Limitations of Level-Pool Routing in Reservoirs

D. L. Fread[a], M., ASCE, George F. McMahon[b], M., ASCE, and Janice Lewis[c]

ABSTRACT

Storage routing and derivative techniques predominate in reservoir routing studies, having been incorporated into most of the hydrologic analysis, system operations, and optimization models presently in widespread use. Storage routing is defined for purposes of this study as any routing technique which expresses reservoir storage as a single-valued function of stage, and hence it is sometimes termed "level-pool" routing. Level-pool reservoir routing is often perceived to be suitable for most applications, despite the fact that this simplification can introduce significant errors. The NWS DAMBRK model was modified by the authors for use in comparing reservoir discharge and stage hydrographs produced by dynamic (one-dimensional St. Venant continuity and momentum equations) and level-pool routing techniques. The objective of this effort is to determine the degree to which level-pool routing approaches dynamic routing for dimensionless reservoir and inflow hydrograph characteristics. Though error-characteristic relationships have not yet been fully derived, this paper documents case studies and sensitivity analyses.

Introduction Storage routing and derivative techniques predominate in reservoir routing studies, having been incorporated into most of the hydrologic and hydraulic analysis, system operations, and optimization models presently in widespread use. Storage routing is defined for purposes of this study as any routing technique which expresses reservoir storage as a single-valued function of storage or stage, and hence it is sometimes termed "level-pool" routing. It is considered to be "level-pool" even if resulting storage- or stage- discharge relationships used for routing incorporate a friction or bottom slope, as these relationships do not include momentum effects or time derivatives. Storage routing in watersheds, valleys and in reservoirs was established as a legitimate technique in 1943 by C. O. Clark[1], a hydraulic engineer with the Corps of Engineers in Winchester, Virginia at the time. His paper generated a storm of controversy among fellow

---

[a] Senior Research Hydrologist, National Weather Service Hydrologic Research Laboratory, Silver Spring, Maryland

[b] Senior Water Resources Engineer, Post, Buckley, Schuh & Jernigan, Inc., Atlanta, Georgia

[c] Hydrologist, National Weather Service Hydrologic Research Laboratory, Silver Spring, Maryland

Corps of Engineers hydrologists (discussions-Franklin F. Snyder and Gordon R. Williams), the Weather Bureau (discussions - James S. Sweet and Ray K. Linsley), the Conservation Service (discussions - L. K. Sherman and Victor Cochrane), the Geological Survey (discussion - L. C. Crawford), the Bureau of Reclamation (discussion - R. E. Kennedy), and academia (discussion - E. F. Brater). As is well known, many of these people have pioneered the development of hydrology as a science and academic discipline. The discussion focused on three points: the efficacy of the unit hydrograph as a routing method; the validity of storage-discharge relationships; and the conclusions drawn by Clark concerning effects of reservoir storage on outflow. A somewhat heated controversy arose from Clark's radical assertion that, under certain conditions, his theory predicted a rapid decrease in upstream reservoir stage would cause a pressure wave to propagate downstream, increasing stages and discharges at the reservoir. Nearly all the respondents produced wave celerity and momentum formulas contradicting this hypothesis, and stated emphatically that, in all their years of experience, they had observed no such thing!

As an interesting historical note, some of the Conservation Service and academic discussions indicated that, while the unit hydrograph approach had merits, there were little if any data upon which to develop and verify significant parameters. The Weather Bureau commenters maintained a single stage-outflow relationship was not adequate for forecasting in large river basins, which should be accomplished by a more deterministic, segmented procedure combining and lagging observed discharges above the point of interest; Since then, Snyder developed methods for developing synthetic unit hydrographs; the Corps has incorporated unit hydrographs, Snyder's work, and other "level-pool" routing methodologies into its widely-used watershed routing models, such as HEC-1 and HEC-5. The Soil Conservation Service (SCS) has developed widely-used rainfall-runoff and overland flow methodologies, based on readily-obtainable empirical data. These methodologies have come to be known as the SCS Curve Number procedure. The Weather Service, meanwhile, has developed a sophisticated river forecasting system, the NWSRFS, incorporating multi-parameter runoff models and a dynamic routing model (DWOPER) for combining and routing river and reservoir discharges. Because of the flexibility and robust attributes of DWOPER, the model is becoming more frequently applied in cases where hydraulic effects significantly affect the results. In analysis of more rapidly - varying flow conditions such as dam failures, the DAMBRK spinoff of DWOPER is generally recognized and used by most governmental water resources agencies as well as the private sector.

There is no concensus as to which methods are appropriate for routing in reservoirs, other than a qualitative recognition that, while dynamic routing is better, storage routing is often good enough. The HEC-1, HEC-2, and HEC-5 models, developed by the Corps of Engineers, are widely used for design, project operations, and drainage studies. Currently these models employ calculator-based "hydrologic" overland and riverine routing techniques. With recent rapid increases in computing power, the "full-equation" dynamic routing methods employed in DWOPER are becoming more popular for routing in reservoirs and rivers, though still requiring significantly greater attention and skills to run successfully than previous-generation techniques. Recently, many advances have been made in reservoir system operations optimization technology, though most rely on the level-pool assumption. The authors are attempting to quantify the differences between dynamic and level-pool routing in reservoirs, relating these differences to measurable reservoir and inflow hydrograph characteristics. The designers, operators, and optimizers then will have a method of assessing if the simpler routing techniques truly are "good enough" to solve their particular problems, whether the extra effort required for dynamic analysis is warranted, and possibly if error terms can be developed as additional constraints to optimization methods using the level-pool assumption. Because extensive work has been performed in dynamic - level-pool routing comparisons for channels and floodplains, this effort is confined to reservoirs alone, providing unique opportunities for comparison of the two routing methods.

