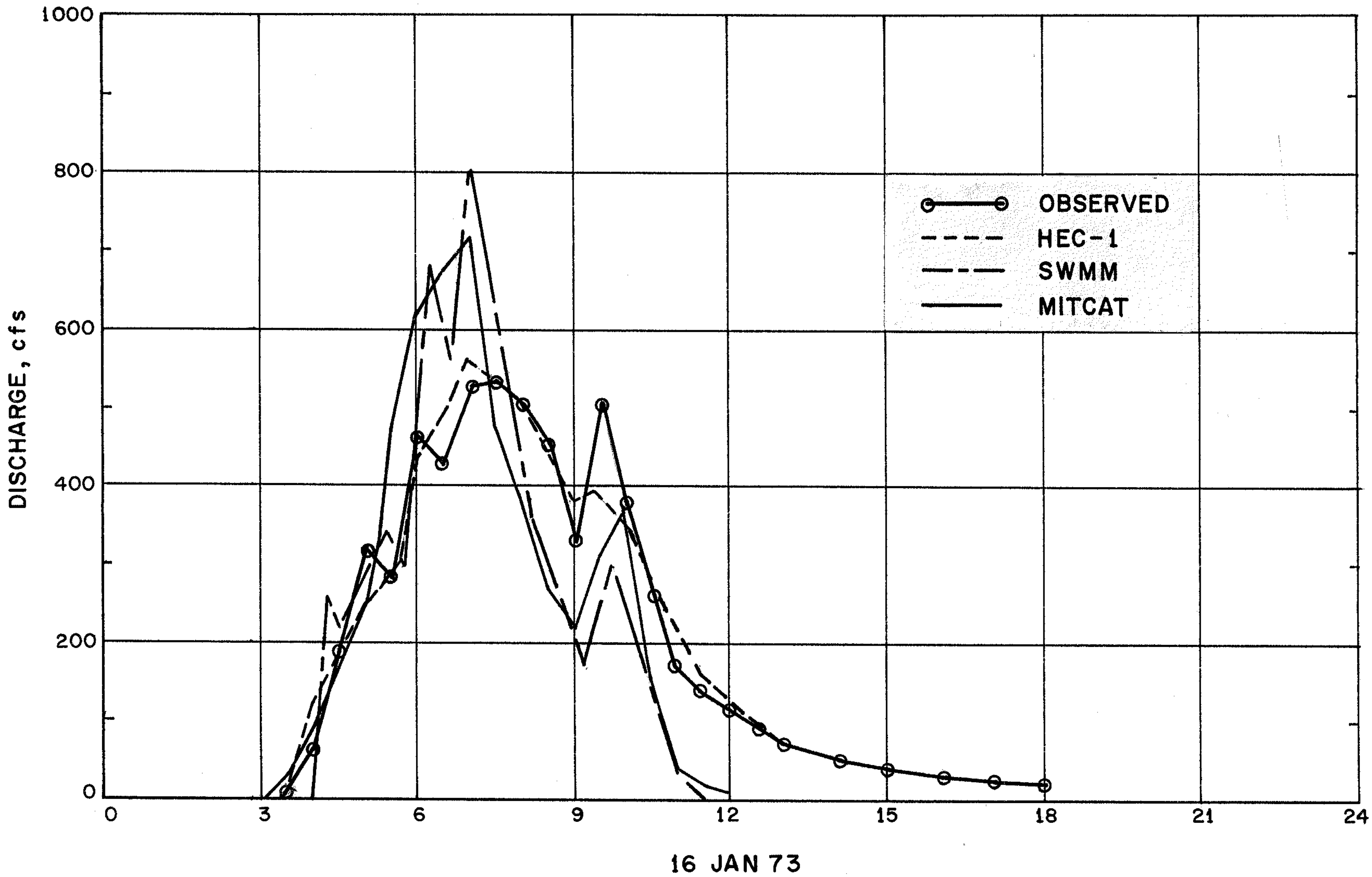


FIGURE 3

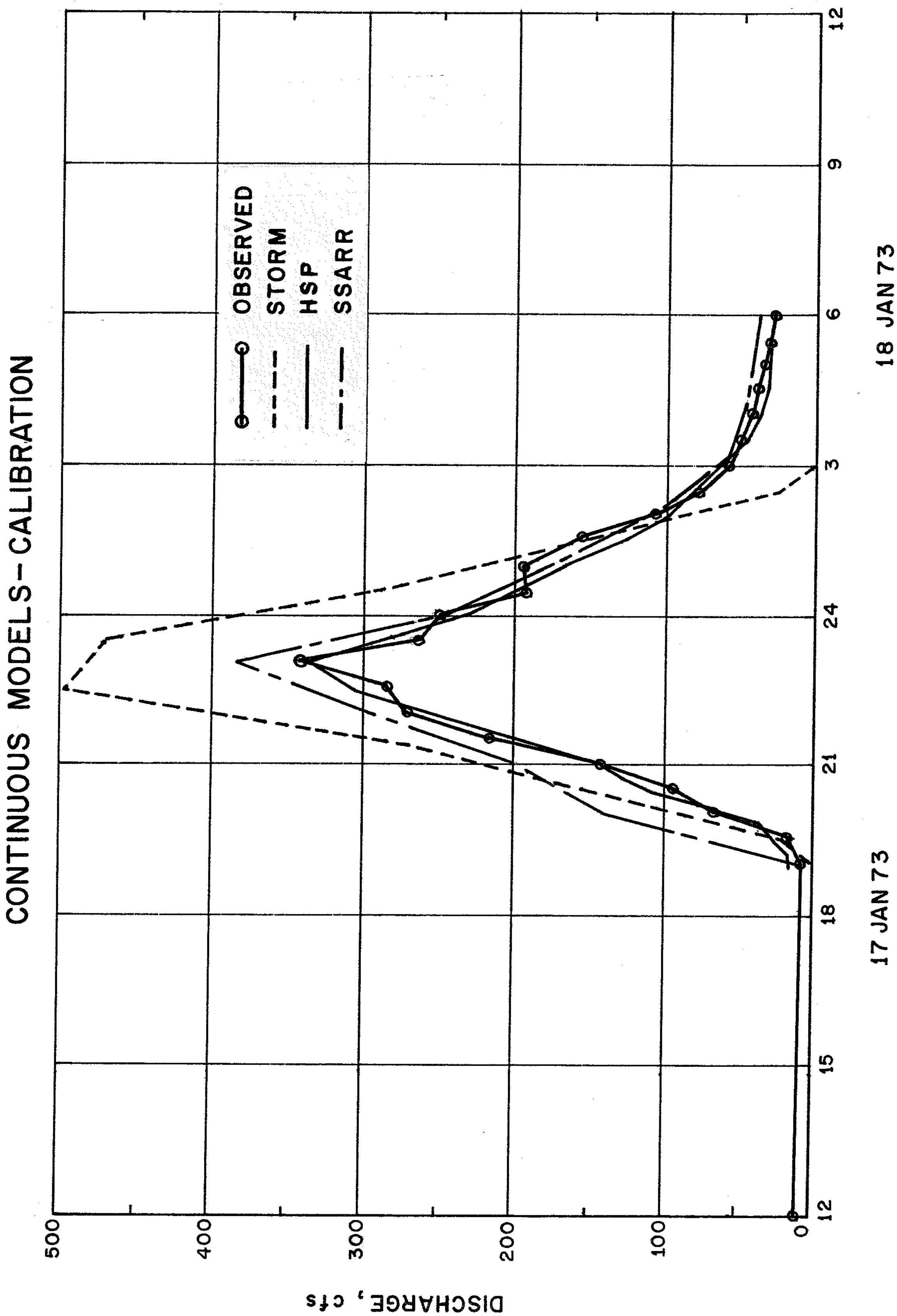

CONTINUOUS MODELS-CALIBRATION
OBSERVED
STORM
HSP
SSARR
DISCHARGE, cfs
0
100
200
300
400
500
12
15
18
21
24
3
6
9
12
17 JAN 73
18 JAN 73

