ASSURED WATER SUPPLY FOR THE WASHINGTON METROPOLITAN AREA

Daniel P. Sheer
Interstate Commission on the Potomac River Basin
6110 Executive Blvd., Suite 300
Rockville, MD. 20852
January 1983

EXECUTIVE SUMMARY

ASSURED WATER SUPPLY FOR THE WASHINGTON METROPOLITAN AREA

Daniel P. Sheer
Interstate Commission on the Potomac River Basin
Rockville, Maryland

In 1982, the Washington Metropolitan Area took an important step that will guarantee adequate water supply well into the 21st century. Yet, no large reservoirs were built, no new wells drilled, no large pipelines constructed. State-of-the-art water resources management techniques substantially increase the yield of the existing supplies, meet future water demands, and improve the aquatic environment. Agreement among the local jurisdictions implemented the innovative operating procedures.

Implementation required eight separate agreements among agencies including the federal government, the states of Maryland and Virginia, the District of Columbia, two local utilities, and the Interstate Commission on the Potomac River Basin. These were signed on July 22, 1982, climaxing three decades of uncertainty about the water supply of the Washington Metropolitan Area. During that period, population of the region doubled under the cloud of dire warnings of the need for a reliable water supply source. Severe droughts of the mid-1960s came and went. Proposed solutions included as many as sixteen major reservoirs, recycling of estuarine water containing a substantial proportion of treated wastewater, well fields, high flow skimming, and assorted other facilities. By 1977, after 25 years of study, the problem was nowhere near solution.

The Washington Metropolitan Area relies largely on the Potomac River for water supply. But the Potomac is virtually unregulated; its flow varies from extreme flood--over 200 billion gallons per day--to extreme drought: less than 400 million gallons per day at Washington. In the years since the record low flow of September 1966, the area's combined Potomac withdrawals have often exceeded 400 million gallons per day. The operating procedures implemented in July 1982 provide a dependable supply for Washington of about 950 million gallons per day.

Coordinated regional operation of water supply facilities is the key to this solution. Operation of local reservoirs are meshed with those at Bloomington Dam, completed in 1981 by the U.S. Army Corps of Engineers and the recipient of the American Society of Civil Engineers 1981 Award of Merit.

But, Bloomington is only one of the many upstream reservoirs considered necessary in the 1960s and 1970s to solve the problem. Faced with politically savvy opponents, plans for other new and costly dams in the beautiful and historic Potomac Valley were thwarted. The situation called for a largely non-structural solution.

Developing an implementable solution to the Washington Metropolitan water supply problem required a unique combination of organizations and expertise. Beginning in the late 1970s, local elected officials, utilities, university researchers, and federal, state, and interstate agencies all worked in close cooperation toward a single goal. An important factor for public officials is the cost saving involved: the non-structural solution costs from $200 million to $1 billion less than the cost of implementing any previously proposed structural solutions.

Improved yield is achieved by several methods. Daily demand and flow forecasting techniques are used to schedule releases from Bloomington Reservoir, over 200 miles and 5 days travel time upstream. Flexibility inherent in the local distribution systems is used to save water in existing local reservoirs on small tributaries. During droughts, Potomac withdrawals of all utilities are coordinated on a daily basis to minimize the water flowing by the intakes over and above instream flow requirements. A new small local reservoir ($30 million) is being built to improve operational flexibility by providing a means to correct for forecasting errors. In sum, the operating techniques squeeze the most out of the existing water supply infrastructure.

The political nature of the problem posed additional engineering challenges. Not only was it necessary to develop new solutions, techniques had to be developed to demonstrate beyond question the feasibility of coordinated regional operations, and the impact they would have on each utility and the environment. This was accomplished using simulation and gaming techniques. Simulation of the benefits to each utility of regional operation were used as a basis for cost sharing in Bloomington and Little Seneca Reservoirs. Instream habitat simulations were used to help define operating rules which improved fisheries potential, while meeting water demands.

Prior to the signing of the agreements, the water supply officials of the region participated in two drought exercises (the water equivalent of war games). These served not only to test and improve the operating procedures and the provisions of the agreements, but also to familiarize the officials with the use of advanced engineering techniques in day-to-day drought management.

Mathematical models, optimization and simulation techniques, and other innovative tools of systems analysis have been used at the university level for many years. Their successful application in the Washington Metropolitan Area demonstrate their value in dealing with complex engineering and politicial problems. Overall system yield has been increased by nearly 50%, and individual project yields by as much as 200%, without infringing on the autonomy of local goverments.

Innovations included:

* The combination of optimization and simulation techniques to provide practical rules for operation of the entire system.

* The first large scale implementation of the National Weather Service River Forecast System (NWSRFS), based on a soil moisture accounting model and its direct integration with reservoir operations.

* The development and implementation of a technique to produce probabilistic water demand traces, and the application of that technique in water resource system design and operation.

* The combination of distribution analysis and hydrologic modeling to develop operating procedures for a complex water distribution system--one that includes many independent water suppliers.

* The use of risk analysis to identify the start of potential droughts and to quantify the risks of continued drought.

* The use of drought games to test and improve water supply operating procedures and to illustrate the use of those procedures to decision makers.

* Substitution of a small local reservoir for much more costly upstream impoundments.

The joint operating scheme is designed to minimize interference with normal utility operation. Joint operations do not begin until drought conditions, which are defined using risk analysis, exist.

When required, releases from the Bloomington Dam, 200 river miles--and several days--upstream from Washington, are scheduled using demand and flow forecasting techniques. The release is set to assure a very low probability of shortage, given the uncertainty in the forecasts and the availability of local supply downstream.

Downstream operations strive to maintain balanced storage in the metropolitan area reservoirs on a daily basis. Modest daily corrections balance the system. Weather information, upstream flow conditions, and other factors are fed through a central computer system to aid in allocating the flow of the Potomac River and reservoirs.

Writing the contracts to implement the joint operations and cost sharing was a formidable task. The interstate nature of the agreements, the unique character of the government of the District of Columbia, and the congressionally-mandated responsibilities of the U.S. Army Corps of Engineers created a complex situation. But as a result of the drought exercises and careful education of utility managers, the negotiators were absolutely convinced of the feasibility and desirability of joint operations.

Eight separate but interlocking contracts were executed on July 22, 1982. The basic agreement focuses on operating rules. Other agreements concern cost sharing and the modification of pre-existing agreements and contracts.

Providing the Washington area with an adequate water supply was a complex engineering, social, economic, environmental, and institutional problem. Large scale structural solutions had been proposed and found wanting. A fresh approach was required. It was provided by advances in water resources engineering analysis over the last 20 years.

The techniques of water resources engineering systems analysis--linear programming, synthetic hydrology, statistical analysis, hydrologic modeling, and computer simulation--were adapted to produce a predominantly non-structural engineering solution to the problem. Many of the techniques were used together for the first time, and others were subject to major modification specifically to address this problem.

An "insoluble" problem of almost 30 years standing was resolved. The "impossible" task of achieving regional cooperation was accomplished. Between $200 million and $1 billion were saved compared to previously evaluated alternatives. Moreover, the solution was not achieved at great environmental expense. In fact, the environmental benefits of increased minimum instream flow and the recreational opportunities provided by Little Seneca Lake may outweigh any environmental impacts.

Significantly, the integration of engineering analysis and the decision making process, made possible by computer simulation, played an essential role in implementing the solution. Without the convenient and credible framework for decision making provided by the model, negotiations between the parties would have been far more difficult.

Perhaps the most important aspect of the solution to the WMA water supply problem is the example it sets. Here is proof that non-structural engineering alternatives, including better management of existing facilities, can solve some of the most difficult socio-political problems and achieve substantial cost savings. Because the replacement value of our existing facilities is substantially greater than the present value of expenditures on new facilities at current rates, the potential benefits of widespread application of the types of engineering analysis used in the Washington area are enormous.

ASSURED WATER SUPPLY FOR THE WASHINGTON METROPOLITAN AREA

Daniel P. Sheer
Interstate Commission on the Potomac River Basin
Rockville, Maryland

On July 22, 1982, the federal government, the states of Maryland and Virginia, the District of Columbia, two local utilities, and an interstate agency executed eight separate agreements, assuring the Washington Metropolitan Area (WMA) an adequate supply of water well into the next century. The agreements ended a nearly thirty year search for solutions. The proposed solutions included as many as sixteen major reservoirs, recycling of estuarine water containing a substantial proportion of treated wastewater, well fields, high flow skimming, and assorted other facilities, in multiple combinations.

In 1977 the U.S. Army Corps of Engineers, in the Northeastern United States Water Supply Study, evaluated nine alternatives, each costing between $200 million and over $1 billion in today's construction dollars. All proved infeasible for a variety of political, social, environmental, and economic reasons. In that same year, after ten years of negotiations, and with no implementable options for additional supply, the Corps (which suppies water for Washington, D.C. and some Virginia suburbs), the affected states, and the local water utilities agreed on a formula for allocating water during shortages (Potomac River Low Flow Allocation Agreement). Even this agreement was opposed by the U.S. Fish and Wildlife Service as providing inadequate instream flow for aquatic life.

In contrast, the agreements reached in July, 1982 are based primarily on almost costless, improved, cooperative operations of existing facilities, using state-of-the-art flow and daily demand forecasting techniques. Construction of one small local reservoir ($30 million) is included, but even that reservoir is important not so much for the quantity of water it stores, but for the additional operational flexibility it provides. Overall system yield has been increased by nearly 50%, and individual project yields by as much as 200%. Improved operations not only meet water supply needs for decades to come, they also provide substantial instream flow and water quality improvements. Innovative engineering provided a superior, non-structural solution to this difficult problem.

This success story is indicative of the "coming of age" of the application of systems analysis techniques in the field of water resources engineering. Innovations included:

* The combination of optimization and simulation techniques to provide practical rules for operation of the entire system.

* The first large scale implementation of the National Weather Service River Forecast System (NWSRFS), based on a soil moisture accounting model and its direct integration with reservoir operations.

* The development and implementation of a technique to produce probabilistic water demand traces, and the application of that technique in water resource system design and operation.

* The combination of distribution analysis and hydrologic modeling to develop operating procedures for a complex water distribution system--one that includes many independent water suppliers.

* The use of risk analysis to identify the start of potential droughts and to quantify the risks of continued drought.

* The use of drought games to test and improve water supply operating procedures and to illustrate the use of those procedures to decision makers.

* Substitution of a small local reservoir for much more costly upstream impoundments.

The agreements were made possible by the extraordinary integration of engineering analysis and the political decision making process. Here again, the use of systems analysis in the appropriate institutional framework made it possible to build consensus among a diverse and independent group of decision makers working to solve the complex problem. The institutional arrangements used to facilitate this integration may well serve as models for future efforts in water resources systems design.

A Fickle River

The Washington Metropolitan Area and the Nation's Capital sit astride the Potomac at its transition from free-flowing river to tidal estuary. Three million people, 75% of the population of the entire Potomac basin, live in the Washington region. Three suppliers provide nearly all of the water supply needs of the Washington area. The Washington Suburban Sanitary Commission (WSSC) provides water for suburban Maryland, and the Fairfax County Water Authority (FCWA) provides water for most of Fairfax and northeastern Prince William counties in Virginia. The Washington Aqueduct Division U.S. Army Corps of Engineers, (WAD), wholesales finished water to the District of Columbia and the County of Arlington and City of Falls Church in Virginia. (Figures 1,2)

The area has three primary sources of raw water. Until 1982, when a new 200 mgd intake and 50 mgd treatment plant on the Potomac were completed, the FCWA met nearly its entire demand from the Occoquan

Reservoir at the mouth of the Occoquan River. The reservoir has about 11 billion gallons of useable storage and a "safe yield" of 55 mgd. It feeds two treatment plants with a combined peak capacity of 112 mgd.