Study Objectives This study extends research performed by Kopsky and Smith[3] on criteria for selection of a reservoir routing method. This work compared reservoir peak outflow using dynamic (DAMBRK) routing to that computed using storage routing for catastrophic flooding associated with probable maximum flood (PMF) events and for static pool (zero-inflow) dam failures. The portion of Kopsky and Smith's work most closely related to the authors' work involves comparison of outflow ratios for dynamic and storage routing of the PMF. The current study, however, examines effects of a wide variety of flooding conditions on several stage, discharge, and time statistics, with the following objectives:

a. Conceptualization of a manageable number of measurable dimensionless reservoir and inflow hydrograph characteristics, representing the most significant parameters affecting differences between dynamic and storage routing.

b. Design of numerical experiments comparing results of dynamic and storage routing for a range of these characteristics sufficient to represent the majority of existing dams worldwide.

c. Development of a model capable of inexpensively performing large numbers of numerical experiments and compiling pertinent statistics of each with a minimum of input data.

d. Determination of sensitivity of numerical experiment results to individual dimensionless characteristics, resulting in possible elimination of some and/or addition of new characteristics.

e. Formulation of graphical and/or symbolic relationships between error statistics (with dynamic routing results representing the "true" condition) and the dimensionless reservoir characteristics.

f. Determination of the significance of experimental results to reservoir design and operations, as well as to operational "optimization".

This work, when completed, will form the basis for subsequent publications. Progress and conclusions drawn from parially completed and continuing work on Tasks a-d above are subsequently documented.

Dimensionless Reservoir Characteristics Four reservoir and inflow hydrograph characteristics were developed for initial testing. The first is the length characteristic, σ_l, which is essentially a depth/length ratio:

$$\sigma_l = \frac{DD}{0.9 \cdot RL \cdot 5280}$$

where DD is the average reservoir depth in feet and RL is the reservoir length in miles at initial pool level. All "σ"s are also represented as "S"s in subsequent discussion and graphs. The significance of the "0.9" will be discussed when describing the prismatic reservoir concept.

The second is the width characteristic, a ratio of the reservoir volume to the average length and depth:

$$\sigma_w = \frac{43560\ VOLRES}{(0.9 \cdot RL \cdot 5280 \cdot DD)^{1.5}}$$

in which VOLRES is the reservoir volume at initial pool in acre-feet.

The third characteristic is the volume characteristic, simply the ratio of the inflow hydrograph volume, VOLH, to the reservoir volume at initial pool:

$$\sigma_v = \frac{VOLH}{VOLRES}$$

This characteristic differs from a similar characteristic proposed in Kopsky and Smiths' paper due to its relation to initially occupied rather than available storage.

The fourth characteristic investigated is the time characteristic, a ratio of gravity wave travel time through the reservoir to the time to peak of the inflow hydrograph:

$$\sigma_t = \frac{0.9\ RL\ 5280}{3600 \cdot \sqrt{32.2 \cdot DD} \cdot TPG}$$

in which TPG is the time to peak of the inflow hydrograph in hours.

The first two characteristics, S_l and S_w, can be considered to represent physical reservoir characteristics, and the second two, S_v and S_t, can be considered inflow hydrograph characteristics. Using four values of each of these characteristics, a wide range of reservoir and inflow hydrographs can be examined using 4^4 or 256 numerical experiments.

Numerical Experiments In order to simplify the process of comparing dynamic and storage routing, a simplified "prismatic" reservoir was developed, into which a triangular inflow hydrograph was assumed to flow at a point 10% of the reservoir length RL from the top. To insure numerical convergence and to prevent zero depths, dynamic routing reaches extended into the reservoir to a point where the depth equalled

10% of the initial depth at the dam, thus using 90% of the total reservoir length. Because wave translation with storage routing is instantaneous, this assumption is of no consequence to the level-pool routing procedure. The reservoir cross-section was assumed to have a parabolic shape, shown in Figure 1. In this Figure, the width exponent PM can be used to calibrate volumes of prismatic reservoirs to those of actual projects of known length and height. It should be noted the reservoir cross section in most cases will not represent that for the dam itself, as dams are often built to bridge natural valley constrictions. The width of the dam defined in the model input data should be a typical valley width in the vicinity of the dam. The assumed inflow hydrograph was assumed to be triangular, with pertinent parameters shown in Figure 2.

Pertinent data from nearly 20 dams were collected and attempts made to group projects based on the ranges of the two dimensionless reservoir characteristics S_l and S_w However, this work is not yet complete and publication of results would be premature. In addition, comparisons of level-pool and dynamic routing made thus far involve only a few of these projects. The values of inflow hydrograph characteristics tested (S_v and S_t) in this study were 0.1, 0.2, 0.5, and 0.8 each. Examining 20 projects with four unique S_l and S_w values would require 320 comparisons. Statistical comparisons for two dams are summarized in subsequent sections. These projects are the Clarks Hill project on the Savannah River, and a potential water-supply reservoir site in West Georgia.

<u>Model Development</u> A specially-modified version of the NWS DAMBRK computer model was developed to perform the level-pool - dynamic routing comparisons. This model, called DBCOMPAR, was designed to run on a 640 K-byte personal computer with a math coprocessor and a hard disk drive. The model was designed to satisfy two principal objectives:

To efficiently perform numerous comparisons of level-pool and dynamic routing by characteristic values using minimal input data;

To provide comprehensive statistical summaries and comparisons of the two routing methods.

The model was designed to generate normal DAMBRK input data such as cross-sectional geometry and spacing, computational time step, and Manning's "n" values using very few parameters with default values. The model also determined spillway dimensions and crest elevation according to S_v and S_t values which defined the reservoir inflow hydrograph for both level-pool and dynamic routing. Spillway rating data were also developed internally by the model once dimensions had been established. Only one control line of data and two additional lines of data per reservoir are required for simulation. Because the input parameters are relatively easily-determined for any reservoir, this model provides a powerful tool for use by water managers and designers for determining which routing method is appropriate. A brief description of the model input data structure follows:

Line 1: Output control data and number of input datasets (lines 2 and 3)