FIGURE 4

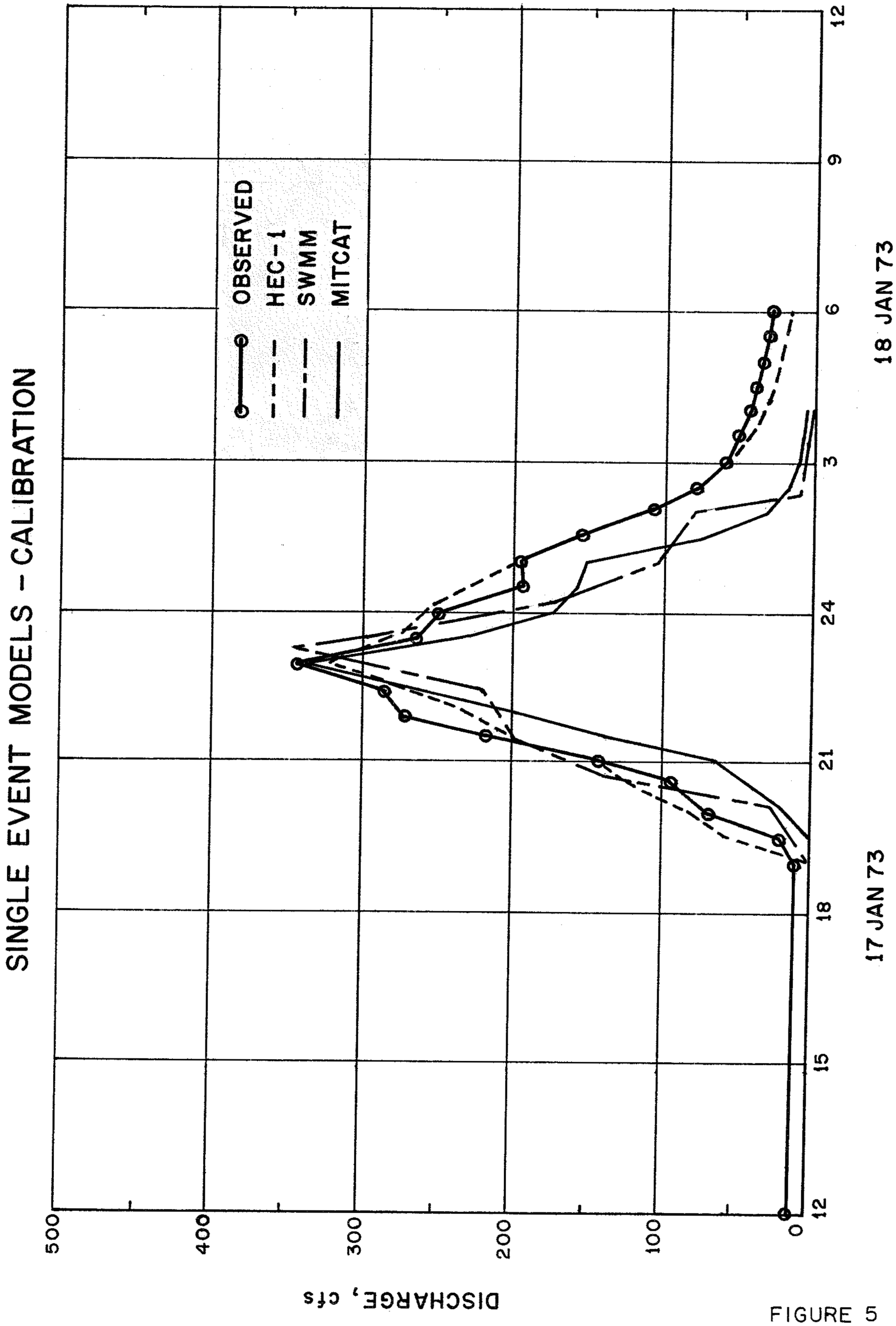

SINGLE EVENT MODELS - CALIBRATION
OBSERVED
HEC-1
SWMM
MITCAT
DISCHARGE, cfs
0
100
200
300
400
500
12
15
18
21
24
3
6
9
12
17 JAN 73
18 JAN 73