The WSSC takes most of its supply from the Potomac through a 400 mgd intake and 240 mgd (peak) treatment plant located just downstream of the new FCWA intake. In addition, the WSSC has two reservoirs on the Patuxent, with a combined useful storage of about 10 billion gallons. The Patuxent reservoirs have a combined "safe yield" of 45 mgd, 10 mgd of which is committed to maintaining flow below the lower dam. The peak capacity of the Patuxent treatment plant is 65 mgd. The WAD is entirely dependent on the Potomac for supply. It has two intakes, a 200 mgd gravity intake at Great Falls, and a 400 mgd pumping station at Little Falls just above the District line. The WAD intakes are the farthest downstream of the three major suppliers. (Table 1)

The Potomac at Washington drains over 11,000 sq. mi. with an average flow of about 6 billion gallons per day. It is a notoriously fickle river, with daily flows that range over almost three orders of magnitude from floods of 200 billion gallons per day to drought flows of less than 400 mgd. The drainage is almost entirely uncontrolled. The only sizable dams in the basin are at Savage River and Bloomington, both in the headwaters of the North Branch in Western Maryland and West Virginia, over 200 miles upstream of Washington.

Savage Reservoir, in western Maryland, began as a WPA project in the 1930s and completed by the Corps in the early 1950s. It controls about 130 sq. mi. and can store about 12 billion gallons for flood control or water quality flow maintenance purposes. It has been used to provide a dependable flow of 60 mgd in the North Branch at Luke, Maryland, as well as supply for the small town of Westernport, just downstream. Savage Reservoir was in operation on September 13, 1966, when the minimum one-day flow of 388 mgd was recorded at the Little Falls gauging station. Since that record low flow, the dependable yield of the Potomac for water supply, including contributions from Savage, has commonly been taken as 388 mgd.

Bloomington Dam, on the North Branch Potomac which forms the boundary between Maryland and West Virginia, controls some 210 sq. mi. of drainage just over the ridge from Savage. It provides flood control and recreation in addition to conservation storage. It is the third highest dam east of the Mississippi, yet it impounds only 31 billion gallons of water because of the steep gradient of the stream. Of the conservation storage, 55% is allocated for water quality control in the North Branch. The remaining 45% has been purchased by the WMA utilities for use in water supply, as part of the agreements mentioned above. The "safe yield" of Bloomington is 135 mgd. (Figure 3)

Wastewater collected from the customers of all three suppliers is discharged to the tidal Potomac below Little Falls, and is not available for reuse. Therefore the water available is simply the sum of the available supplies. (Table 2)

Summing the safe yield of Bloomington and the Potomac River gives 523 mgd as the dependable Potomac flow. From this must be taken the required minimum Potomac instream flow, 100 mgd. This leaves 423 mgd of Potomac flow for water supply. Adding the safe yields of the local reservoirs gives the dependable yield for WMA water supply from all sources, 513 mgd.

By 1977, average demands for the summer months were often in the range of 450 to 470 mgd. Peak day demands had well exceeded the sum of the safe yields, even counting water from Bloomington, which was four years from completion. Withdrawals from the Potomac had surpassed the 423 mgd dependable flow. The Corps' North East Water Supply (NEWS) Study was predicting the possibility of regional shortages as large as 80 mgd by 1980, and 365 mgd (almost 35%) by the turn of the century. The FCWA, as yet without a Potomac intake, nearly emptied its Occoquan Reservoir that year, and Fairfax County nearly closed schools and businesses in a desperate attempt to save water.

A Century-Old Problem

The critical problems of the late 1970s had been building for a long time. In 1857, when Congress first directed the Corps to develop a dependable supply for the Nation's Capital, the Potomac was looked on as an inexhaustable source. This perception continued through World War II, despite severe droughts, particularly in the early 1930s. But by 1955, demands had grown to the point that a modest drought inspired the Congress to direct the Corps to prepare a long range water resources development plan for the Potomac basin, including the Washington area. Responding to the Congressional request, the Baltimore District Corps of Engineers in 1963 published a full development basin plan as comprehensive, thorough, and well documented as any developed before or since. The plan, called for the construction of sixteen major reservoirs and over 400 smaller impoundments for water supply, flood control, recreation, and water quality improvement. Most of the water storage was, in fact, for water quality flow maintenance. The plan found little support.

In most cases, the proposed reservoirs would have flooded a significant percentage of the productive land in the rural, mountainous western counties of the basin. Upper basin residents perceived the primary benefits to be downstream, -- water for municipal water supply and wastewater dilution. A major controversy ensued, and the District Engineer's recommendations were never submitted to Congress. A separate less-controversial report of the North Branch had been prepared, prior to the release of the 1963 plan.

This was considered by Congress and led to the authorization of the Bloomington Lake in 1962.

The northeast drought of the mid-60s also affected the Potomac. When Congress authorized the NEWS Study in 1965, the Corps began its second major study of the Washington area problem. In 1966, the "bottom" fell out of the river. Based on the drought of the 1930s, 500 mgd was considered an absolute minimum flow for the river at Little Falls. That mark was broken on September 11, and the flows kept dropping for another week, to 388 mgd. In this particular case, the arrival of a hurricane averted impending disaster.

The design of the WSSC's Potomac intake was inadequate to handle the reduced river flow, and after the drought, the WSSC applied for a permit to build a weir to alleviate the problem. Unfortunately for the WSSC, water supply for the U.S. Congress came from the Corps intakes downstream. The WSSC was not issued a permit, and thus began the negotiations which led to the Low Flow Allocation Agreement in 1977.

In 1969, the State of Maryland took a major positive step in the direction of providing more water; it set up the Maryland Potomac Water Authority (MPWA). The authority guaranteed to purchase just enough of the water supply to be stored in Bloomington to meet the requirements for securing a federal appropriation. Funds were forthcoming, and construction at Bloomington started in 1971.

Meanwhile, the Chief of Engineers revised the recommendations in the 1963 Baltimore District Engineer's report, including only six reservoirs. The Secretary of the Army reevaluated the Chief's report in light of an increase in the interest rate charged for water resources projects. The Secretary recommended the construction of only two of the reservoirs: Verona, on the Shenandoah River near Staunton, Virginia, and Sixes Bridge, on the Monocacy River at the Maryland, Pennsylvania border. The report finally went to Congress.

By the time the recommendation was considered by Congress, the use of water to dilute waste in the tidal river was discouraged by the passage of the Federal Water Pollution Control Act Amendments of 1972. Advanced waste treatment was being proposed for all wastewater treatment plants in the Washington area. Eliminating the need for dilution had the effect of reducing the required minimum flow at Little Falls by about two-thirds. The Congress directed the Corps to reformulate the Verona and Sixes Bridge projects as soon as possible. The task fell to the NEWS staff.

Their report, completed in early 1973, evaluated many new concepts for increasng supply, including high flow skimming using the Patuxent and Occoquan Reservoirs, reuse of water from the tidal river, pumping from the Rappahannock and Susquehanna Rivers, and restricting water use during emergencies. The Corps again recommended the immediate construction of Verona and Sixes Bridge reservoirs. In addition, the Corps recommended the construction of an Experimental Estuary Treatment Plant to test the feasibility of recycling water from the tidal river. Despite the enormous construction cost estimates for recycling ($1.4 billion in 1982, in addition to the cost of the two reservoirs), the Corps felt that recycling was a promising alternative. This was no doubt due to the difficulty in securing authorization for any additional upstream reservoirs. (Table 3)

Congress authorized and funded the experimental estuary treatment plant and preliminary design of the two reservoirs. But, it conditioned any further appropriations on: a) the completion of tests of the estuary treatment plant, b) the completion of a third major study of the problem by the Corps (the Washington Metropolitan Area Water Supply Study, WMAWSS), and, in an unusual action, c) the review of both of the above by the National Academies of Science and Engineering.

By this time the WSSC had been trying for seven years to secure a permit for its weir. In 1974, the Corps and the WSSC agreed on a first draft of the Low Flow Allocation Agreement designed to ensure the WAD an equitable share of the available flow during drought. The Corps concluded it needed Congressional authorization before signing the document. Virginia and the FCWA, by then contemplating using Potomac water, demanded to be parties to the agreement. When Congress consented to the Low Flow Allocation Agreement in 1976, it stipulated that two conditions be met before the Corps could issue a permit for the WSSC weir. First, the agreement had to be signed; and second, the weir could not conflict with the Corps recommendations under its new Washington area study.

Pioneering Efforts

In 1976, frustrated by the failure to find implementable regional solutions for the area's problem, the WSSC undertook a study to determine what it could do to ensure its own supply (the Bi-County Water Supply Study, BCWSS). The organizational structure of the study was unique, and effective. The study was directed by the Bi-County Water Supply Task Force, organized by the WSSC and composed of the local elected officials of Prince George's and Montgomery counties who would be required to approve the recommendations. In this way, the appropriate officials were directly exposed to the engineering design process, and given an understanding of and a stake in its results. Two advisory committees were also formed, a Citizen Advisory Committee and a Technical Advisory Committee.

The citizen members were appointed by the county executives, the technical members by the WSSC, which funded the study. Both advisory committees met regularly with the study consultants, and made recommendations directly to the task force. As a result of this organizational arrangement, the consultants became acutely aware of most of the concerns and objectives of the informed public. The consultant could thus concentrate on the alternatives most likely to be implementable. In addition, the engineering rationale behind the recommendations were well understood and appreciated by a diverse and influential group of community representatives.

In 1976, the FCWA applied to the Corps for a permit to construct its Potomac intake. The Corps began preparing an Environmental Impact Statement (EIS) while negotiating the Low Flow Allocation Agreement. The Office of the Chief of Engineers had serious reservations concerning the 1974 draft agreement. At the insistence of the Corps, a provision allowing any party to the agreement to "freeze" the allocation formula in 1988 was added. Since the suburbs were expected to grow faster than the city, this provision had the effect of ensuring the WAD of a minimum share of Potomac flow, regardless of suburban growth. The provision was onerous to the WSSC and FCWA, however.

In 1977 a modest drought hit the Potomac basin; it was substantially more severe in the Occoquan sub-basin in Virginia. The drought really demonstrated the seriousness of the problem. As stated earlier, the Occoquan fell to alarmingly low levels, and Fairfax County seriously considered closing schools and businesses. As flows in the Potomac fell to their lowest levels in 10 years, the WSSC's ability to meet its demands, without its weir, were seriously threatened. The Corps granted the WSSC permission to construct a temporary, emergency weir. Rock filled gabions were airlifted into place with military precision, forming a 1500-foot-long weir. (Figure 4)

The Low Flow Allocation Agreement was signed in January 1978. It included the "1988 freeze" provision, despite the objections of Maryland, Virginia, the WSSC, and the FCWA. Both Maryland and Virginia utilities needed permits to start construction, and their only alternative was to pursue the matter to a distant and uncertain end through federal courts.