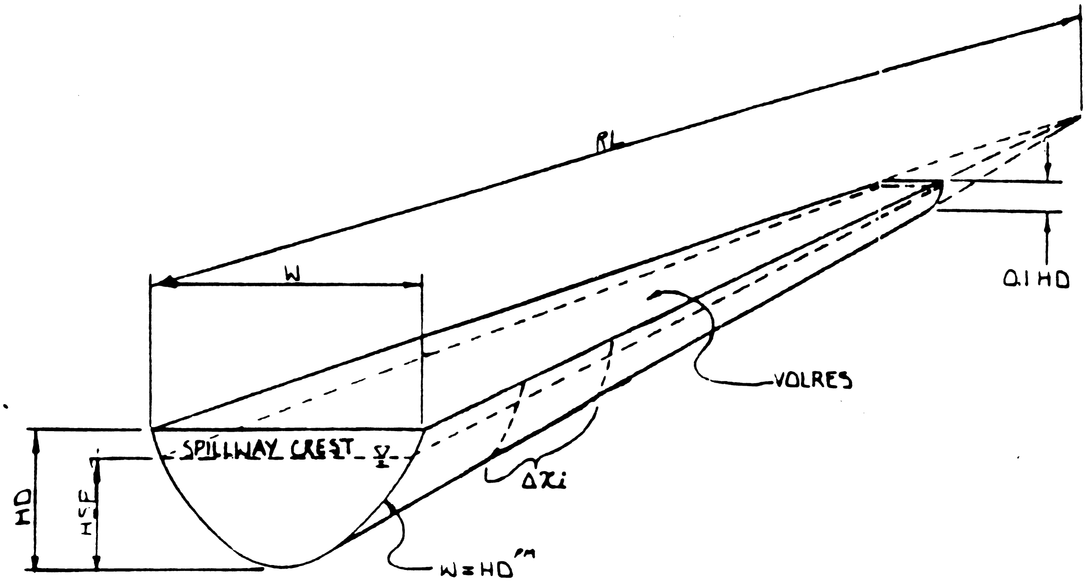


FIGURE 1 PRISMATIC RESERVOIR

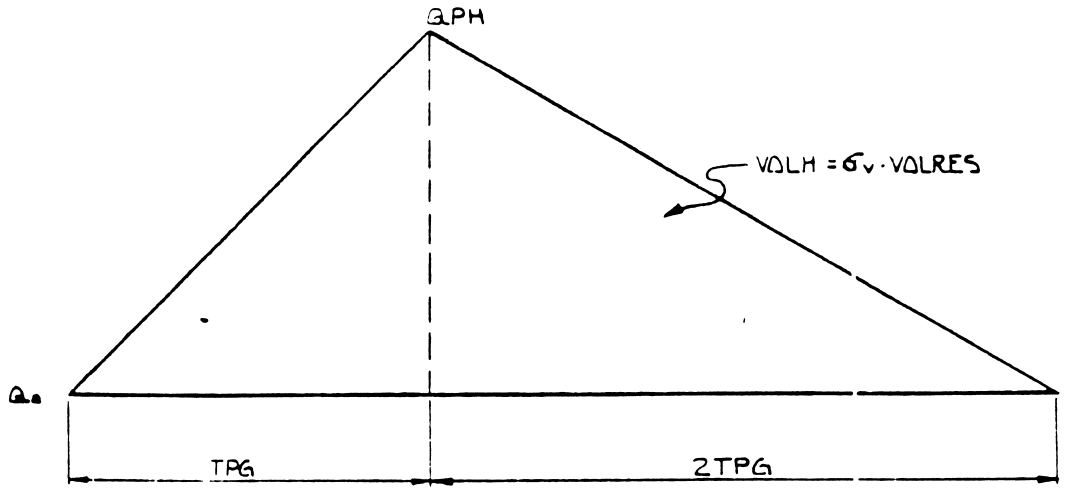


FIGURE 2 INFLOW HYDROGRAPH

Line 2: Dam height, valley width, cross-section power function exponent, reservoir length at initial pool, ratio of spillway crest height to dam height (default = 0.95, width determined such that discharge capacity at the top of dam equals the inflow hydrograph peak), Manning's "n" for reservoir (default = 0.02), and duration of routing (default = 3·TPG + 6·TTR, where TTR is the celerity travel time through the reservoir)

Line 3: Number of cross sections (default = $7.31 \cdot RL/TPG/DD^{0.5}$), TPG/TTR ratio, ratio of initial base flow to inflow hydrograph peak (if zero, base flow = 50 cfs), and Manning's "n" value of upper 1/4 of reservoir (remainder of reservoir = 0.02, default = 0.045, used to enhance model convergence at lower depths in the upper end of the reservoir)

Input data lines 2 and 3 are repeated for each set of reservoir or inflow hydrograph characteristics desired. The model automatically selects a computational time step for each run based on its specific reservoir and inflow hydrograph characteristics.

Some of the statistical comparisons made by the model (there are 44 in all, computed for the reservoir midpoint and at the dam) include mean, variance, standard error, ratio of peaks for computed stage and discharge hydrographs and for the rising limbs only of these hydrographs, and times to peak stage and discharge. Statistical comparisons for the rising limb are of particular interest in forecasting and operational applications. Printer plots of stage and discharge hydrographs are also provided by the model.

<u>Sensitivity Analysis</u> Because the flood hydrograph rising limb is of greatest concern from an operational standpoint, the principal statistical parameters used to determine sensitivity to the four characteristics are:

1. SEHRN - the standard error of HL-HD (level-pool computed stage minus dynamic-routing computed stage) for the rising hydrograph limb at the dam, normalized about the "true" peak stage; or the standard error divided by the peak stage computed using dynamic routing.

2. SEQRN - the standard error of QL-QD (level-pool computed discharge minus dynamic-routing computed discharge) for the rising hydrograph limb at the dam, normalized about the "true" peak discharge; standard error divided by the peak discharge computed using dynamic routing.

3. RHRMEAN - Ratio of the mean value of the error in stage (HL-HD) for the rising hydrograph limb to the computed peak stage using dynamic routing (HMD).

4. RQRMEAN - Ratio of the mean value of the error in discharge (QL-QD) for the rising hydrograph limb to the computed peak stage using dynamic routing (QMD).

Figures 3 and 4 show percentage values of SEHRN for four S_v values plotted against S_t, determined by application of DBCOMPAR to the Clarks Hill and West Georgia reservoirs, respectively. Figures 5 and 6 show percentage values for SEQRN comparably plotted. Figures 7 and 8 show percentage values of RHRMEAN the two projects. Figures 9 and 10 show RQRMEAN. The values of the length characteristic S_l for the two projects are nearly the same, 0.00035 for Clarks Hill and 0.00039 for West Georgia. The width characteristics for the two projects, however, are quite different, at 2.739 and 0.413, respectively.

Before investigating the sensitivity of model results to the four characteristics, testing using varying reservoir Manning's "n" values and cross-section was performed. As expected, higher "n" values did slightly magnify the differences between level-pool and dynamic routing computed results. However, a value of 0.02 is felt to be suitable for most reservoir applications. Cross-section spacing has little influence except when too large to allow for model convergence.