FIGURE 5

CONTINUOUS MODELS—CALIBRATION

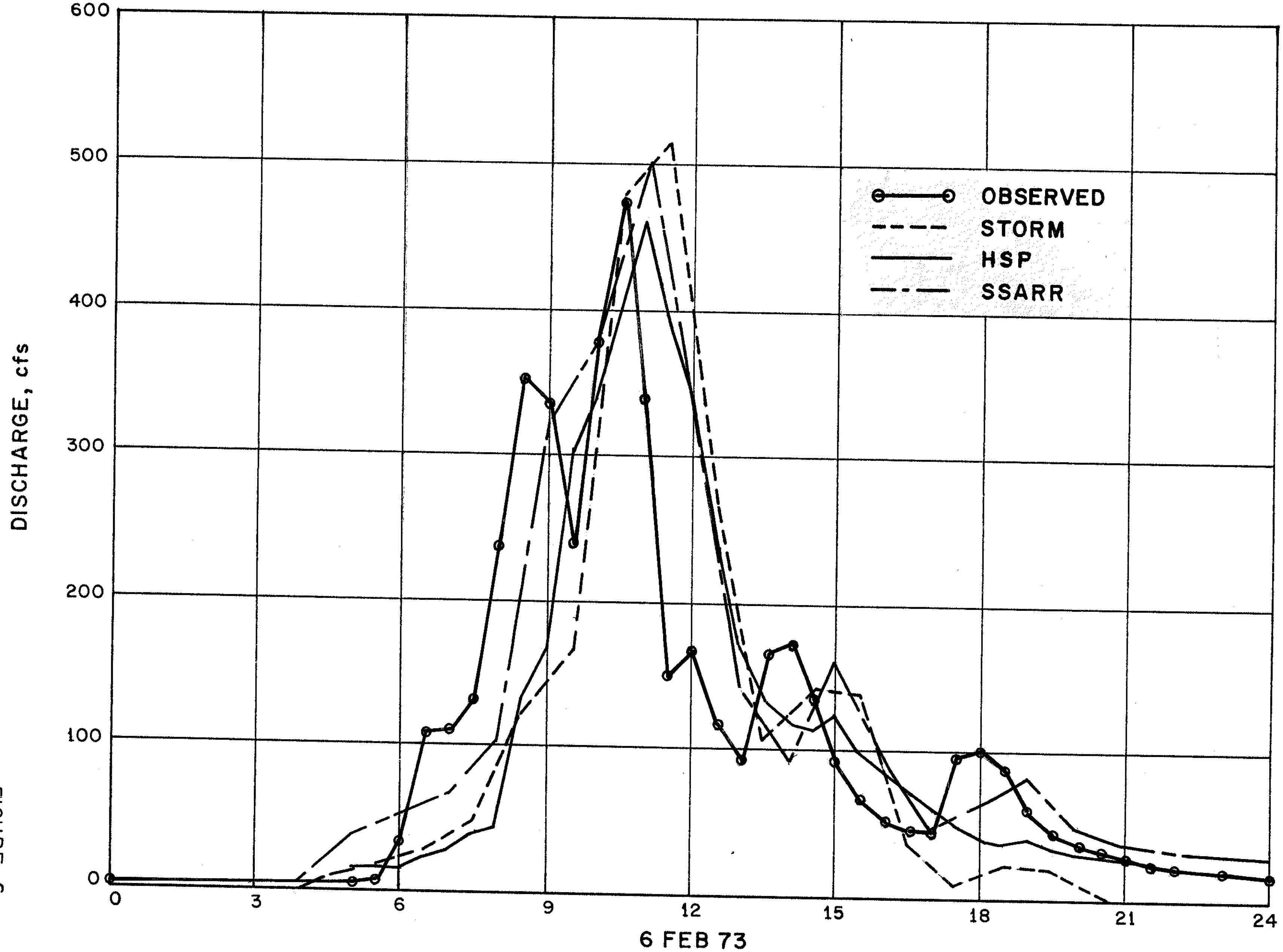


FIGURE 6

SINGLE EVENT MODELS - CALIBRATION

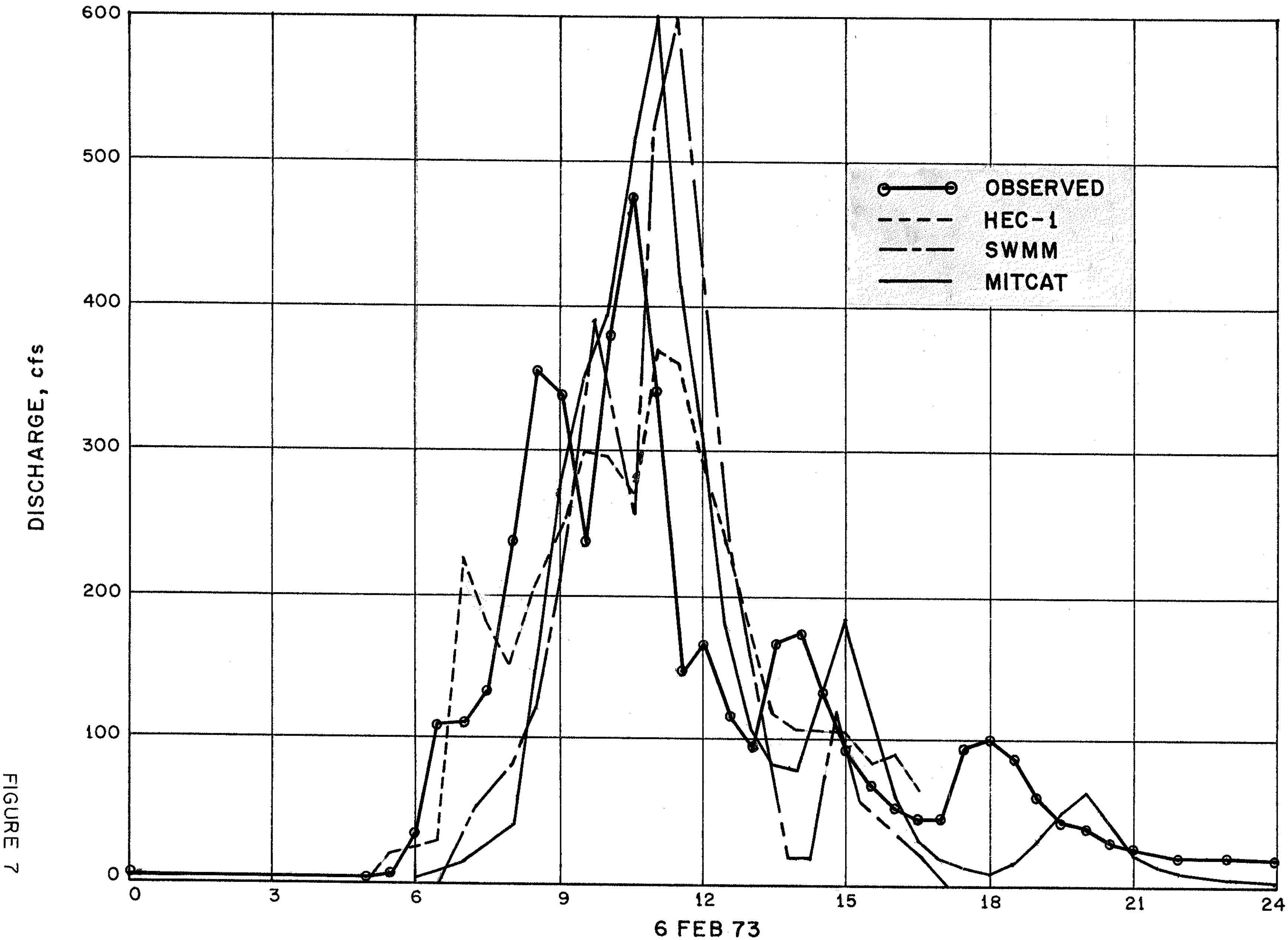


FIGURE 7