The Fish and Wildlife Service of the U.S. Department of the Interior, not consulted during negotiations, objected strongly. Fish and Wildlife insisted that the 100 mgd minimum instream flow agreed to by the Low Flow Allocation Agreement signatories was inadequate, and suggested flows as high as 1500 mgd as more reasonable to protect fisheries. Maintaining such flows would have denied the suppliers use of any Potomac water for extended periods during most summers. In a memorandum of understanding, the Maryland Department of Natural Resources agreed to undertake a study (the "Low Flow Study") to determine minimum flows, and the Corps agreed to abide by the recommendations of that study.

In August 1978, with the Environmental Impact Statement completed, the Corps granted the FCWA permit. Construction started soon after. The WSSC was still out of luck, however; the Congress had insisted that the permit be in accord with the Corps' Washington Water Supply Study, and the study was not scheduled for completion until 1983.

In 1978 the Maryland's Bi-County Task Force produced three primary conclusions. First, the WSSC should not plan to construct all the facilities necessary to meet peak demands during the worst of droughts; small shortages of seven or fewer days duration were acceptable. Second, the WSSC could provide for its own needs for 15 to 20 years by building either of two facilities, a small reservoir on Little Seneca Creek in Montgomery County, or a large raw water pipeline between the WSSC Potomac and Patuxent Treatment Plants. Third, the WSSC and the Maryland counties should proceed immediately with the planning and design of both facilities, and the construction of one, preferably Little Seneca Lake.

Not surprisingly, given the structure of the Bi-County Study, the recommendations were very well received locally. The WSSC received the approval of both counties, began design of Little Seneca, and applied to the Corps for the necessary permit. The U.S. Environmental Protection Agency which routinely reviews proposed Corps permits, strenuously objected to the Little Seneca permit. The objections centered on potential water quality problems in the lake, alteration of natural habitat, and the possibility that an independent solution to the WSSC's problem would foster environmentally disruptive independent solutions to the problems faced by the other utilities.

The WSSC continued to seek a permit to build its weir. A rider removing the congressional stipulation that the Washington Area Study be complete before the permit was granted was attached to a bill naming a monument in New Mexico for the late Senator Montoya of that state. President Carter signed that bill in June 1981. Construction started immediately. (Figure 5)

Attacking the Regional Problem

The Washington area water supply problem was obviously a complex engineering, social and political problem. While there was no shortage of standard technical or even non-standard solutions, none of the solutions considered to the overall problem before 1977 had been socially or politically feasible. Yet, by 1977, all the elements of an acceptable solution were present.

The organization of the Maryland Potomac Water Authority (which guaranteed repayment of initial water supply costs of Bloomington Lake), and the signing of the Low Flow Allocation Agreement both demonstrated that regional cooperation, though difficult, was possible. The Metropolitan Washington Council of Governments (COG) had developed a regionally acceptable method of forecasting population growth with the support of all the local jurisdictions. These forecasts were to provide a credible basis for forecasting water requirements. COG also was in the process of developing a regionally acceptable plan for implementing its Water Shortage Emergency Plan, to be used when it became necessary to implement the Low Flow Allocation Agreement.

The WMA had also moved to voluntarily reduce its water requirements. Both the WSSC and FCWA adopted progressive pricing policies to encourage water conservation and discourage excessive peak use of water. Building codes in the Washington area suburbs had been revised to require the installation of water saving devices in new construction. Limits placed on wastewater treatment plants stressed flow reduction to meet requirements.

In the late spring of 1977, the Interstate Commission on the Potomac River Basin (ICPRB), then working with the COG on water quality management, first realized that altering operations of existing water supply facilities had not been adequately considered in previous regional water supply planning efforts. In particular, ICPRB performed an analysis which completely abandoned the concept of "safe yield" operation of the Patuxent and Occoquan Reservoirs, concentrating instead on the maximum yield which could be derived if those reservoirs were operated in concert with the free-flowing Potomac.

Safe yield of a reservoir is generally defined as the constant rate of withdrawal which will just empty the reservoir given a repeat of the worst drought in the historical record. During the drawdown, withdrawals exceed inflows, and the minimum storage (0) occurs just as inflows begin to exceed withdrawals.

The analysis continued and total water requirements in the year 2000 were projected at 750 mgd. The 90 day long, 50 year recurrence interval low flow in the Potomac (90-Q-50) was 580 mgd. This 90 day duration flow produced the worst deficit. The total deficit over the 90 day period would be:

$$
\begin{array}{rl}
 & 750 \text{ mgd} \times 90 \text{ days} = 67.5 \text{ billion gallons} \\
- & \underline{580 \text{ mgd} \times 90 \text{ days} = 52.5 \text{ billion gallons}} \\
 & \text{Deficit} = 15 \text{ billion gallons}
\end{array}
$$

But, the storage in the Occoquan and Patuxent reservoirs alone totaled almost 20 billion gallons. Conclusion: the WMA was not short of water if it could only efficiently use the already available local storage.

This is a classic illustration of a principle of operations research - the fewer constraints on the solution, the better its performance. Safe yield operation of the local reservoirs was a tremendously restrictive constraint. It had been assumed in all previous studies.

Systems analysis need not always employ the most sophisticated techniques to be effective; the simplicity of the above analysis was a decided advantage. With the help of the COG the idea received wide publicity, and had a rapid impact on local decision makers. Large, two way transmission lines (raw water interconnections) were immediately proposed to implement the idea, providing the ability to move reservoir water to the Potomac treatment plants as needed and Potomac water to the reservoirs, as available. The Federal, Interstate, State, Regional Advisory Committee (FISRCA) to the Corps WMAWSS urged the Corps to investigate the potential of such interconnections. (Figures 6,7)

The Search for Flexibility

The Corps moved with dispatch. It funded two interconnection studies, the first dealing with cost, sizing, and operation of raw water interconnections. The second was to investigate the potential for improving yield by improving the existing distribution systems and perhaps expanding the treatment plants for the Potomac and the local reservoirs. These were called finished water interconnections.

The concept behind the finished water interconnection study was as follows: When Potomac water was available, the use of the reservoir treatment plants would be reduced to well below their "safe yield"; the water thus saved would then be available to support use of the reservoirs at well above the safe yield level when the Potomac flow was low. Modest treatment plant expansion might be required to meet peak demands when either the Potomac was low, or use of the reservoirs was being minimized, and new distribution lines would be constructed to allow such operations while maintaining adequate pressure.

The study involved distribution system modeling of all the major water systems in the Washington area. Model runs were made to determine the ability of the systems to maintain adequate pressure and acceptable velocities while allocating demands between reservoir and river sources. New lines were added to the models to try to improve system performance. Once the ability of the distribution systems to adapt to different demands was determined, a feasible operating rule which minimized use of the local reservoirs whenever possible was devised. This rule was then incorporated in a hydrologic simulation model which tracked reservoir levels over the drought of record using demands projected for year 2030.

The conclusions of the finished water interconnections study were unexpected. No amount of construction of new distribution lines could increase the ability to improve yield by altering system operation. To the contrary, the EXISTING distribution systems, with proposed improvements required for NORMAL, non-drought operations, could be operated so as to ensure the availability of water to support the peak capacity of the reservoir treatment plants whenever the Potomac was low. In fact, simulation of operations using 2030 demands failed to lower the reservoirs below 40% of capacity.

In retrospect, the reasons for the flexibility of the system are obvious. First, the major parts of the system are designed to handle peak demands (160% of the Washington area average) which occur quite infrequently. Smaller system components are designed to accommodate fire flows, proportionately even larger. Nearly all the time this excess capacity is available to accommodate flexible operating rules designed to maximize yield.

Minimum flows in the Potomac generally occur in the fall and do not coincide with peak demands, which occur in July and August. Peaking problems are minimized when full capacity operation of the reservoir treatment plants is needed.

The reason for the availability of water in a local reservoir to support withdrawals over and above the safe yield, given a flexible operating rule, is also simple. The critical period for safe yield analysis on the local reservoirs is approximately nine months. The critical period for low flows in the Potomac is much shorter, about four months; it is a much larger river than those that feed the local reservoirs, and the demands are a much smaller percentage of the average flow. Therefore the rule amounts to taking water from the reservoirs at a higher rate, but for a shorter time. The volume of water taken is still the same.

The Corps called the new operating rules "reregulation"; and the WSSC and FCWA immediately indicated that they would implement such procedures. The rules increased the yield of the Patuxent for water supply from 35 mgd to 65 mgd (the capacity of the treatment plant). The Occoquan yield went from 55 mgd to 112 mgd. The total increase is nearly 90 mgd, or 100%. Pumping costs are lower for the FCWA, since its Potomac intake is at a higher elevation than the Occoquan. There is a small increase in operating costs for the WSSC, where pumping costs from the Patuxent are somewhat less than from the Potomac. The increase in yield is nearly cost-free.

Analyzing the Risk

Risk analysis, the technique which makes defining the start of a drought and quantifying the risk of continued drought possible, was first applied locally in response to the Occoquan drought of 1977. As the reservoir dropped to record low levels at the end of August, and concern over the water supply for 650,000 people grew more and more serious, ICPRB contacted the Systems Group of the U.S. Geological Survey for help in quantifying the danger. A simulation starting with the reservoir at its then current contents, assuming current demands and a repeat of the drought of record left the reservoir completely dry for an extended period. (Figure 8)

While this did indicate a potential water supply problem, it provided little indication as to the actual probability that a problem would occur. In an attempt to estimate that probability, a similar simulation was run for every year in the hydrologic record. Four of 26 years emptied the reservoir! The risk of disaster was real indeed.

Worse, 4 of 26 was certainly an underestimate of the real probability. Most of the twenty-six years in the record had normal or above normal streamflow during the summer; streamflow during the summer of 1977 had been quite low. The ground was extremely dry, and could be expected to soak up substantial rain without producing runoff. Certainly the streamflow following normal summers was not representative of what might happen in the fall of 1977. In order to make the risk estimates produced by the multiple simulations valid, a set of "equally likely", rather than historical, streamflows had to be used.

Two methods were available for producing equally likely streamflow traces. The first used statistical analysis to determine the serial correlation in monthly streamflows. With that information, the techniques of synthetic hydrology were adapted to produce equally likely synthetic traces of streamflow conditioned on the low flow of previous months. The technique is simple and inexpensive, and requires only historical streamflow data to implement.

Alternatively, the NWSRFS Extended Streamflow Prediction technique can be used. Extended Streamflow Prediction employs a rainfall-runoff model, calibrated by adjusting the model parameters so that historical daily rainfall and other meteorological inputs produce streamflow outputs which match historical streamflows. The model is then brought to "current conditions" by using the meteorological data of the past few months as input. Equally likely traces are generated by running historical meteorological data for every year in the record, starting on the date of the forecast, through the model. The key assumption here is that, unlike streamflow which depends on the dryness of the ground, a repeat of any year's weather is in fact equally likely. The difficulty of producing accurate long range weather forecasts bears out this assumption. (Figure 9)

In the East, the value of Extended Streamflow Prediction is most apparent in the late spring and early summer. Evapotranspiration during the summer substantially exceeds average rainfall. Therefore, ground water, and thus base flow, steadily and predictably decreases through the season. Differences in the condition of the ground at the beginning of the summer can change the probability of extreme low flow at the end of the summer by as much as tenfold. If the ground is wet at the beginning of the summer, a water supply drought is extremely unlikely. Conversely, dry conditions at the beginning of the summer indicate that the potential for serious drought exists, and that precautions should be taken. The technique can identify the start of a potential drought early enough that modest changes in operations can avoid the prospect of serious shortages later on. (Figure 10)

In 1977 the technique of risk analysis was immediately applied to determine the risks associated with continuing drought in the Occoquan sub-basin. Even in late October, the dry soil conditions increased risks of running the Occoquan Reservoir to unacceptably low levels by a factor of 2. Changing the rate of withdrawal assumed in the simulations determined the reduction necessary to reduce risk to acceptable levels. Only a modest decrease was enough to reduce risk at the end of October by a factor of 5, from 15% to 3%.