Conclusions Analysis of Figures 3 - 10 indicates that for these two projects with significantly different S_w values, very little variation in SEHRN, SEQRN, RHRMEAN, and RQRMEAN between the two is observed throughout the range of S_t values. This may indicate the S_w characteristic is insignificant and can be excluded, further simplifying the processes of comparing dynamic and storage routing techniques and developing reservoir routing characteristic relationships. Studies of additional reservoirs, increasing the range of the S_l and S_w characteristics will be necessary to make this determination. Because the Clarks Hill and West Georgia projects closely approximate each other in the length characteristic, S_l, additional tests were performed using "shortened" and "stretched" reservoirs, with preliminary results supporting the conclusion that the width characteristic is excludable. However, analysis of ratios of peak discharges, stages, and times to peak (which are of great interest in design and operations), are not complete, and therefore this conclusion is not yet final.

One goal of these efforts is to assist reservoir designers and operators select the appropriate routing technique to solve their unique problems. This goal is best achieved by refining analytical techniques to enable efficient evaluation of the routing technique before application. The DBCOMPAR model is ideally suited to this application. The characteristic relationships developed using DBCOMPAR will further simplify this process by allowing nomographic evaluation of the two routing techniques.

The most important objective, namely that of quantifying the differences between level-pool and dynamic routing, has not yet been fully accomplished. However, examination of Figures 3-10 show the differences in rising limb statistics to be measurable and quite large, with SEHRN and SEQRN ranging from 8% for large-volume, slowly-peaking floods to nearly 40% for low-volume, rapidly-rising events. Because of instantaneous translation, the level-pool assumption always oversimulates stage and discharge at the dam on the hydrograph rising limb. The differences in computed peak stages and discharges, based on data analyzed to date, range from 0 to 15%. The effects of these differences on reservoir operations and optimization schemes can be