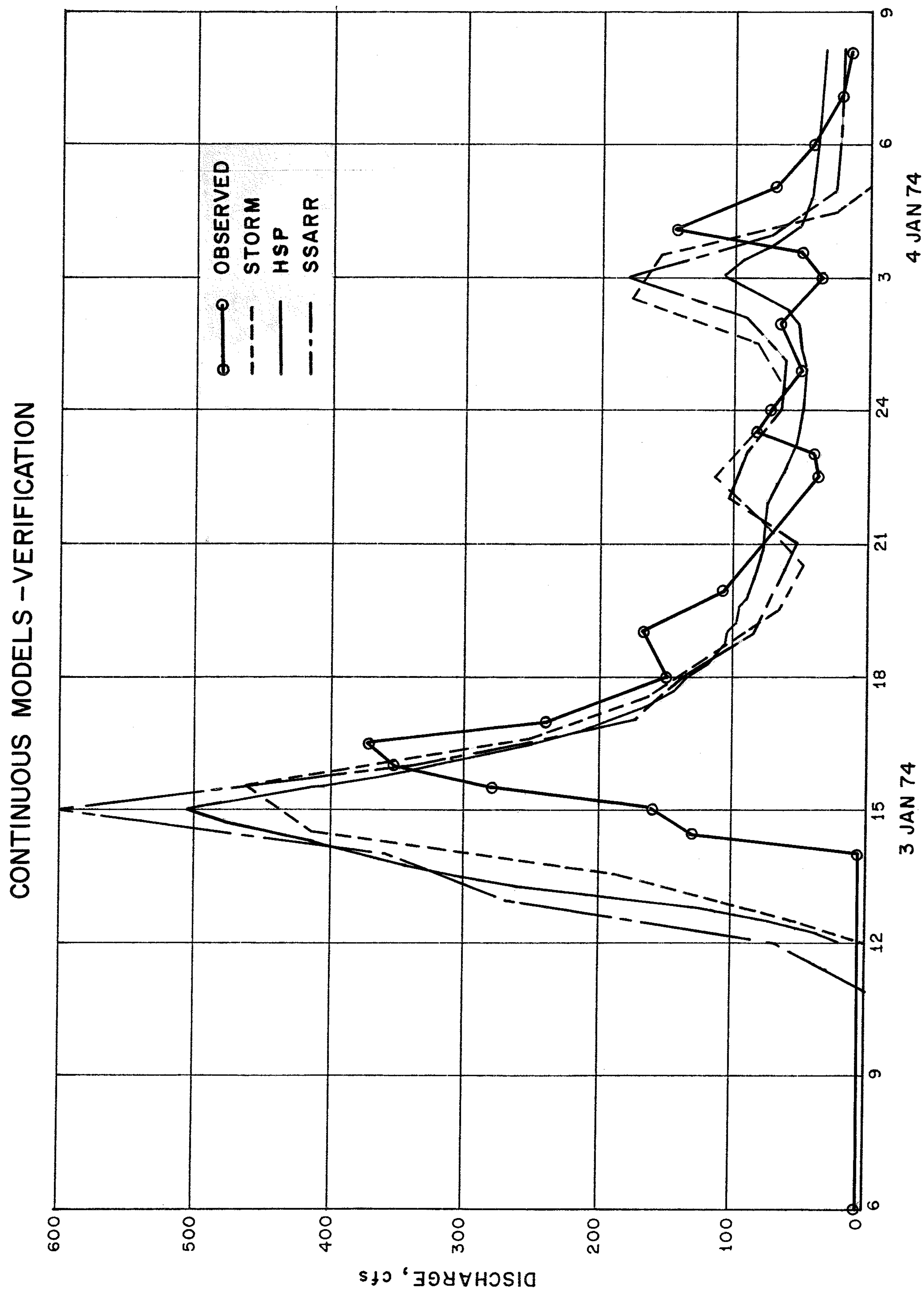

CONTINUOUS MODELS -VERIFICATION
OBSERVED
STORM
HSP
SSARR
DISCHARGE, cfs
600
500
400
300
200
100
0
6
9
12
15
18
21
24
3
6
9
3 JAN 74
4 JAN 74

FIGURE 8.