The credible, quantitative assessment of risk was most useful to the FCWA in the politically charged atmosphere surrounding the 1977 drought. To use Potomac water the FCWA's new treatment plant had to be located in a relatively undeveloped portion of the county, and that location was opposed by citizen groups concerned about development patterns. FCWA was accused of "manufacturing" the drought to justify its new treatment plant. Risk analysis allowed the utility to unassailably demonstrate the existence of the problem, to determine the required reduction in demand, and to prove that heroic measures such as closing businesses were not required to save additional water.

Operating Rules

In late 1977, the Department of Geography and Environmental Engineering, of The Johns Hopkins University in cooperation with ICPRB, received grants from the Maryland Department of Natural Resources, the Virginia State Water Control Board, and the Maryland Water Resources Research Center (through the U.S. Office of Water Research and Technology) to investigate future operating rules for Bloomington Lake which would increase its yield for water supply. The first work involved using linear programming (an optimization technique) to establish upper bounds on yield. Assuming perfect forecasting of demand and flow on a weekly average basis, and perfectly coordinated operation of upstream and downstream reservoirs, the study evaluated the tradeoffs between safe yield operation and upstream operations to meet downstream demands. (Figure 11)

The results were surprising. The upper bound was over a billion gallons per day, far in excess of projected demands. Moreover, that kind of yield could be achieved while still meeting upstream demands more than twice as large as expected. Unfortunately, while the results made sense to the analysts, they were extremely difficult to explain to the managers and operators.

The Potomac River Interactive Simulation Model (PRISM) was developed at Johns Hopkins to overcome the problem of explanation. As originally programmed, PRISM was a computer game, to be played by the utility operators. At its heart was a reasonably realistic weekly simulation model of reservoir and utility raw water operations. The computer provided the players with the information they would have in operating through a real drought, and asked them to make operational decisions. The effects of those decisions were then simulated and the results became information needed for the next round of decisions. Good decisions and good luck (the forecasts were not always right) were needed to keep water shortages from occurring and the amount of water wasted to a minimum.

The main cause of shortages and wasted water was the long travel time between the upstream reservoirs and the Washington area. Releases made a week in advance and predicated on a forecast of no rain were almost always too large; rain fell sometime during the week, somewhere in the 11,000 sq. mi. basin. The extra water flowed, unused, past the intakes to the estuary. But if releases were based on a forecast of rain, inevitably no rain materialized and large shortages developed. PRISM graphically illustrated the problems of operating under uncertainty and the benefits of cooperative operations in the local area, without the necessity of a real drought to drive the message home.

The Corps recognized the value of the simulation model inherent in PRISM and adapted it to its own use in the Corps Washington area study. In 1979, the Corps integrated the results of the PRISM modeling, the finished water interconnection study, their new demand forecasting work, and many other studies to produce the Metropolitan Washington Area Water Supply Study interim report. In a radical departure from previous recommendations, the Corps emphasized local solutions to the problem, specifically reregulation, a small local reservoir, and a raw water interconnection between one or both of the local reservoirs and the Potomac. The Corps noted that regional cooperation in operations and construction of facilities could greatly reduce cost, but noted the potential difficulties in reaching the necessary regional agreements.

The local utilities decided to try to work together. In conjunction with the states of Maryland and Virginia and the District of Columbia, they asked the ICPRB to form a section for Cooperative Water Supply Operations on the Potomac, to be called CO-OP. Founded in late 1979, CO-OP's task was to develop, integrate, and formalize the tools and techniques required for joint daily operations of the utilities during droughts. When the Corps formally presented its interim report to the states and utilities in December 1979, the utilities agreed to work toward the formation of a WMA Water Supply Task Force, patterned on the successful Bi-County task force, to try to formulate a regional solution and negotiate the required agreements. CO-OP became the technical staff to the new task force.

CO-OP completely revamped the PRISM model to develop daily operating rules. Daily operations were vital because of: a) the daily nature of utility operations, b) the latest information from the USGS indicated that travel times from the upstream reservoirs were not seven but four to five days, c) forecasts changed day to day, and d) water use varied substantially day to day. The first two were easily incorporated in the new daily model.

CO-OP entered into an agreement with the National Weather Service to attack the forecast problem. Working closely together, the two agencies calibrated the NWSRFS for the entire Potomac basin, and modified the computer programs to produce the output necessary for risk anaylsis.

CO-OP, the utilities, Johns Hopkins and the National Weather Service all contributed to the development of techniques for producing synthetic demand traces. The traces had to preserve not only the variability of daily demand, but also the cross-correlation of demand between the utilities and the tendency of demands to increase substantially during hot, dry, drought-like weather. The latest 10 years of demand and meteorological data were analyzed using econometric techniques to build the forecast model. The forecast model was then used as the core of a synthetic generator similar in form to a synthetic streamflow generator.

Some basic assumption about water supply emerged. There is substantial serial correlation in daily demand; by far the best predictor of tomorrow's demand is today's. Of all the weather parameters investigated, temperature is the most important. Day of the week also influences demand. For the inner city area served by the WAD, demands are significantly lower on the weekends. For the suburbs, day of the week exerts little influence on the average demand, but makes a substantial difference in variability. (Figure 12)

Using the Model

The Washington Metropolitan Area Water Supply Task Force, composed of one member each from the Montgomery and Prince George's County Councils, the Fairfax County Board of Supervisors, and the D.C. City Council, had its first meeting in February 1980. It approved a work plan to:

a) Define the demands to be met;

b) Determine the available supply;

c) Evaluate alternatives for additional supply; and

d) Choose the most desirable alternatives.

A citizens advisory committee, with members appointed by the executives of each of the jurisdictions represented on the Washington Metropolitan Area Water Supply Task Force was also formed. The technical advisory committee to the Washington Metropolitan Area Water Supply Task Force consisted of the chief operating officer of the WSSC, WAD, and FCWA. The General Manager of the WSSC chaired both the Water Supply Task Force and the technical advisory committee. The committees rapidly agreed to use the Corps Washington area study's demand projections, completing the first task.

CO-OP was asked to help determine the available supply, using the new CO-OP model. The first review of the model results made it clear that close cooperation between CO-OP and the utility staffs was necessary to refine the CO-OP model to accurately reflect all the constraints on daily operation. This took about six revisions of the model.

The effort resulted in increased credibility for the model. The Water Supply Task Force Technical Advisory Committee and CO-OP then began experimenting with different forms of operating rules. One of the best, called the difference rule, is also one of the simplest. To determine upstream releases under this rule, the natural flow in the Potomac at Washington on the date of the release is subtracted from the total demand (including required instream flow) from all sources expected on the day the release will arrive. This is equivalent to assuming (or forecasting) that the flow will remain unchanged over the time of travel. The difference (hence "difference rule") represents the total additional water which will be needed if the natural flow remains constant. The difference is adjusted by subtracting the amount desired to be taken from the local reservoirs and adding a safety factor.

The difference rule was used to evaluate the supply capabilities of existing and proposed projects. The rule was simple and practical. There was no operational experience with the NWSRFS (then being calibrated for the Potomac by CO-OP and the National Weather Service). Any improvement in operations made possible by improved short range (5-7 day) forecasts would provide a margin of safety in the estimates of reliability. But because of the large drainage area, low flows in the Potomac are relatively stable. Thus, the assumption that flow would not change over the travel time produced generally reasonable forecasts for use in simulation.

The simulations demonstrated that it was possible to meet the Washington area water requirements, including a 100 mgd flow-by, through the year 2000 - without the additional pipeline and small reservoir (cost $100 million) recently recommended by the Corps. But, a critical examination of the results by the technical advisory committee revealed an undesirable consequence of not upgrading the existing system.

Several of the droughts simulated drew the reservoirs down significantly during the late summer. Such drawdowns would call into question the ability of the utilities to meet their long term demands during those droughts, where the techniques of risk anaylsis applied. The reason for the drawdowns was not lack of water, but lack of local operational flexibility.

Reregulation was the source of existing local flexibility. When releases from the upstream reservoirs (made 5-7 days ahead) turned out to be inadequate, withdrawals from the local reservoirs could be increased to take up the slack. The increase was limited by the capacity of the treatment plants on the local reservoirs, about 180 mgd. Given the minimum withdrawals required from the reservoirs, about 30 mgd, the available flexibility was on the order of 150 mgd.

Unfortunately, 5 to 7 day flow forecasts are not that accurate. To ensure enough water downstream, the margin of safety in the upstream releases must be about 100 mgd. Most of this water (almost 70% of the water released from the upstream reservoirs) flowed by the intakes unused. Further, because the extra release is in the Potomac, the average use of the local reservoirs was undesirably low. The local reservoirs stayed full while the upstream reservoirs dropped precipitously.

Little Seneca: Big Flexibility

The availability of additional local flexibility, in the form of a small local reservoir, eliminated the operational problems. Operational simulations showed that the ability to correct for errors in streamflow forecasts as needed, day by day, using releases directly to the Potomac from a small new local reservoir would eliminate the need for a large margin of safety in the upstream release, reduce the unused portion of the releases from 70% to about 10%, and allow full utilization of the storage in the existing local reservoirs. The additional water thus made available was sufficient to meet water requirements through the year 2030, based on Corps projections. (Figure 13)

Little Seneca Reservoir in Montgomery County had been recommended by both the Bi-County study and the Washington area study interim report. The lake would also serve as a recreational asset, and spread regionally, the costs were quite modest. The Water Supply Task Force committees both agreed that Little Seneca should be a regional undertaking, and that an agreement specifying cost allocation for Little Seneca and the reimbursable water supply costs in Bloomington, as well as cooperative operation of all regional water supply facilities, be developed.

The Water Supply Task Force adopted this recommendation, "in principle" in January 1982, and charged the technical advisory committee with negotiating the necessary agreements. Both the WSSC and Montgomery County, in a major move away from factionalism, endorsed the concept of Little Seneca Reservoir as a regional facility.

Construction of Little Seneca still required a permit from the Corps, with an associated environmental assessment or impact statement. Both the U.S. Environmental Protection Agency and the U.S. Fish and Wildlife Service were in a position to influence the Corps' decision on the permit, and both initially objected to the project because of the associated impacts. The issue of required flow-by also needed resolution.

As part of its Low Flow Study, Maryland Department of Natural Resources in conjunction with the U.S. Fish and Wildlife Service and ICPRB, calibrated the Fish and Wildlife Service Instream Flow Group habitat simulation for the Potomac from Great Falls to Little Falls. The Instream Flow Group model attempts to quantify the relationship between flow and available fisheries habitat. Using the simulation, the biologists involved determined that the juvenile stage of the smallmouth bass was an appropriate indicator species, and that extreme low flows for periods as short as one to two days were critical. The insight thus gained was sufficient to guide the modification of the water supply operating rules developed previously.