FIGURE 3: Clarks Hill Reservoir

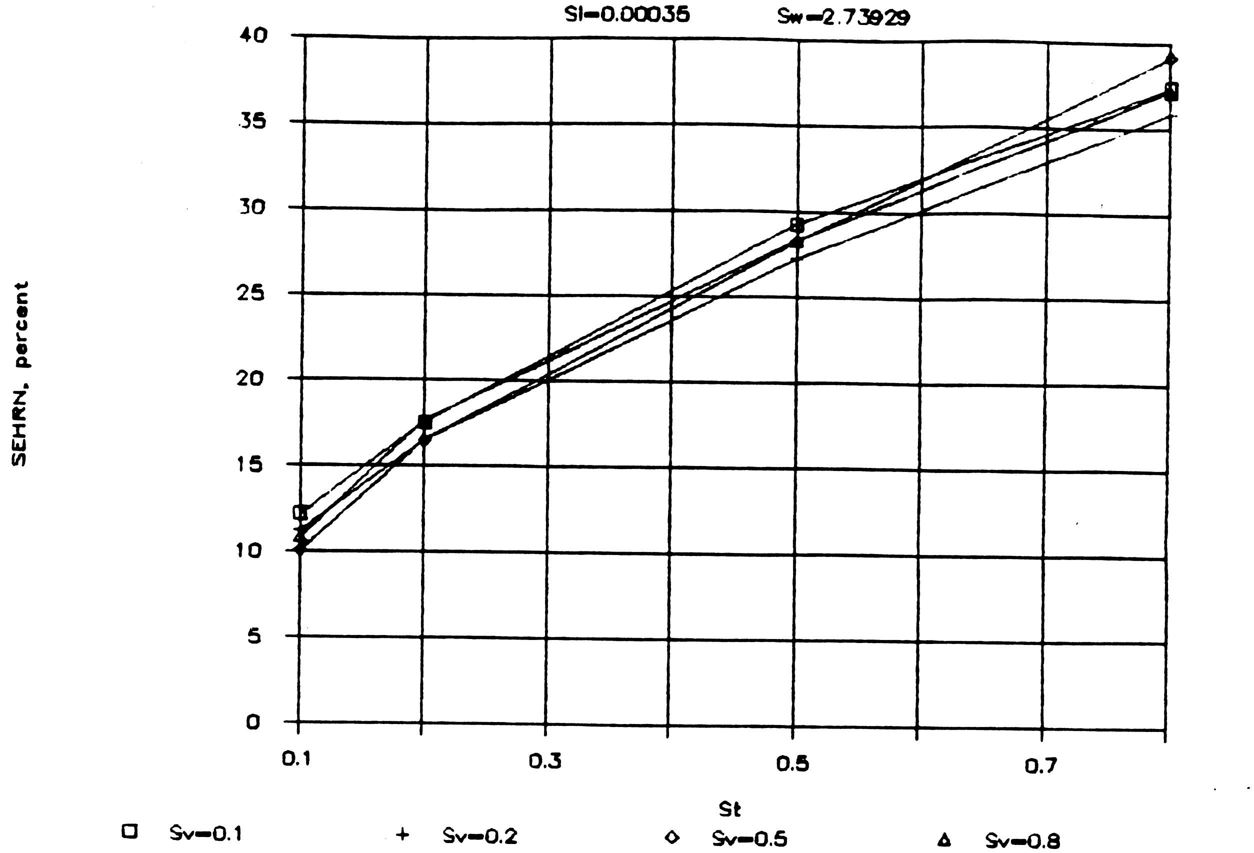


FIGURE 4: West Georgia Reservoir

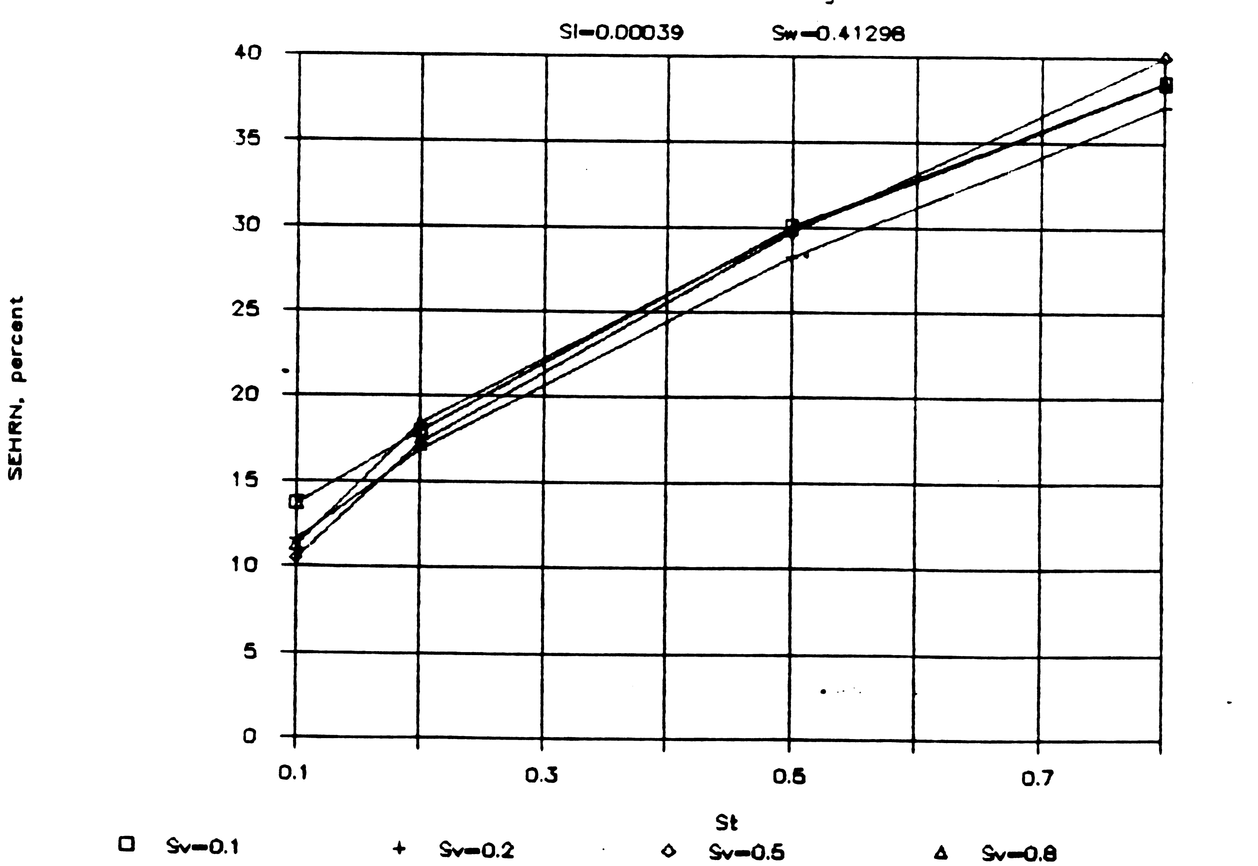


FIGURE 5: Clarks Hill Reservoir

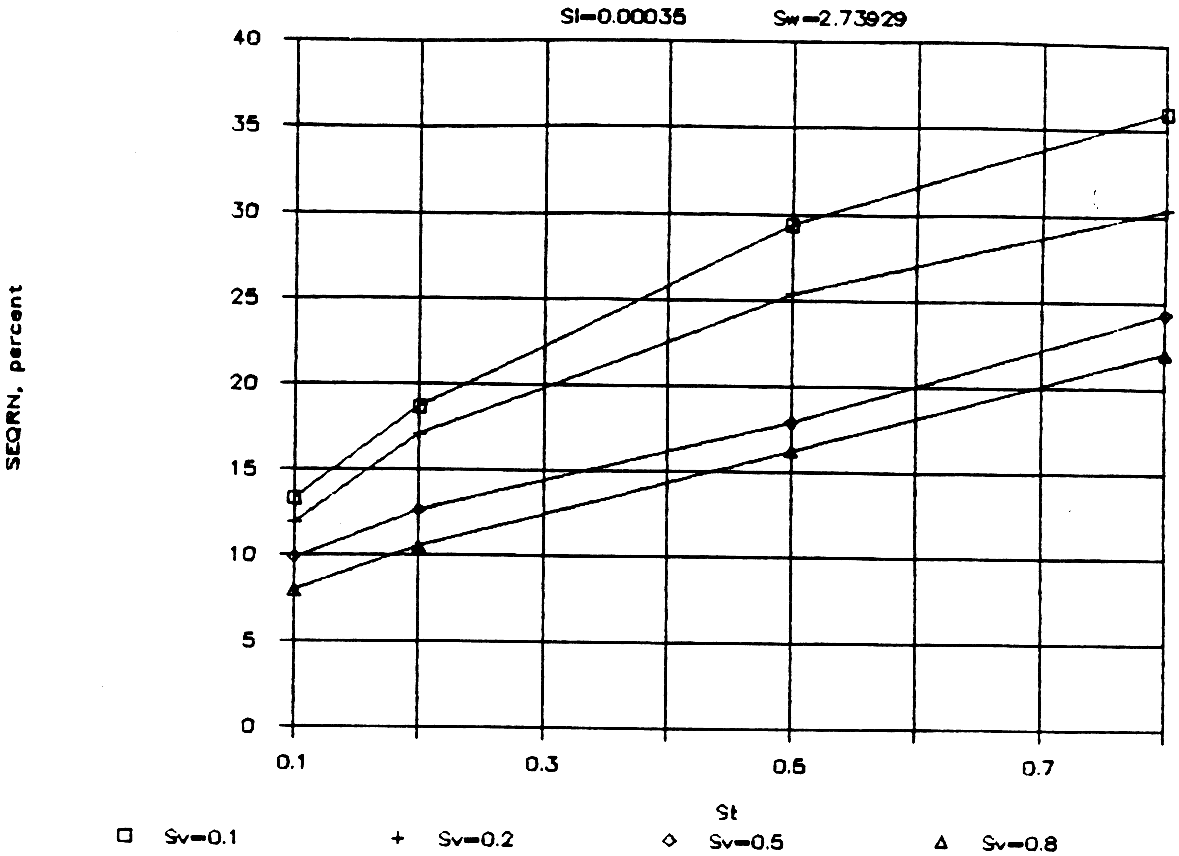


FIGURE 6: West Georgia Reservoir

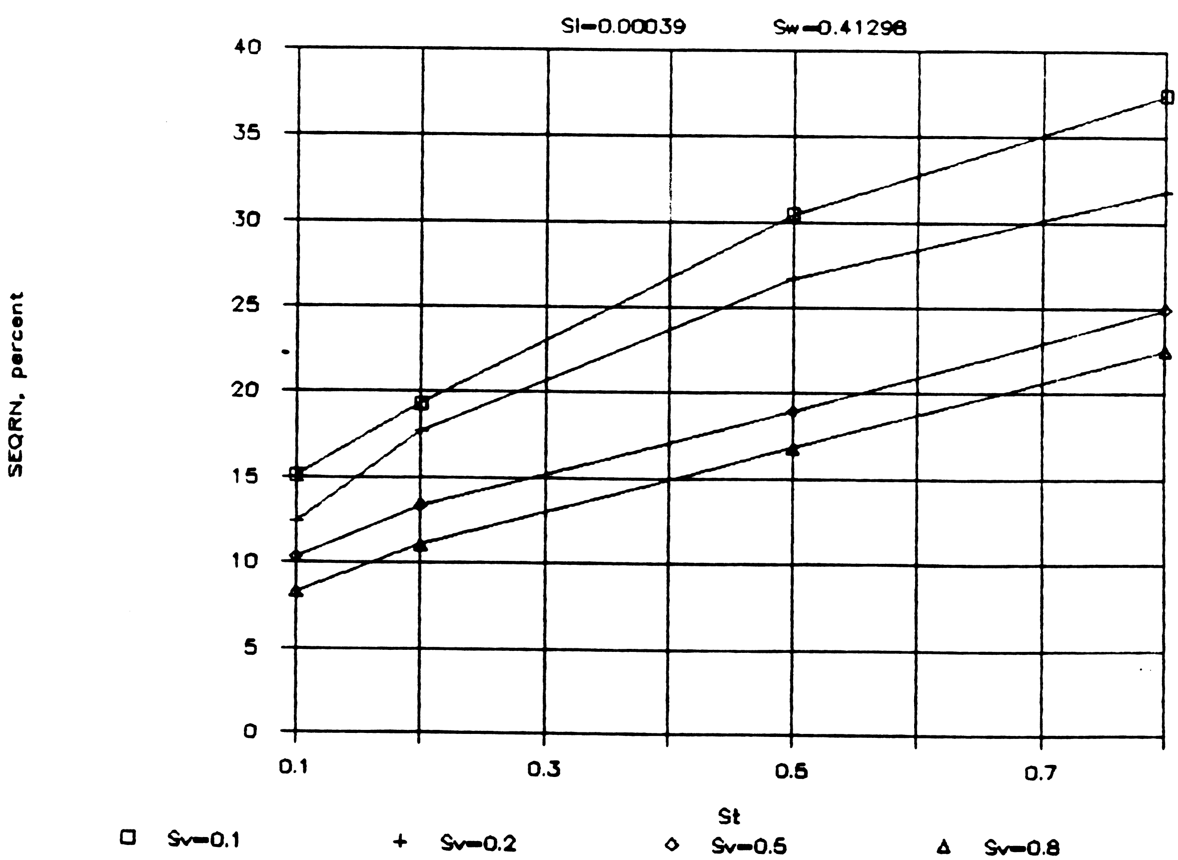


FIGURE 7: Clarks Hill Reservoir

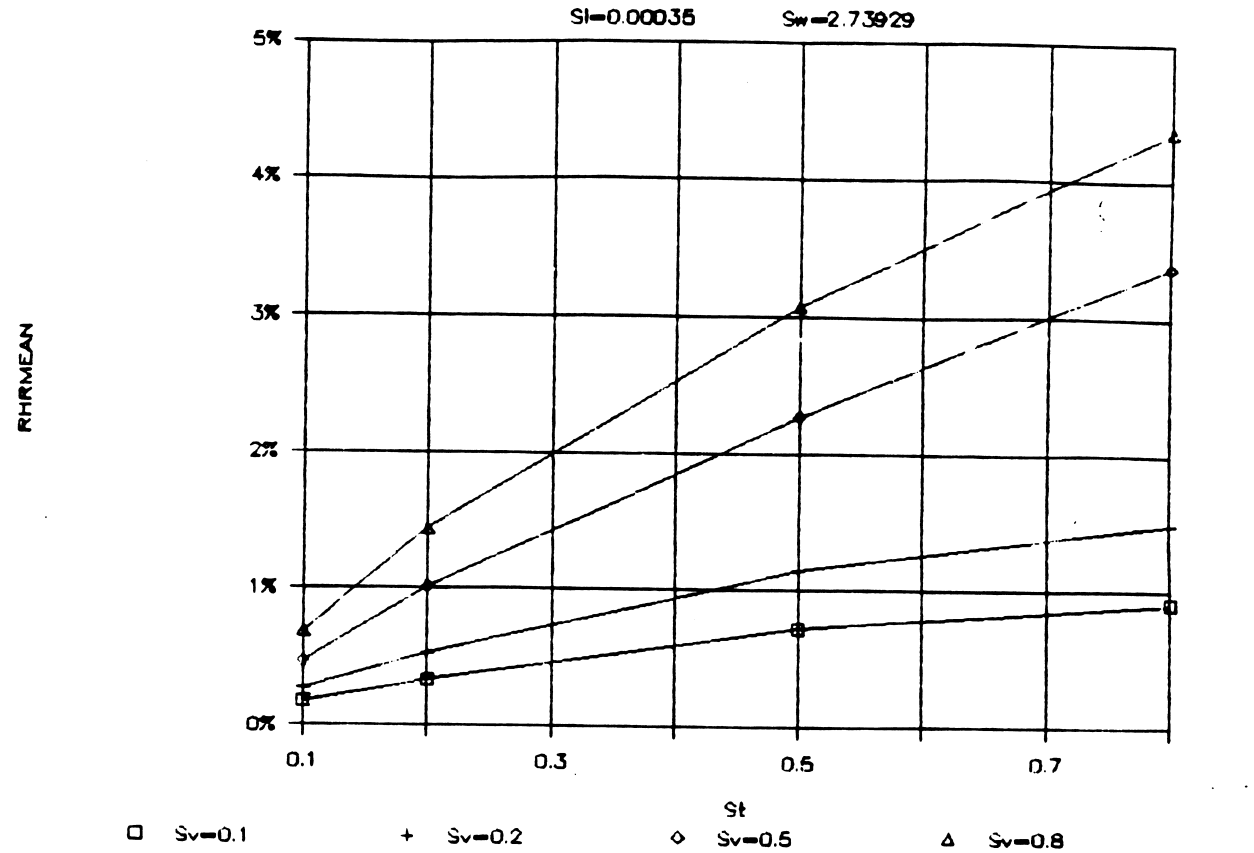


FIGURE 8: West Georgia Reservoir

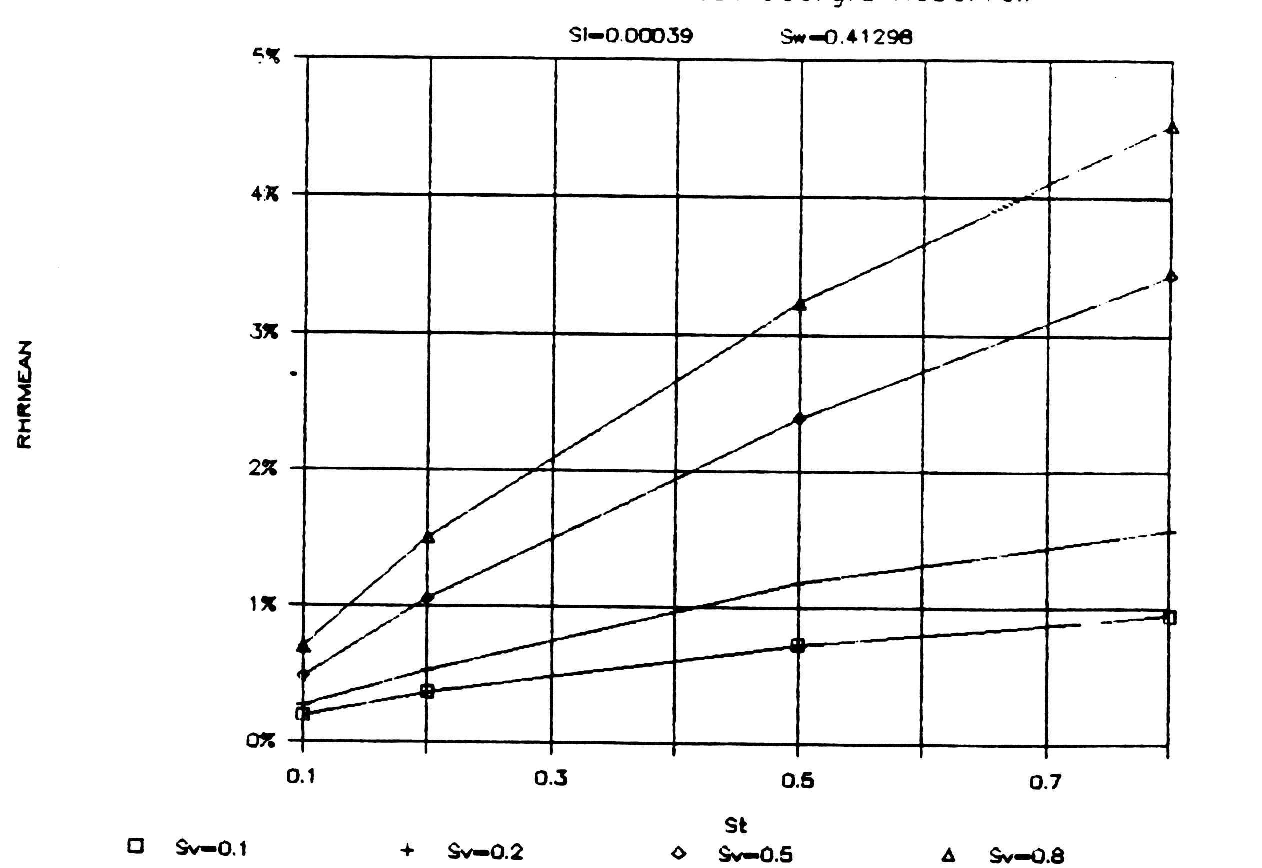


FIGURE 9: Clarks Hill Reservoir

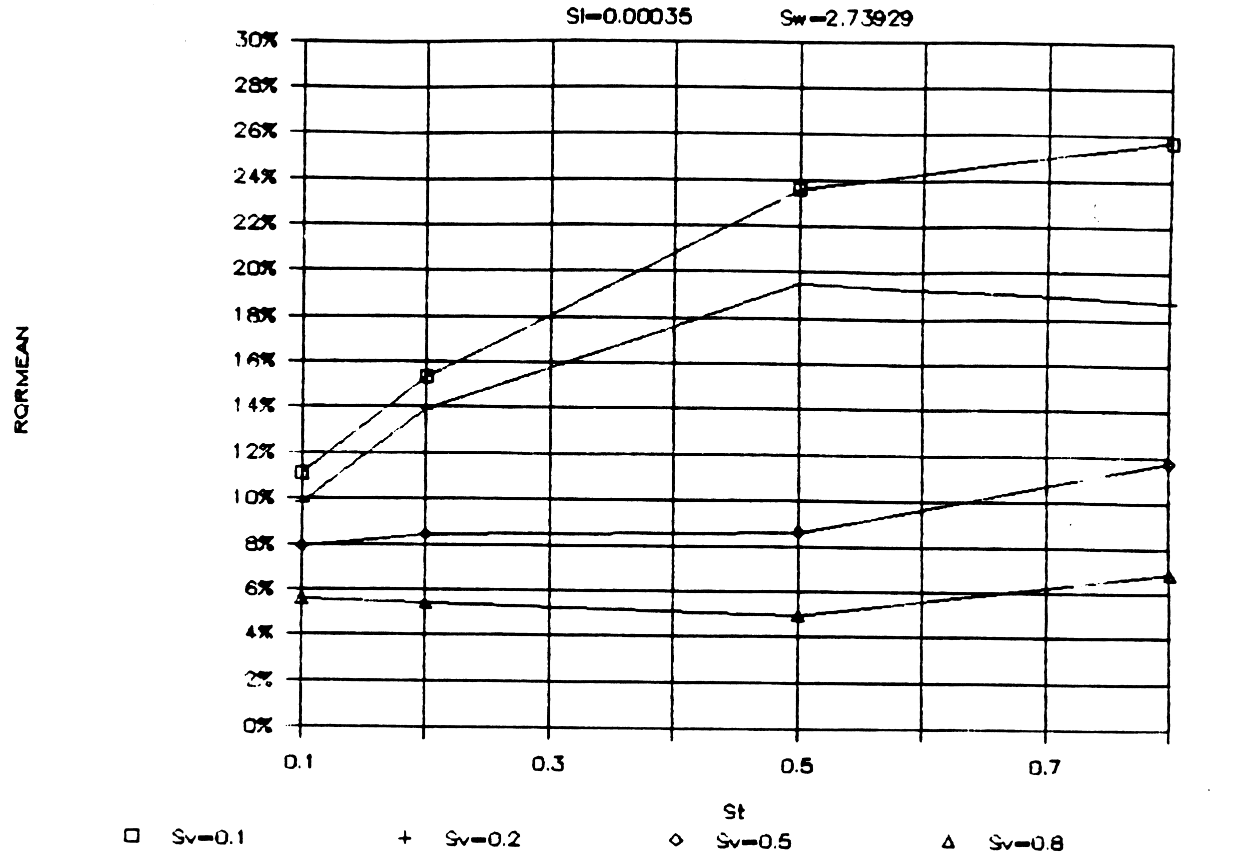
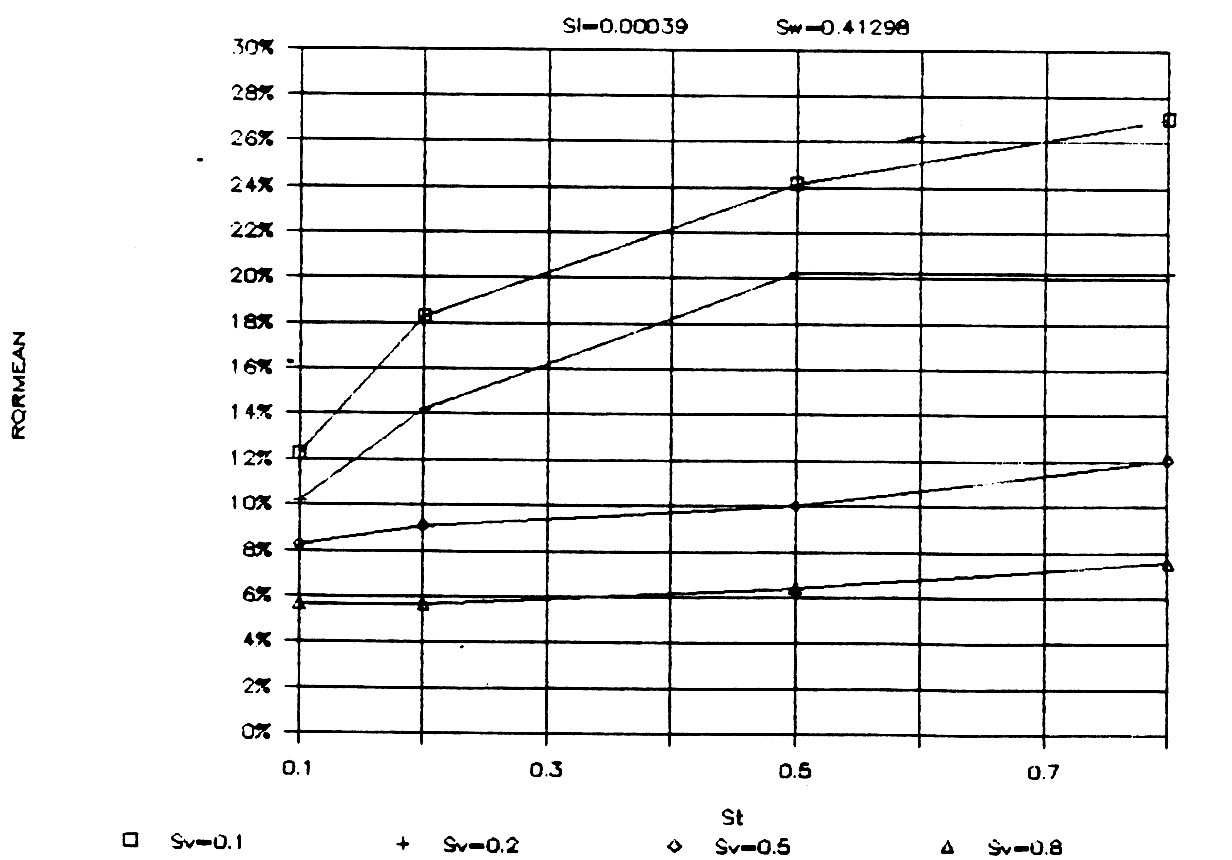


FIGURE 10: West Georgia Reservoir