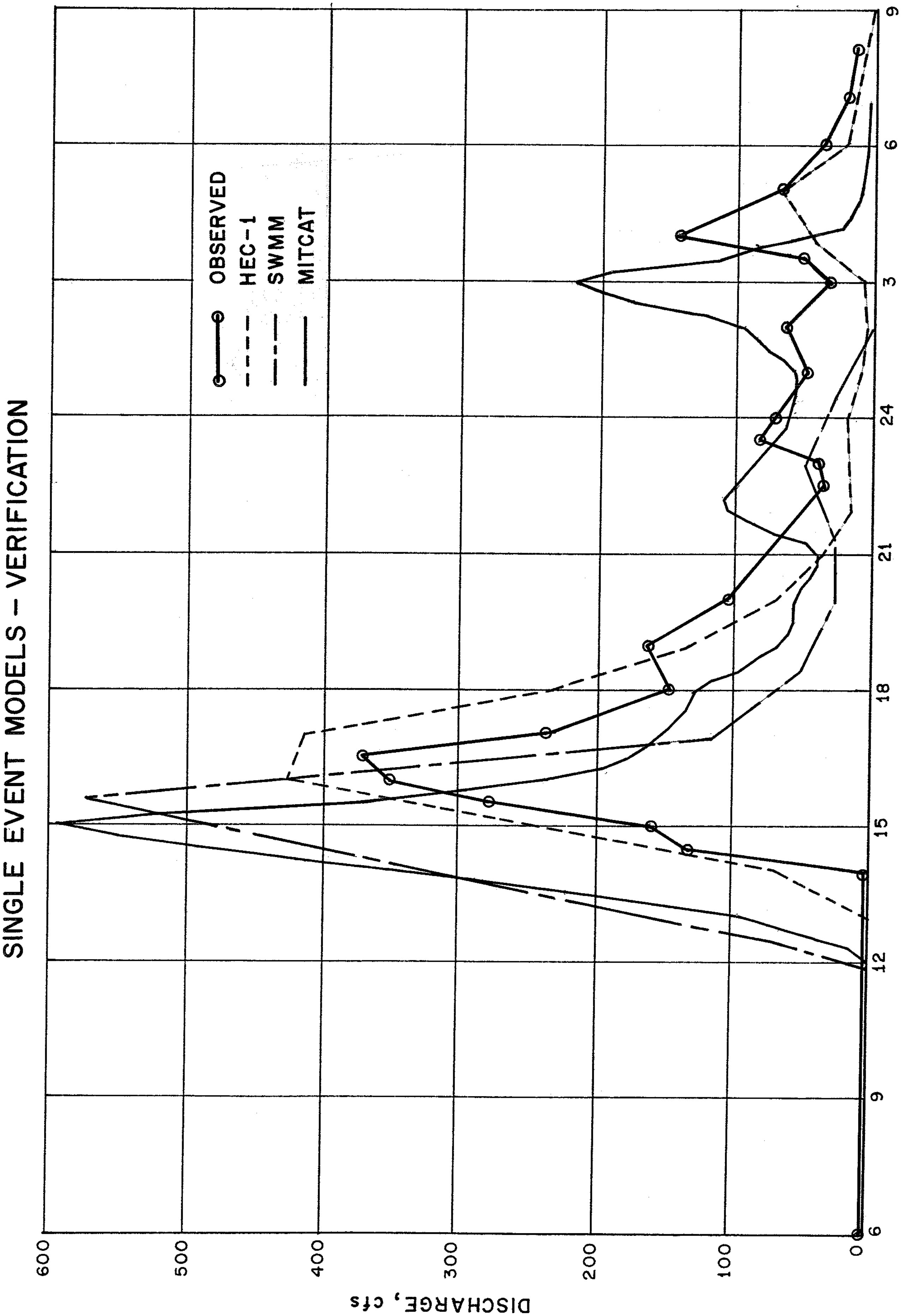

SINGLE EVENT MODELS – VERIFICATION
OBSERVED
HEC-1
SWMM
MITCAT
DISCHARGE, cfs
0
100
200
300
400
500
600
6
9
12
15
18
21
24
3
6
9
3 JAN 74
4 JAN 74

FIGURE 9

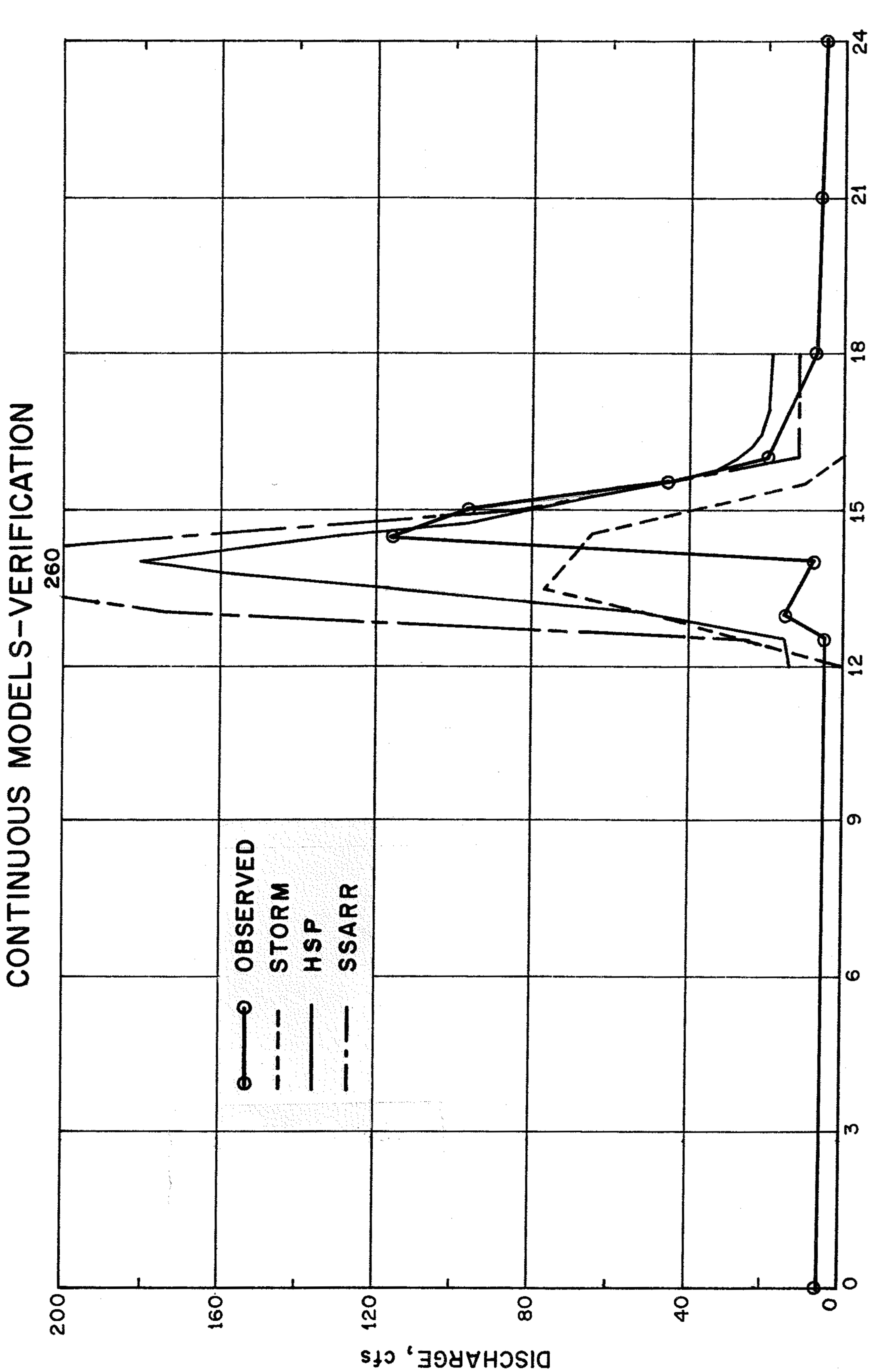

CONTINUOUS MODELS-VERIFICATION
260
OBSERVED
STORM
HSP
SSARR
DISCHARGE, cfs
200
160
120
80
40
0
0
3
6
9
12
15
18
21
24
5 JAN 74