With Little Seneca Lake operational, and using a sliding schedule for flow-by (higher in the early summer and lower in the fall) the frequency of occurrence of extreme low flows could be reduced to below "natural" levels for the stretch of river above Little Falls. The few years in which droughts last into the fall, and thus flows were below natural, were more than counterbalanced by the many years in which augmentation in the early summer kept flows above their natural low. (Figure 14)

The simulation runs used to develop the modified operating rules showed them to be entirely compatible with water supply operations. Water requirements were always met, and the relative risks of water shortage (from risk analysis) were not significantly increased. The results of this low flow study led to a resolution of the issues regarding Little Seneca and flow-by. An Instream Flow Committee was chartered by the Maryland Department of Natural Resources, and organized by ICPRB to advise on the operation of reservoirs to improve fisheries habitat and recreational opportunity. Because most of the capacity of the reservoirs is not needed for water supply except during infrequent extreme drought, this committee has the flexibility to produce substantial benefits on a continuing basis.

The issue of cost sharing remained, and once again the model provided a common basis for negotiation. CO-OP, as the keeper of the model, had no direct role in the negotiations, and thus remained "neutral". Each utility directed its own runs of the CO-OP model, modified to allocate the shortages which could occur under the operating rules which would be used if agreement was not reached. The shortages were allocated using each utility's own interpretation of the riparian doctrine of water rights, and the Low Flow Allocation Agreement. Several hundred simulation runs were made, using different droughts and assumptions, before the utilities were satisfied that an equitable allocation of cost had been devised.

Joint Operation

The implementation of the joint operating scheme is designed to minimize interference with normal utility operation. Joint scheduling of operations does not begin until drought conditions exist. Drought conditions are defined in two ways: a) flow in the Potomac below 200% of expected withdrawals, or b) the probability of meeting all water requirements and refilling all reservoirs by the following June below 98%. The probabilities are defined using the NWSRFS and risk analysis.

When drought conditions exist, releases from Bloomington are scheduled using the difference rule explained above. The CO-OP demand model is used to forecast demand. The desired withdrawals from the Patuxent and Occoquan are set at their safe yields, and, until Little Seneca is operational, a margin of safety of 100 mgd is used. With Little Seneca complete, that margin of safety will not be required. Construction on Little Seneca started in September 1982; completion is scheduled for 1986.

Downstream operations strive to maintain balanced storage in the Patuxent and Occoquan reservoirs. Each morning, target Potomac withdrawals are set for the WSSC and FCWA. Both utilities attempt to meet their remaining requirements from their local reservoirs. Mid-day reports are analyzed in the afternoon and modest corrections in withdrawals are made to further balance the systems.

A convincing demonstration that the procedures developed by CO-OP actually worked took the form of a drought exercise. The NWSRFS was used to produce a "quasi-historical drought" using artifically set antecedent soil moisture conditions and the actual meteorological data from a rainfall short year. (Figure 15)

Each utility manager and the District Engineer of the Baltimore District Corps of Engineers brought a small technical team to the drought exercise, much like a war game with each day compressed to about 20 minutes. Decisions regarding daily operations of the reservoirs and other raw water facilities were made on the basis of information which would be available in real time.

Because the drought was based on a historical meteorological trace, weather forecasts, with all their associated uncertainty, were available. Similar to the exercise done with the PRISM model earlier, the 1981 exercise established lines of communications, and tested operating procedures. The problems found were corrected as the exercise progressed. Not only did the exercise establish beyond doubt that coordinated operations were feasible and could provide adequate water, they also prepared all concerned for dealing with an actual drought. The second annual drought exercise (October 1982) was run with a modified format (one day equal one day) and used to test the reliability of the improved demand forecasting model.

Writing the contracts to implement the joint operations and cost sharing was a formidable task. The interstate nature of the agreements, the unique character of the government of the District of Columbia, and the Congressionally mandated responsibilities of the Corps of Engineers created an extraordinarily complex situation. However, and in large part due to their familiarity with the simulations and the drought exercise, the negotiators (the utility managers) were absolutely convinced of the feasibility and desirability of joint operations.

Eight separate but interlocking contracts were executed on July 22, 1982 (Table 4). They are a tribute to the skill of the lawyers involved and the good will of the participants. After almost 30 years, the problem of assuring an adequate supply of water for the WMA had been resolved.

The Solution: Innovative Engineering

Providing the Washington area with an adequate water supply was a complex engineering, social, economic, environmental, and institutional problem. Large scale structural solutions had been proposed and found wanting. A fresh approach was required. It was provided by advances in water resources engineering analysis over the last 20 years.

The techniques of water resources engineering systems analysis--linear programming, synthetic hydrology, statistical analysis, hydrologic modeling, and computer simulation--were adapted to produce a predominantly non-structural engineering solution to the problem. Many of the techniques were used together for the first time, and others were subject to major modification specifically to address this problem.

An "insoluble" problem of almost 30 years standing was resolved. The "impossible" task of achieving regional cooperation was accomplished. Between $200 million and $1 billion were saved compared to previously evaluated alternatives. Moreover, the solution was not achieved at great environmental expense. In fact, the environmental benefits of increased minimum instream flow and the recreational opportunities provided by Little Seneca Lake may outweigh any environmental impacts.

Significantly, the integration of engineering analysis and the decision making process, made possible by computer simulation, played an essential role in implementing the solution. Without the convenient and credible framework for decision making provided by the model, negotiations between the parties would have been far more difficult.

Perhaps the most important aspect of the solution to the WMA water supply problem is the example it sets. Here is proof that non-structural engineering alternatives, including better management of existing facilities, can solve some of the most difficult socio-political problems and achieve substantial cost savings. Because the replacement value of our existing facilities is substantially greater than the present value of expenditures on new facilities at current rates, the potential benefits of widespread application of the types of engineering analysis used in the Washington area are enormous.

Credits

Washington Suburban Sanitary Commission;
Fairfax County Water Authority;
District of Columbia Department
of Environmental Services;
Maryland Department of Natural Resources;
Virginia State Water Control Board;
U.S. Army Corps of Engineers
Washington Aqueduct Division;
U.S. Army Corps of Engineers Baltimore District;
National Weather Service;
U.S. Geological Survey;
Washington Metropolitan Area Water
Supply Task Force;
The Johns Hopkins University, Department of
Geography and Environmental Engineering;
Interstate Commission on the Potomac River Basin;
Interstate Commission on the Potomac River Basin
Cooperative Water Supply Operations on the Potomac (CO-OP);
Metropolitan Washington Council of Governments.

TABLE 1

Capacities of Washington Metropolitan Area Local Water Supply Facilities

Reservoirs		
Patuxent	10BG	65 mgd treatment
Occoquan	11BG	112 mgd treatment
Little Seneca (under construction)	4BG	
Intakes		
FCWA Potomac		200 mgd
WSSC Potomac		400 mgd
WAD Great Falls		200 mgd
WAD Little Falls		400 mgd

TABLE 2

Safe Yields of Washington Metropolitan Supplies

Potomac River (including Savage Reservoir)	388 mgd
Bloomington Lake	135 mgd
Patuxent Reservoirs (net for water supply)	35 mgd
Occoquan Reservoir	55 mgd
	613 mgd
Less Minimum Flowby	-100
Total of Independently Operated Supplies	513 mgd

TABLE 3

Capital Costs of Alternatives in 1977
Corps of Engineers North East Water Supply Report 1

Alternative		Jan. 1976 Cost[2] (Millions)	Current[3] (Millions)
1A	Estuary Treatment	$599	$964
2A	Estuary Treatment AWT[4]	310	500
3	Estuary Treatment AWT[4], Wells	283	456
4B	Sixes Bridge, Verona, Catoctin Reservoirs	123	198
5A	Little Monocacy, Sixes Bridge, Verona, Catoctin Reservoirs	176	283

1 Bloomington assumed in all alternatives, Bloomington costs not included.

2 Engineering News Record Construction Cost Index = 2300 per News Final Report.

3 Engineering News Record Construction Cost Index = 3700.

4 Advanced waste treatment located upstream of intakes to recycle wastewater.

TABLE 4

List of Water Supply Agreement Signed July 22, 1982

1. Water Supply Coordination Agreement

   Binds all parties to joint operations during drought, assigns responsibility for scheduling release withdrawals to ICPRB CO-OP.

2. Contract for Future Water Supply Storage in the Bloomington Reservoir

3. Novation Agreement for Initial Water Supply - Bloomington Reservoir

   Reassigns ownership from Maryland Potomac Water Authority to WSSC, FCWA, District of Columbia.

4. Novation Agreement Regarding District of Columbia's Payment to the Potomac Water Authority

   Cancels previous contract.

5. Bloomington Lake Payment Agreement

   Provides for legal remedy in case of non-payment.

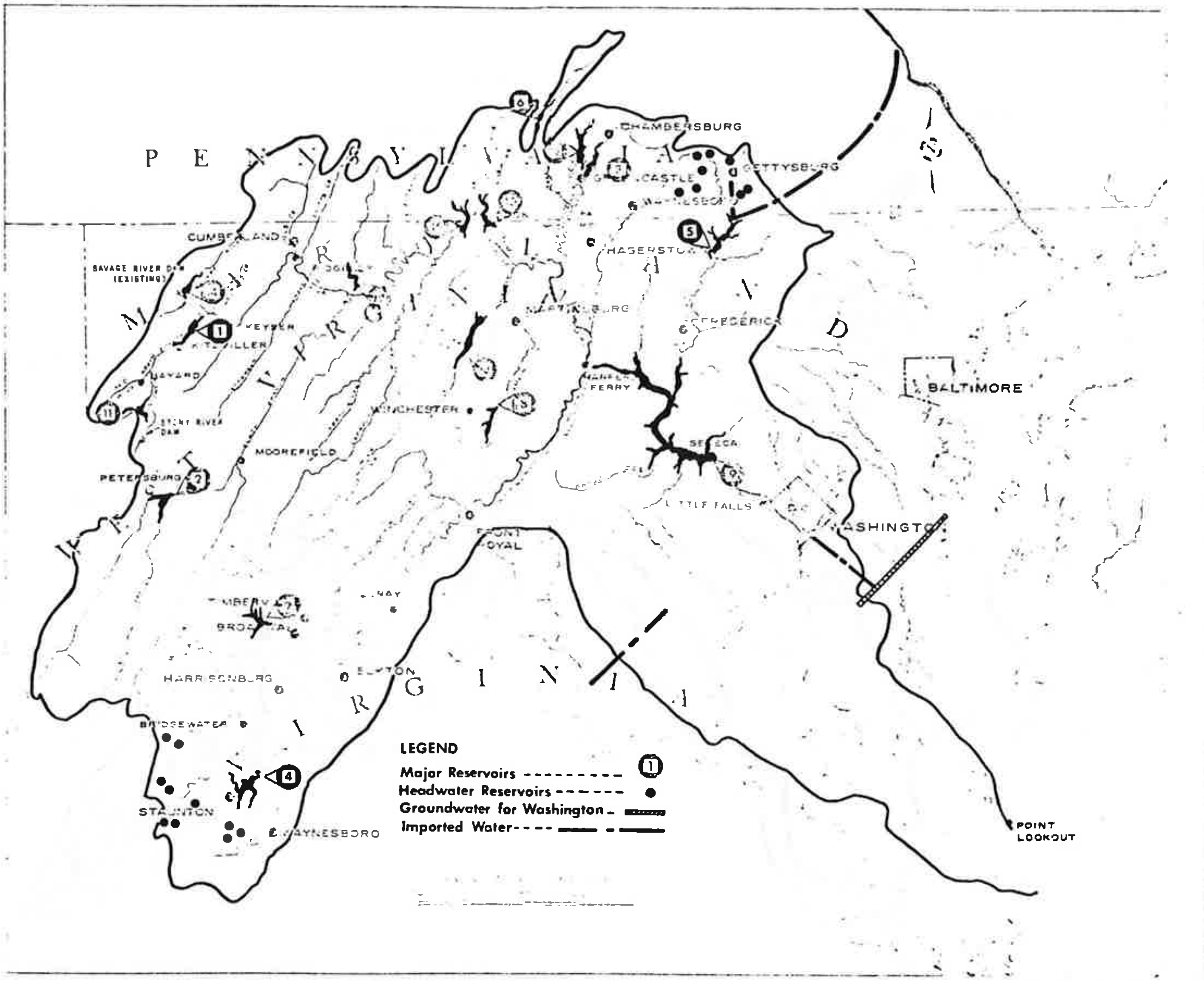
6. Little Seneca Lake Cost-Sharing Agreement

7. Modification No. 1 Potomac River Low Flow Allocation Agreement

   Removes "1988 Freeze" provision.