significant. The authors hope to develop error-corrective relationships which can be incorporated into optimization techniques employing storage routing. The significance of responsive and accurate reservoir routing methodologies to improving project yield has been clearly identified by the New Brunswick Electric Power Commission[2]. By replacing a steady-flow backwater procedure with a one-dimensional unsteady flow model to determine reservoir profiles, rule curve modifications were made possible, markedly improving operations and yield of the Mactaquac project in New Brunswick. Its significance to water control management planning in general is becoming increasingly recognized[4,5] and incorporated into water management policies by the public and private sectors.

References

1. Clark, C. O., "Storage and the Unit Hydrograph", Proceedings, American Society of Civil Engineers, November, 1943, pp. 1333-1359.

2. Ismael, Sayed, and Hayward, D. E., "Application of Dynamic Backwater Modeling to Mactaquac Headpond - Saint John River, N.B", Proceedings, 6th Annual Canadian Hydrotechnical Conference, CSCE, June 2-3, 1983, Ottawa, Canada, pp. 203-220.

3. Kopsky, Raymond J. and Smith, Roger H., "Criteria for Selecting a Reservoir Routing Method", Proceedings of the Symposium on Engineering Hydrology, ASCE, Williamsburg, Virginia, Aug. 3-7, 1987, pp. 696-701.

4. McMahon, George F., "Increased Reservoir Yield Through Improved Flood Forecasting", Proceedings, VIth World Congress on Water Resources, IWRA, Ottawa, Canada, May 29 - June 3, 1988.

5. Wurbs, Ralph A., "Reservoir Management in Texas", Journal of Water Resources Planning and Management, ASCE, Vol. 113, No. 1, January 1987, pp. 130-148.

KEY WORDS

Flood control, Forecasting, Hydraulics, Hydrodynamics, Hydroelectric power generation, Hydrographs, Hydrology, Models, Reservoir operation, Reservoirs