FIGURE 10

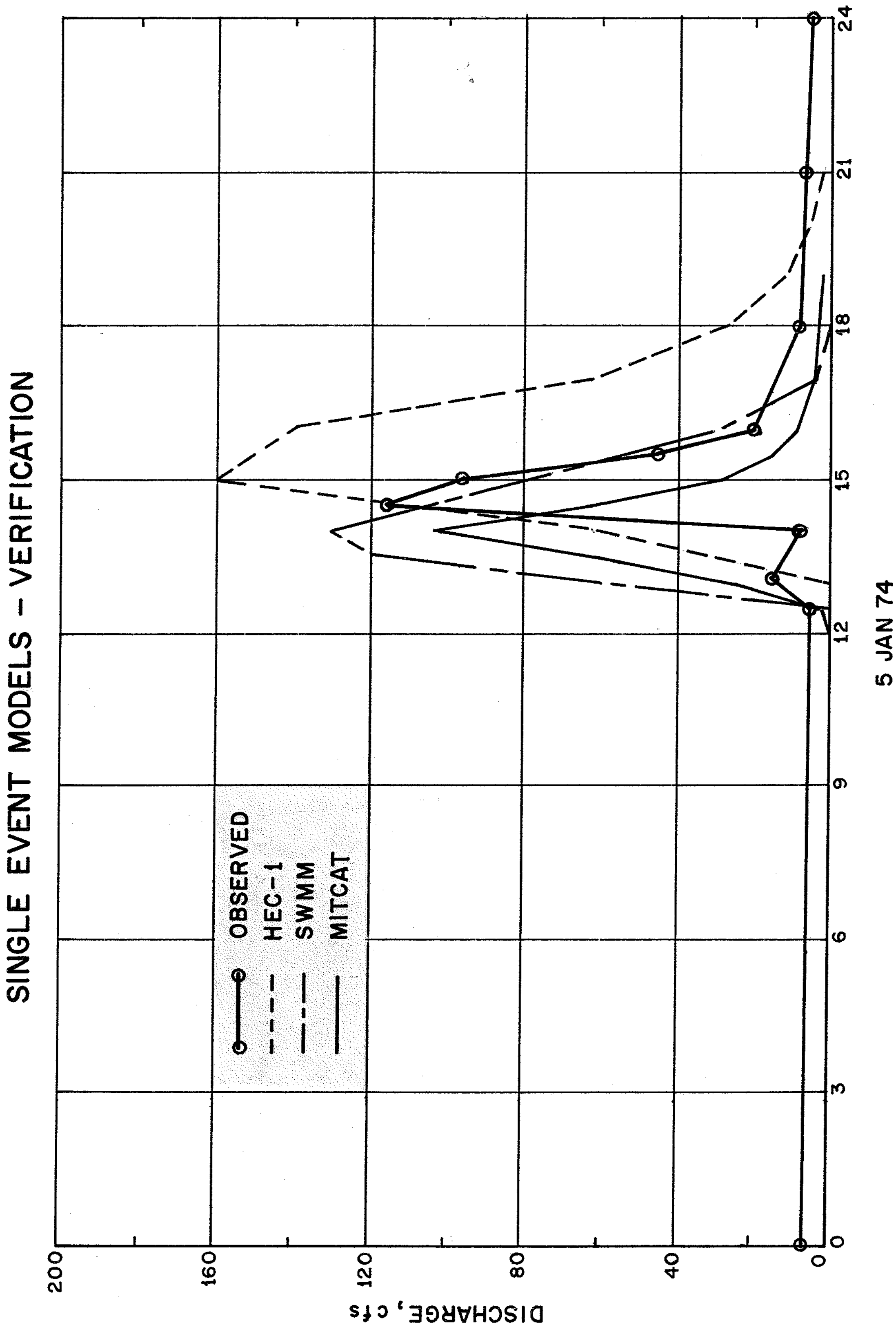
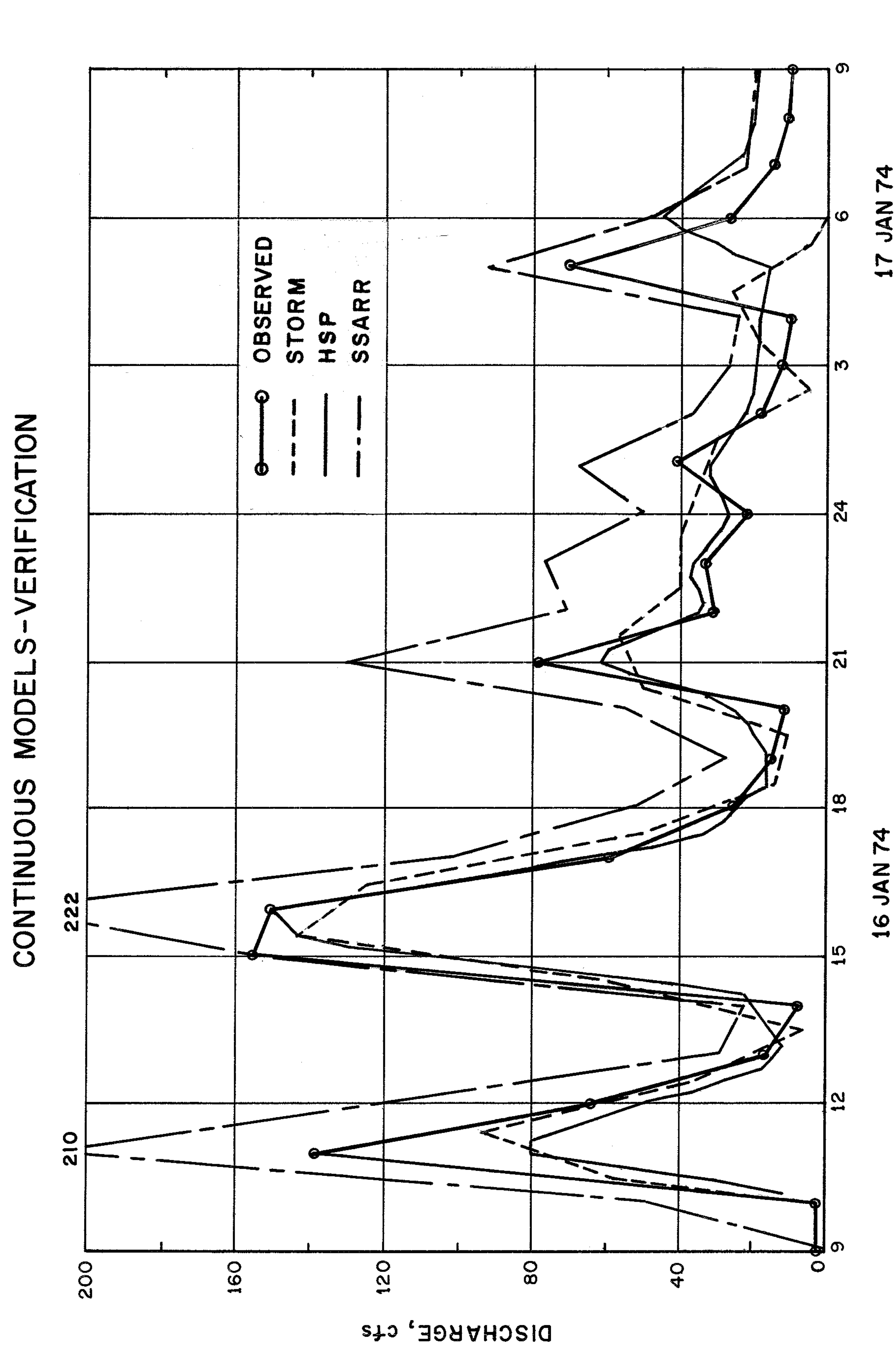
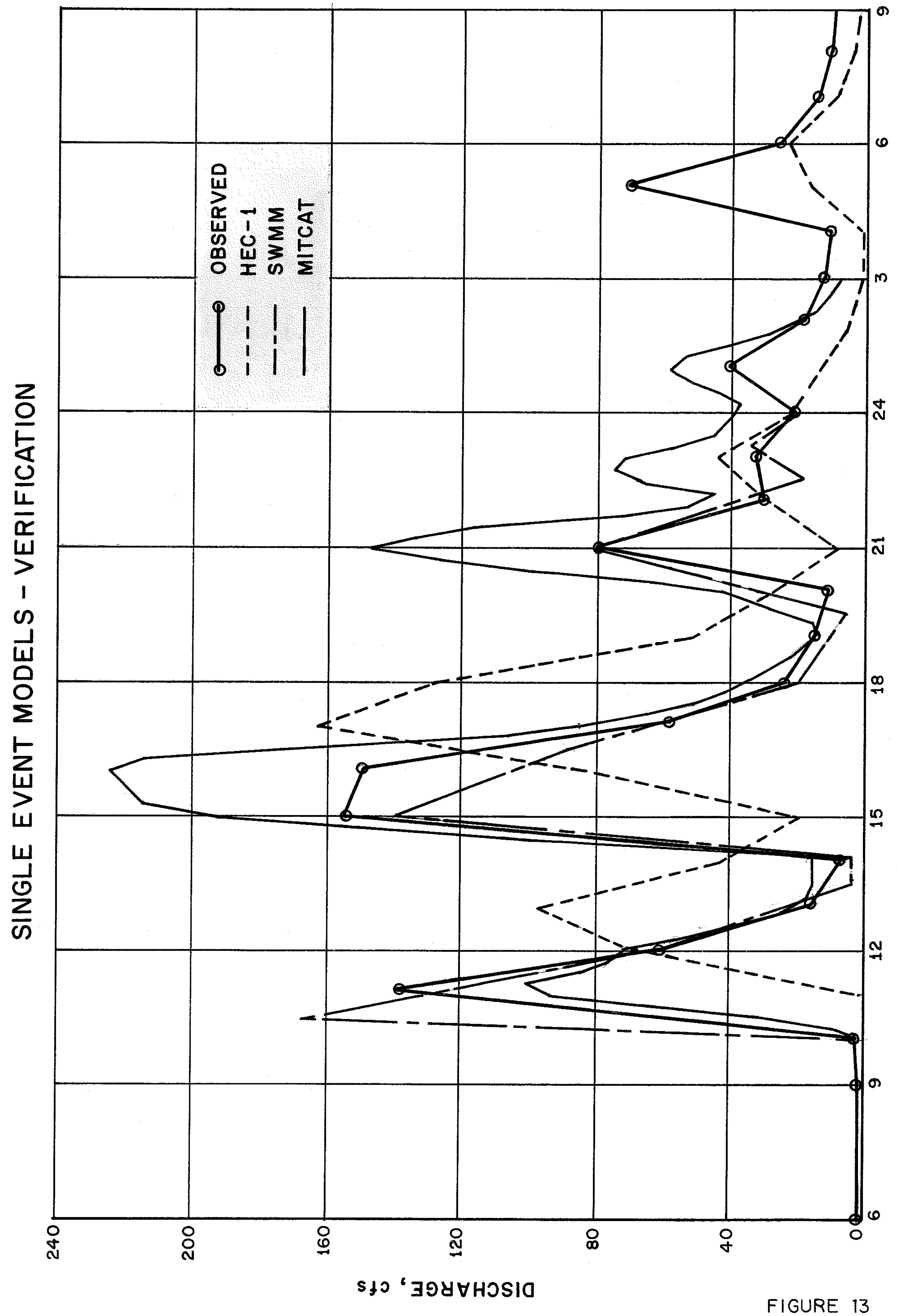