8. Savage Reservoir Maintenance and Operation Cost-Sharing Agreement

   Provides for WSSC, FCWA, WAD, Allegany Co., Maryland cost sharing.



SIXES BRIDGE AND VERONA PROJECTS AND ALTERNATIVE WATER SUPPLY CONCEPTS—PLATE II

The 16 reservoirs recommended in the 1963 COE Baltimore District Engineer's Report

LIST OF MAJOR RESERVOIRS:

1. *BLOOMINGTON*
2. *ROYAL GLEN*
3. *CHAMBERSBURG*
4. *VERONA (STAUNTON)*
5. *SIXES BRIDGE*
6. *WEST BRANCH*
7. *BROCKS GAP*
8. *WINCHESTER*
9. *SENECA*
10. *LICKING CREEK*
11. *MOUNT STORM*
12. *TOWN CREEK*
13. *NORTH MOUNTAIN*
14. *SAVAGE II*
15. *BACK CREEK*
16. *TONOLOWAY CREEK*

DRAINAGE BASINS SERVING THE METROPOLITAN WASHINGTON AREA

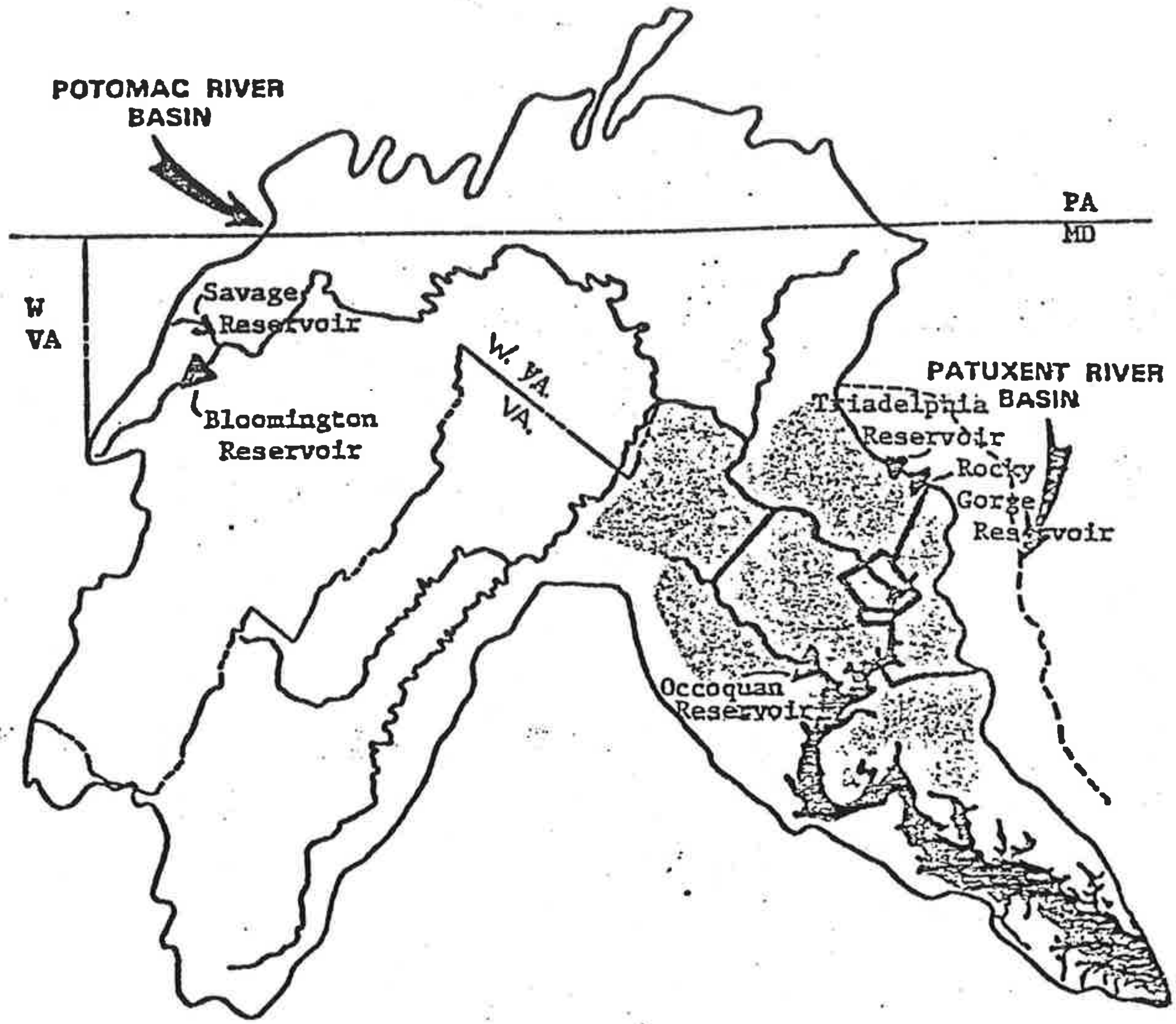


FIGURE 1.