SINGLE EVENT MODELS - VERIFICATION
OBSERVED
HEC-1
SWMM
MITCAT
DISCHARGE, cfs
200
160
120
80
40
0
0
3
6
9
12
15
18
21
24
5 JAN 74

FIGURE 11



CONTINUOUS MODELS-VERIFICATION
OBSERVED
STORM
HSP
SSARR
210
222
DISCHARGE, cfs
0
40
80
120
160
200
9
12
15
18
21
24
3
6
9
16 JAN 74
17 JAN 74

FIGURE 12



SINGLE EVENT MODELS - VERIFICATION
OBSERVED
HEC-1
SWMM
MITCAT
DISCHARGE, cfs
0
40
80
120
160
200
240
6
9
12
15
18
21
24
3
6
9
16 JAN 74
17 JAN 74

FIGURE 13

CONTINUOUS MODELS-VERIFICATION

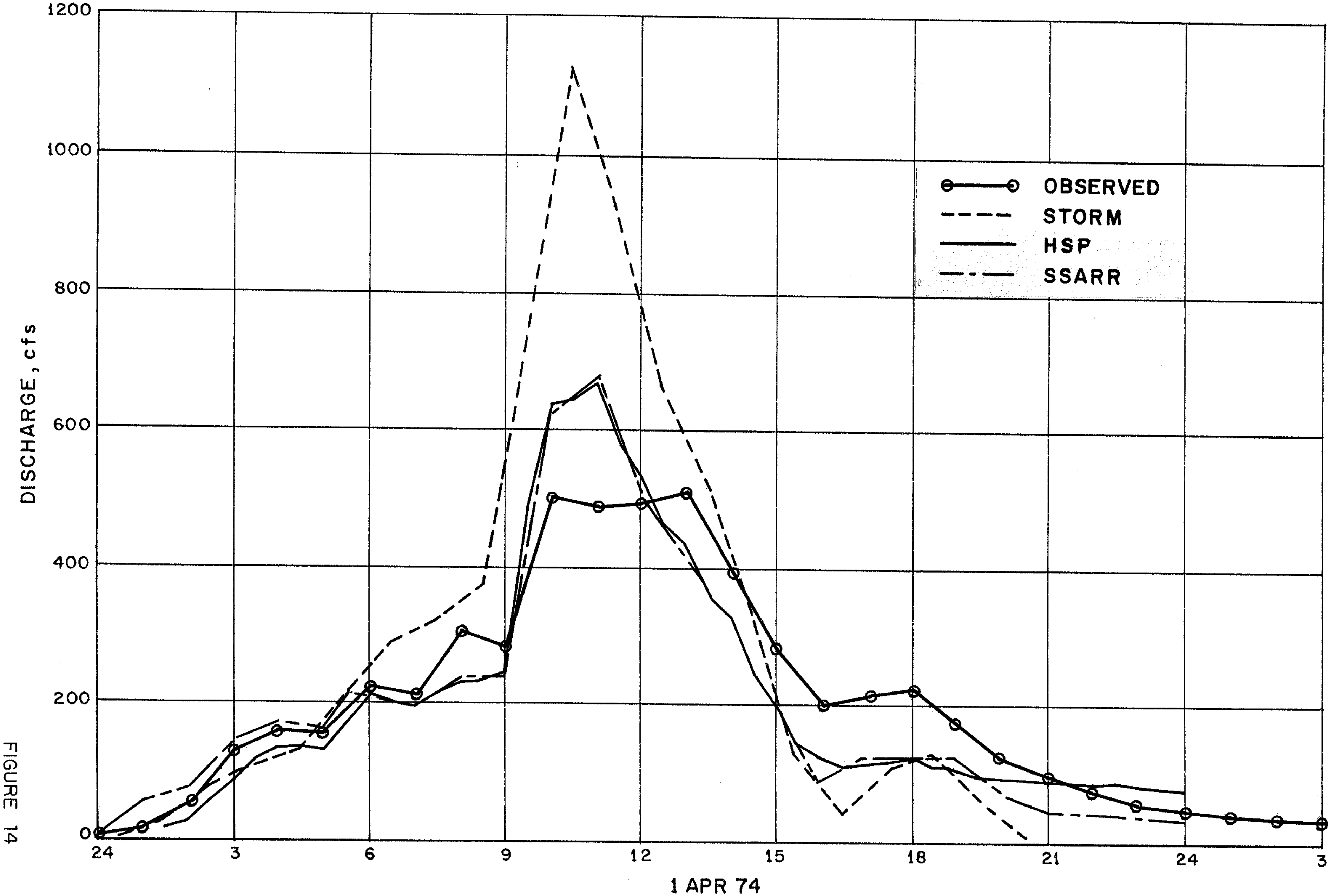
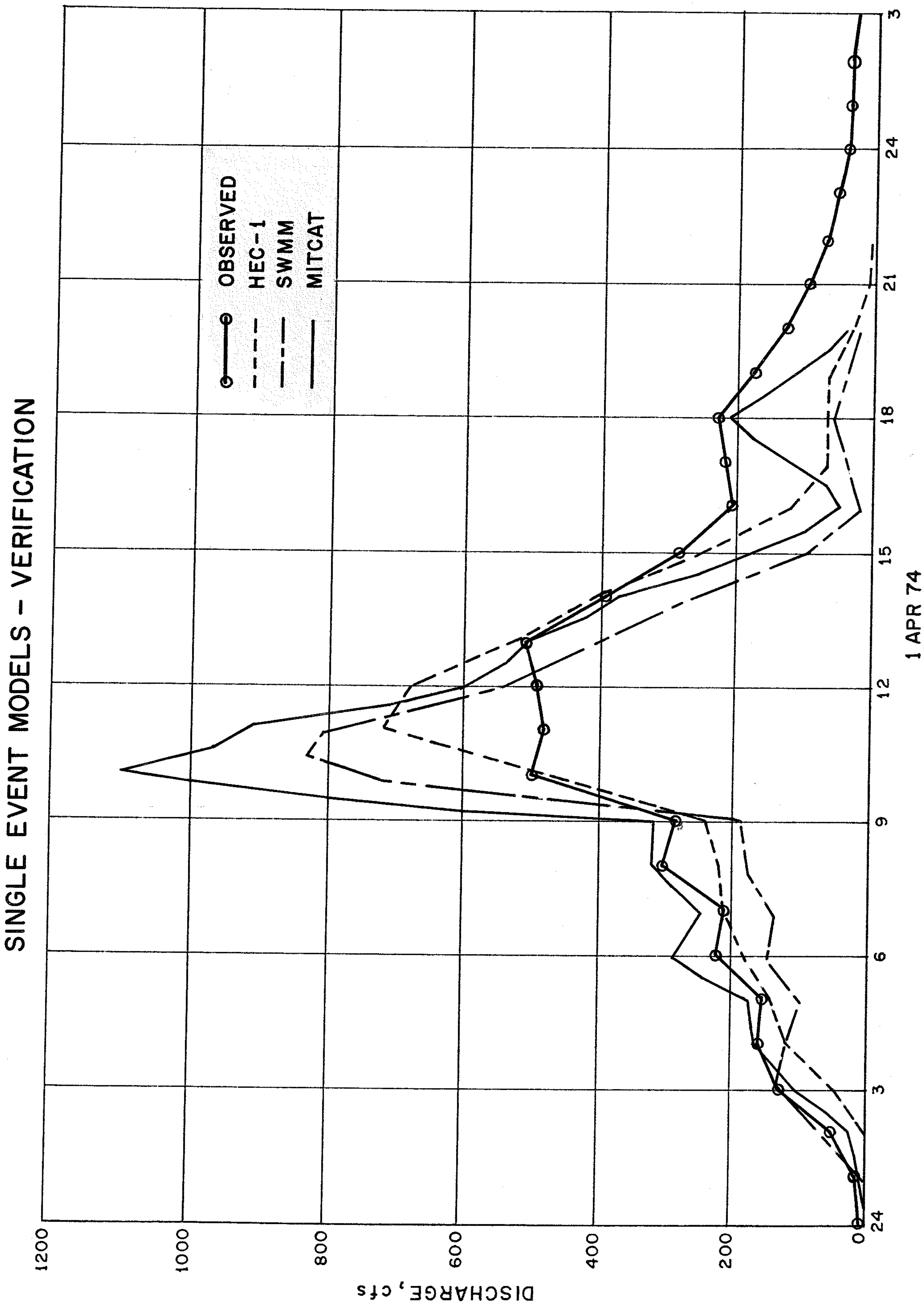


FIGURE 14



SINGLE EVENT MODELS - VERIFICATION
OBSERVED
HEC-1
SWMM
MITCAT
DISCHARGE, cfs
0
200
400
600
800
1000
1200
24
3
6
9
12
15
18
21
24
3
1 APR 74

FIGURE 15

Model Parameters

Several parameters required for the SCS method in STORM were obtained from References 13 and 14. A summary of the important STORM loss parameters is given in Table 7, page 37.

The parameters for the single-event version of HEC-1 (Flood Hydrograph Package) were developed on a number of individual events in the calibration period. Initial estimates of the unit hydrograph characteristics required for HEC-1 for Castro Valley were developed using a U.S. Geological Survey procedure.(15) Seven storms were selected from the calibration period to serve as the basis for development of average unit graph, loss rate, and antecedent moisture parameters. The HEC-1 model has the capability of optimizing the magnitudes of these parameters for individual events on the basis of accurate reproduction of the observed individual events. The optimized parameters are shown in Table 8, page 38. Mean values of the parameters were then used for each of four individual events in the verification period. The results using HEC-1 are presented in Figures 3, 5, 7, 9, 11, 13 and 15.

Recall that the SWMM and MITCAT models were also applied to a total of seven individual events. Table 9, page 38, presents the adopted values for the several parameters used to calibrate these two models. These adopted values, developed from three events in the calibration period, were used to reconstitute four events in the verification period. The results are shown in Figures 3, 5, 7, 9, 11, 13 and 15.

Interpretation of Results

Based on the results from reconstituting four hydrographs in the verification period, none of the models tested exhibited a distinct advantage in accuracy. Each model produced acceptable results, in view of the limited effort of each application.