MAJOR WATER SUPPLY SYSTEMS - METROPOLITAN WASHINGTON AREA

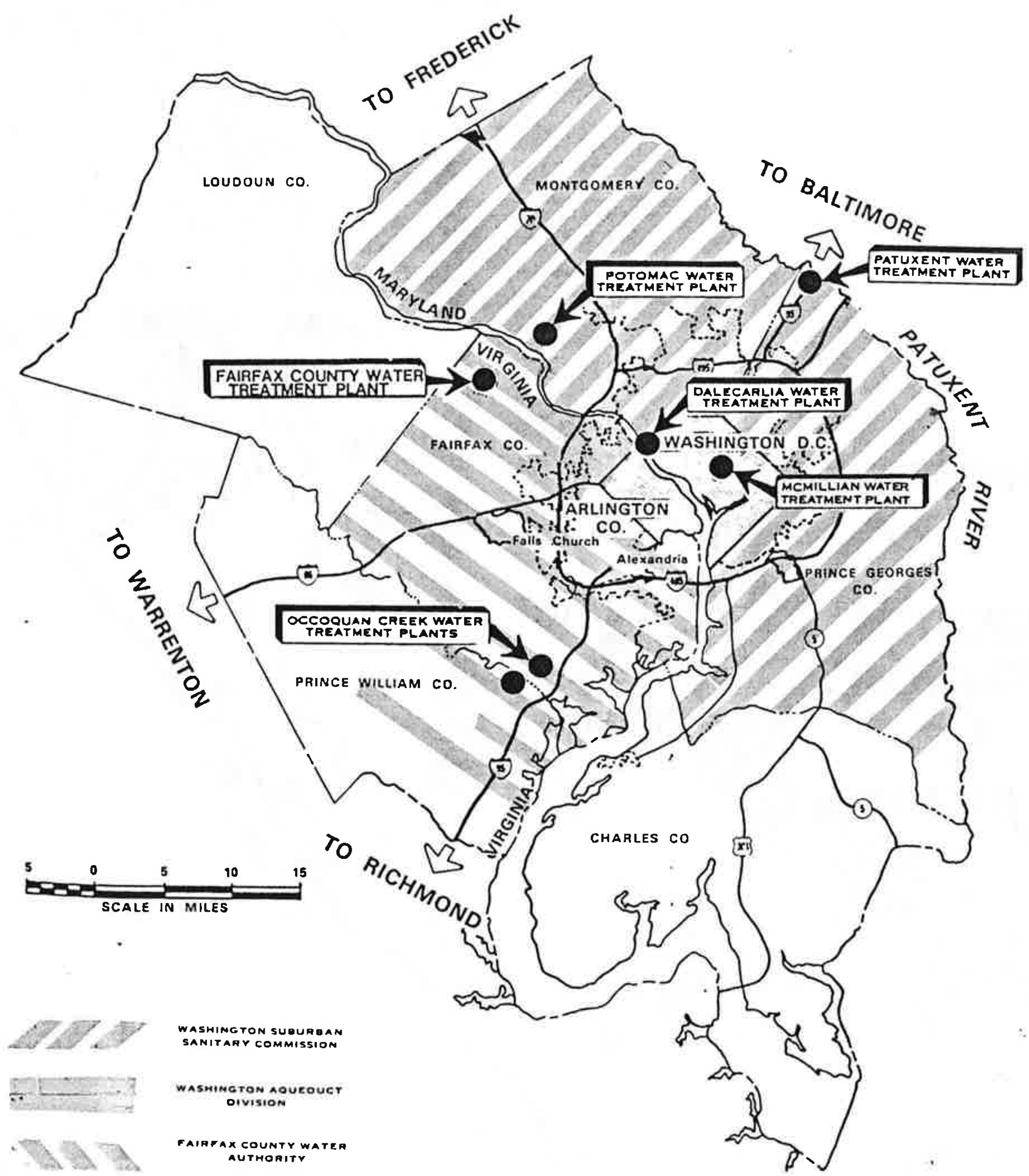


FIGURE 2

POTOMAC RIVER BASIN

SUB DRAINAGE AREA 02·14·10

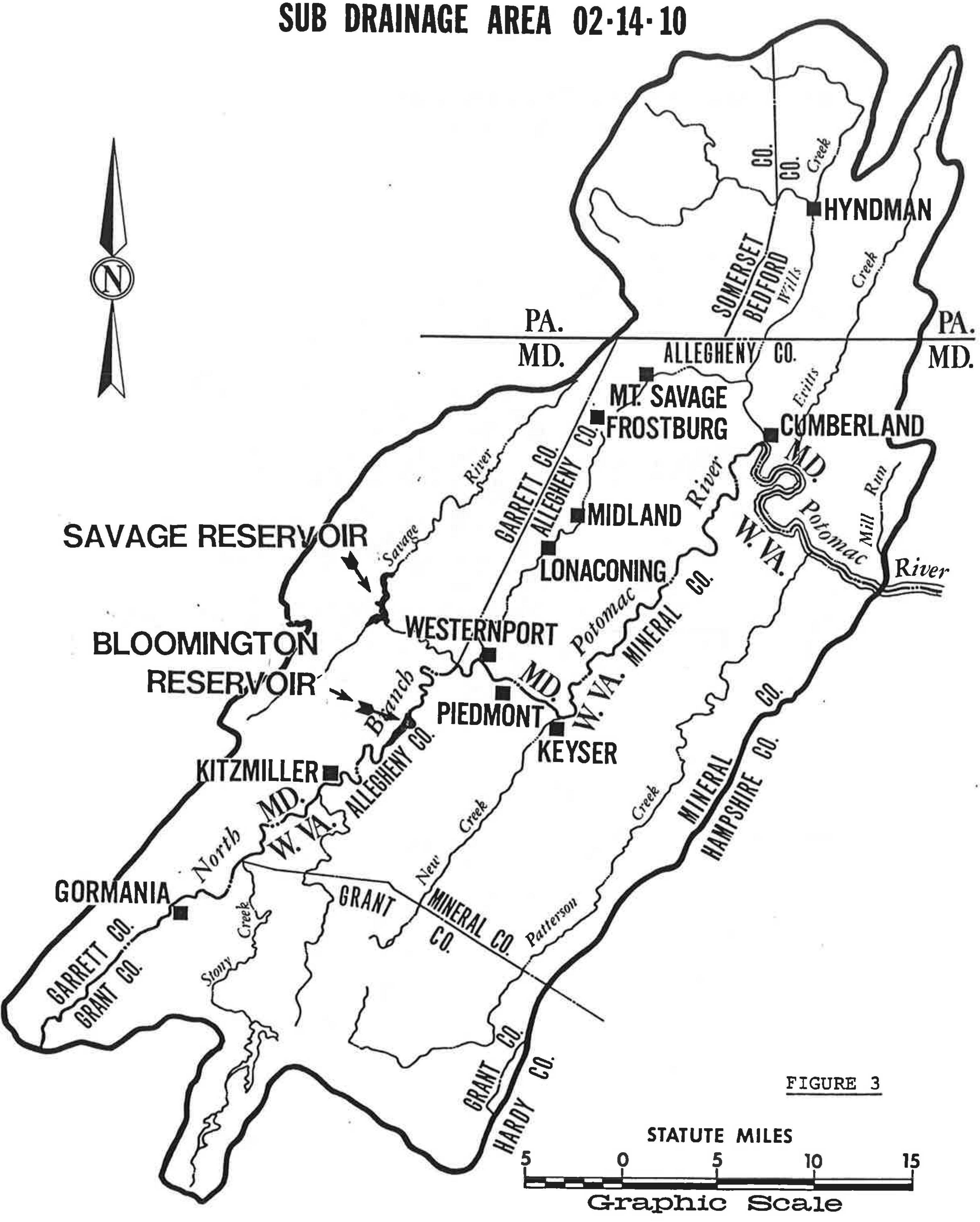


FIGURE 3

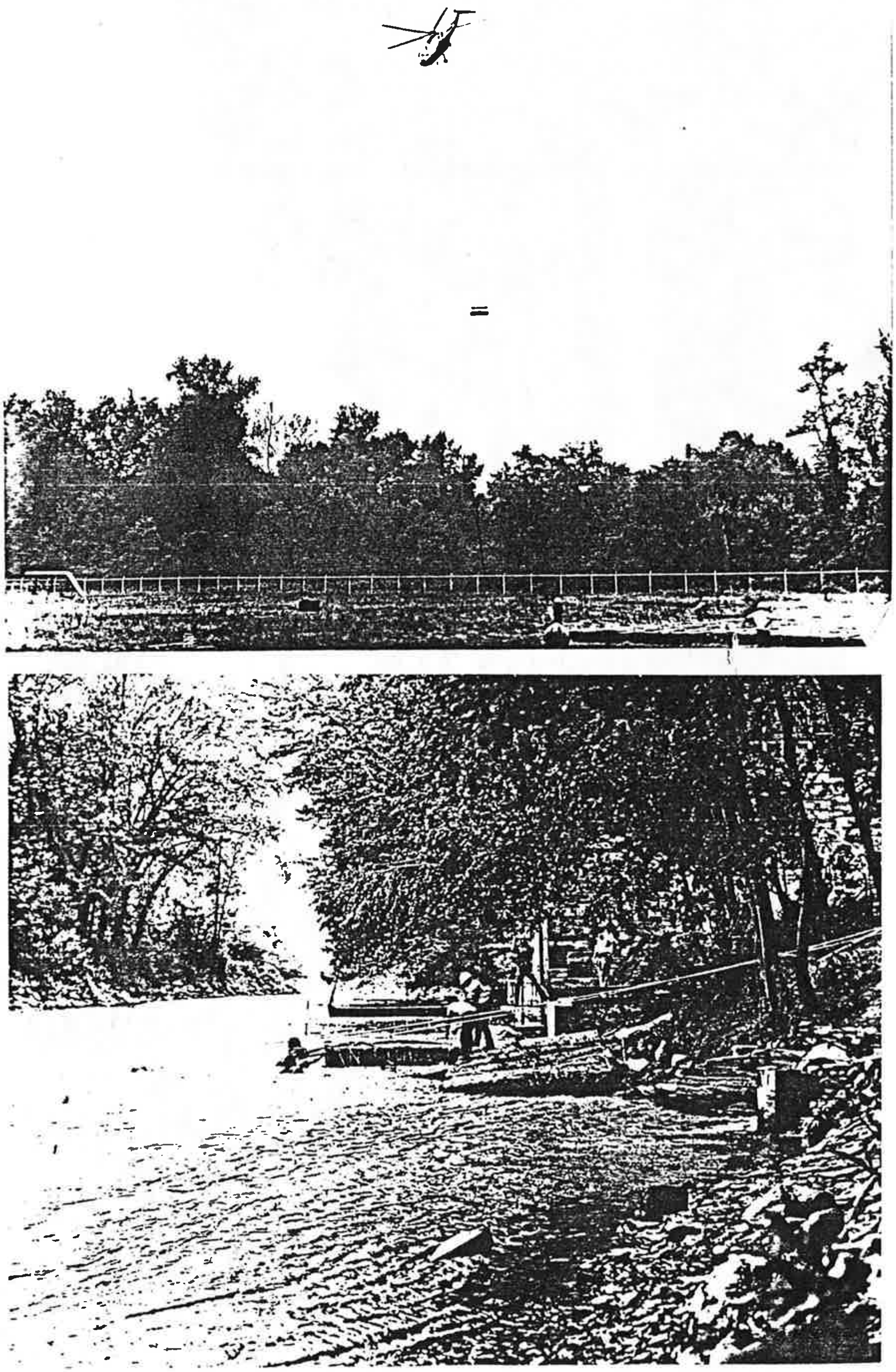


FIGURE 4

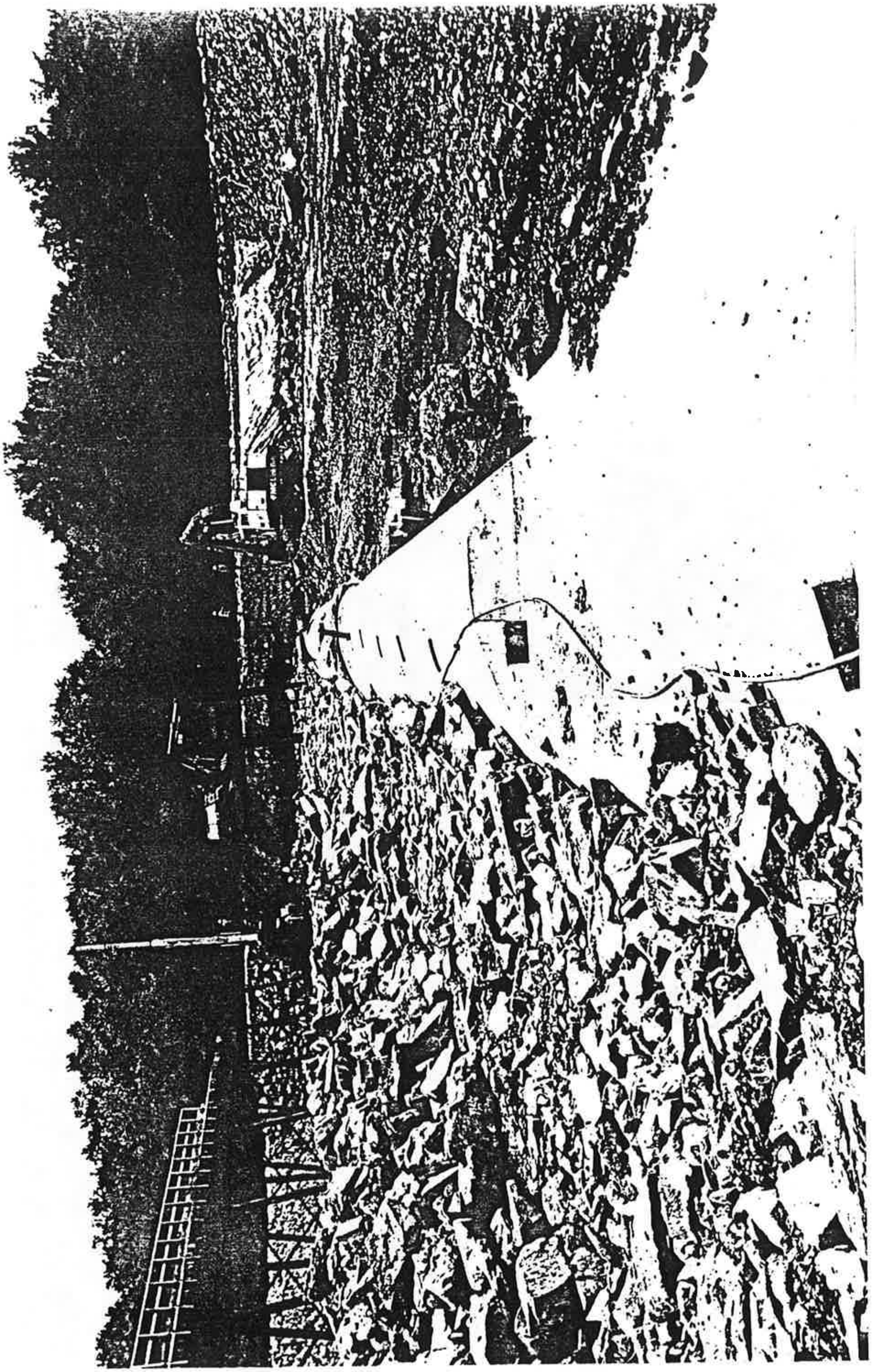


FIGURE 5