TABLE 7

"STORM" MODEL PARAMETERS
FOR SCS METHOD,
CASTRO VALLEY

Drainage Area = 3,136 acres
Time of Concentration = 1.0 hours

Land Use	Per cent of Area	Maximum Initial Abstraction (inches)	Starting Initial Abstraction (inches)	Maximum Soil Moisture Capacity (inches)	Starting Soil Moisture Capacity (inches)	Initial Abstraction Loss Rate (in./hr.)	Max. Deep Percolation Rate (in./hr.)
Single	77	.06	.06	2.16	.70	.1	.01
Multiple	3	.07	.07	.99	.50	.1	.01
Commercial	5	.05	.05	.30	.56	.1	.01
Rural	15	.10	.10	1.44	.60	.1	.01

Triangular Unit Hydrograph Characteristics:

Ratio of time of recession to time to peak = 1.67

Time to peak = 1.10 hours

Time of base = 2.94 hours

Peak Discharge = 2,153 cfs

TABLE 8

HEC-1 OPTIMIZED PARAMETERS FOR THE CALIBRATION PERIOD, CASTRO VALLEY

DATE	TC	R	STRKR	ERAIN	DLTKR	RTIOL	PRECP	XCESS
22 Dec 71	1.06	.21	.21	.47	.51	1.00	.42	.16
27 Dec 71	.94	2.08	.13	.50	.35	10.12	.19	.03
11 Oct 72	.22	.72	.30	.51	.89	3.37	1.45	.45
9 Jan 73	.37	.72	.09	.56	.35	10.12	.67	.45
16 Jan 73	.35	1.99	.11	.52	.45	9.53	1.35	.98
17 Jan 73	.17	1.65	.12	.50	.14	1.00	.70	.48
6 Feb 73	.47	1.30	.17	.46	.40	5.06	1.39	.67

TABLE 9

SWMM AND MITCAT PARAMETERS, CASTRO VALLEY

SWMM Parameters

Impervious area resistance factor	= 0.013	
Pervious area resistance factor	= 0.250	
Depression storage on impervious areas	= 0.04	inches
Depression storage on pervious areas	= 0.06	inches
Maximum infiltration rate	= 0.3	inches/hr.
Minimum infiltration rate	= 0.1	inches/hr.
Decay rate for infiltration	= 0.00115	

MITCAT Parameters

SCS Curve Number for impervious areas	= 98	
SCS Curve Number for pervious areas	= 89	
Initial surface detention	= 0.02	inches

SECTION 5

SIMULATION RESULTS, GENERAL

The ease of data preparation and application was judged to be the most significant basis for differentiation among the models tested. STORM required the least amount of data preparation, while SWMM and MITCAT required the most. HEC-1 required moderate data preparation. The amount of data required is directly related to the type of computations performed by the model. STORM and HEC-1 use lumped-parameter hydrologic methods. These include generalized loss-rate functions based on land use, accumulated loss or some other nongeometric attributes of the watershed or of rainfall-runoff characteristics. These two hydrologic methods usually require a minimum amount of data. By contrast, SWMM, HSP and MITCAT use a hydraulic method to compute the routing of flow over watershed surfaces and in conveyance elements (pipes and channels), namely, the kinematic wave method of routing flows. Considerable effort was required to subdivide the watershed and to determine subcatchment detailed characteristics such as areas, surface slopes, surface roughness, pipe and channel geometry and roughness, and the connectivity of the conveyance elements. Table 10 presents a summary of the relative accuracies of all six models for both the calibration and verification periods. Table 11 summarizes computer processing-time requirements for the continuous models and provides typical requirements for the single-event models. CPU requirements in Table 11 are all for a CDC 7600 computer, except for the HSP which was run on an IBM 370.

TABLE 10

RELATIVE ACCURACY OF INDIVIDUAL EVENT RUNOFF HYDROGRAPHS

Continuous Models

Event	Observed Peak, Cfs	Observed Time to Peak, Hrs.	STORM* Peak	% Diff.	Time to Peak	% Diff.	HSP Peak	% Diff.	Time to Peak	% Diff.	SSARR Peak	% Diff.	Time to Peak	% Diff.
16 Jan 73	530	5.5	710	+34	3.0	-45	555	+ 5	3.5	-36	585	+10	3.5	-36
17 Jan 73	340	4.0	496	+46	3.5	-12	340	0	4.0	0	385	+13	4.0	0
6 Feb 73	472	5.5	512	+ 8	6.5	+18	465	- 1	6.0	+ 9	512	+ 8	6.5	+18
3 Jan 74	372	3.5	462	+24	3.5	0	513	+38	3.0	-14	605	+63	3.0	-14
5 Jan 74	116	2.5	76	-34	1.5	-40	181	+56	2.0	-20	260	+124	2.0	-20
16 Jan 74	155	5.0	143	- 8	5.5	+10	150	- 3	6.0	+20	221	+43	6.0	+20
1 Apr 74	**	**	1123		10.5		672		11.0		682		11.0	

Single Event Models

Event	Observed Peak, Cfs	Observed Time to Peak, Hrs.	HEC-1 Peak	% Diff.	Time to Peak	% Diff.	SWMM Peak	% Diff.	Time to Peak	% Diff.	MITCAT Peak	% Diff.	Time to Peak	% Diff.
16 Jan 73	530	5.5	557	+ 5	3.5	-45	800	+51	3.5	-36	715	+35	3.5	-36
17 Jan 73	340	4.0	320	- 6	4.0	0	345	+ 1	4.2	+ 5	335	- 1	4.0	0
6 Feb 73	472	5.5	372	-21	6.0	+ 9	600	+27	6.5	+36	604	+28	6.0	+ 9
3 Jan 74	372	3.5	427	+15	3.0	-14	575	+55	3.5	0	593	+59	3.0	-14
5 Jan 74	116	2.5	160	+38	3.0	+20	130	+12	2.0	-20	104	-10	2.0	-20
16 Jan 74	155	5.0	162	+ 5	6.0	+20	140	-10	5.0	0	224	+45	6.0	+20
1 Apr 74	**	**	730		11.0		830		10.5		1103		10.0	

*: Results are for Soil Conservation Service option for computing runoff (LEQ-2)

**: Comparison with observed hydrograph not valid

TABLE 11

COMPUTER TIME REQUIREMENTS

CONTINUOUS MODELS,*
PERIOD OF SIMULATION NOVEMBER 1971 THROUGH APRIL 1975

	STORM LEQ-1	STORM LEQ-2	STORM LEQ-3	HEC-1C	HSP	SSARR
CPU Seconds	1.1	4.1	3.9	1.1	29.4	11.0
Time Step, Minutes	60	60	60	60	60	60
Number of Subcatchments	1	1	1	1	2	2
Number of Routing Reaches	0	0	0	0	0	1

(*: HSP was run on an IBM 370/168. All others were run on a CDC 7600, which is approximately twice as fast).

SINGLE-EVENT MODELS,**
PER SINGLE EVENT

	HEC-1	SWMM	MITCAT
Average Execution Time, CPU Seconds	0.129	3.13	28.80
Time Step, Minutes	15	10	15
Number of Time Steps Simulated	150	90	100
Average Execution Time Per Time Step, CPU Seconds	0.00086	0.035	0.288
Number of Subcatchments	1	32	17
Number of Routing Reaches	0	38	11

(**: MITCAT has a greater amount of Input/Output processing than HEC-1 and SWMM).

SECTION 6

ACKNOWLEDGMENTS

The cooperation and assistance of several persons at The Hydrologic Engineering Center is gratefully acknowledged by the writer. Their contributions have significantly assisted in the completion of this study. Kenneth Brooks accomplished the calibration of the SSARR model. Art Pabst assisted in the calibration of HEC-1C and MITCAT. All applications using STORM, HEC-1, HEC-1C, SSARR, SWMM and MITCAT were accomplished by Paul Ely, David Williams, John Koltz and the writer.

Constructive comments on this report were provided by Bill Eichert, Dale Burnett, John Peters, Arlen Feldman and Darryl Davis.

Brook Kraeger of Hydrocomp International, Inc., Palo Alto, California, accomplished the application of HSP.

This report was prepared at The Hydrologic Engineering Center by Jess Abbott under the direction of Tony Thomas and Arlen Feldman.

SECTION 7

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TP-9 Economic Evaluation of Reservoir System Accomplishments
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