SCHEMATIC REPRESENTATION OF PROPOSED RAW WATER INTERCONNECTION ROUTES IN THE MWA

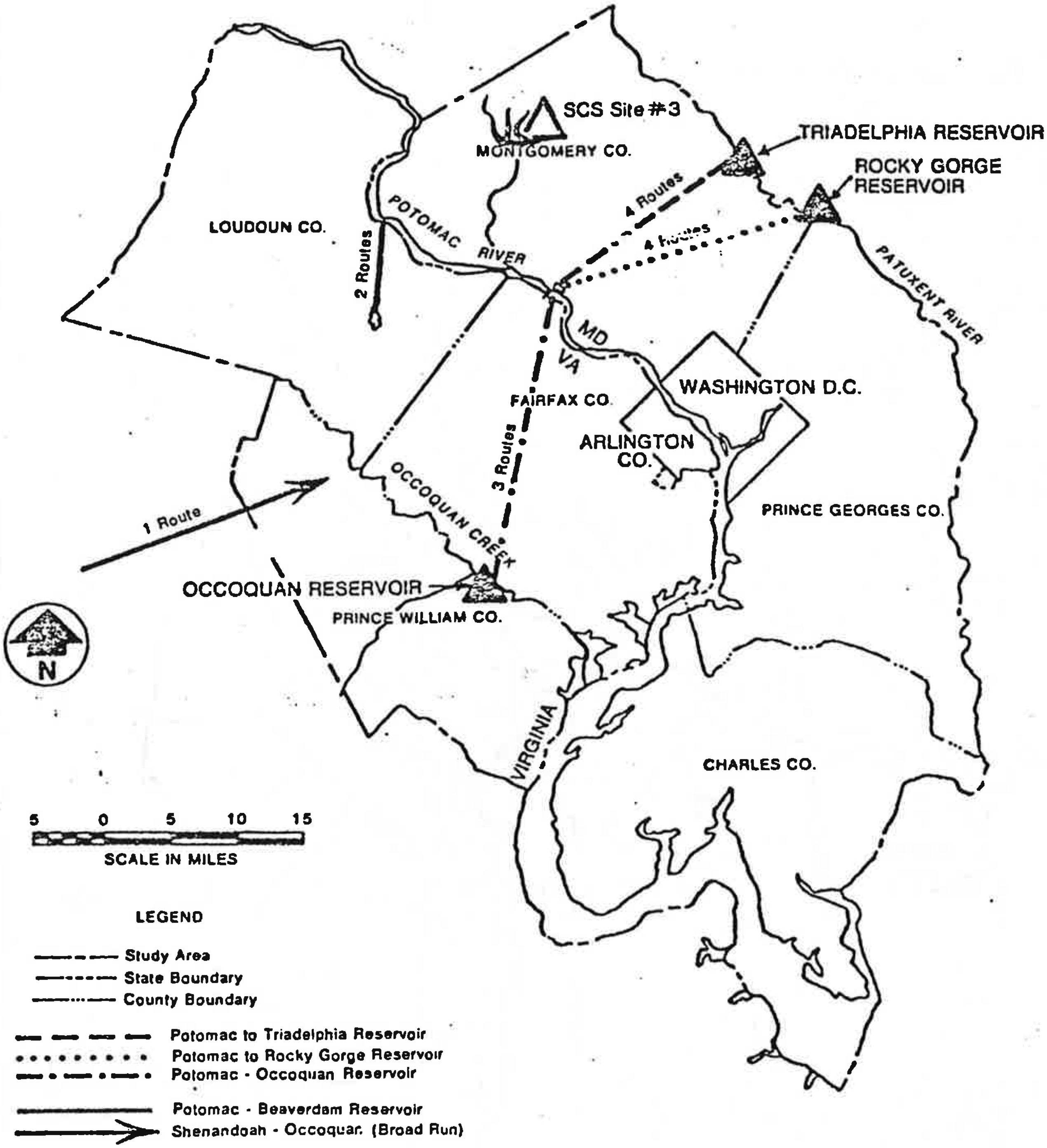


FIGURE 6

GEOGRAPHIC LOCATIONS OF THE
PROPOSED BLACK & VEATCH FINISHED WATER INTERCONNECTION ROUTES

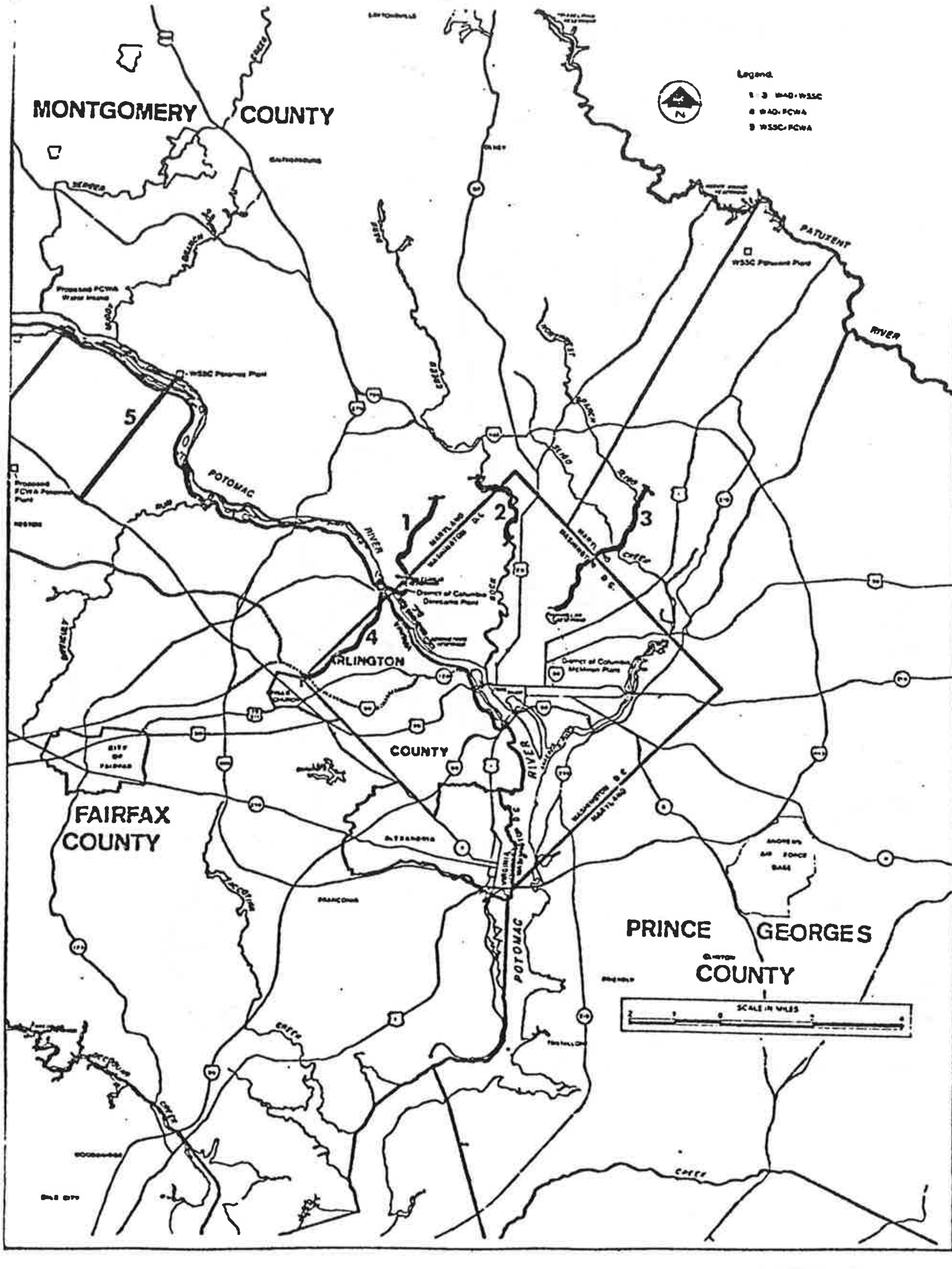
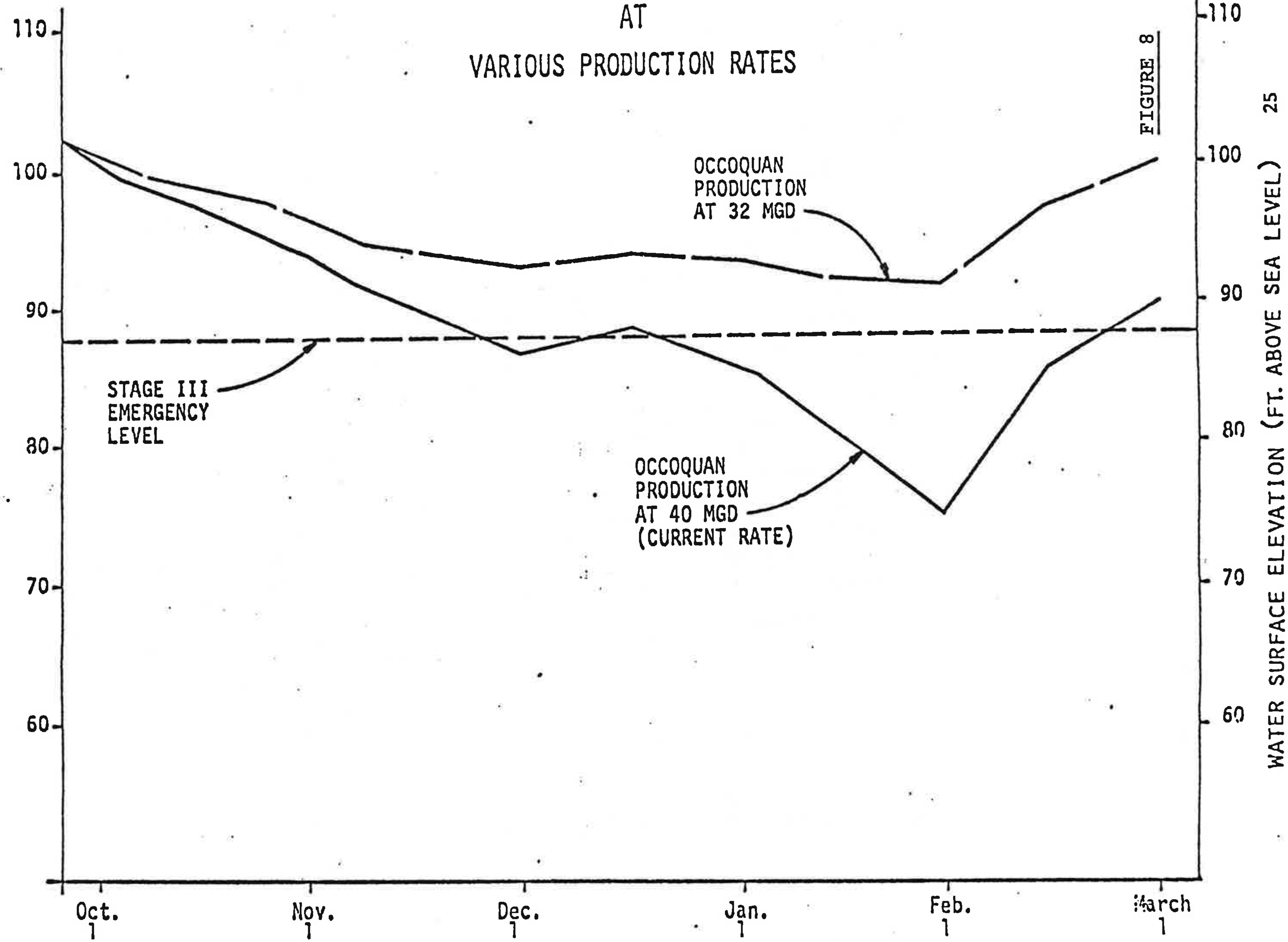


FIGURE 7

FIGURE 8

RESERVOIR LEVELS AT VARIOUS PRODUCTION RATES



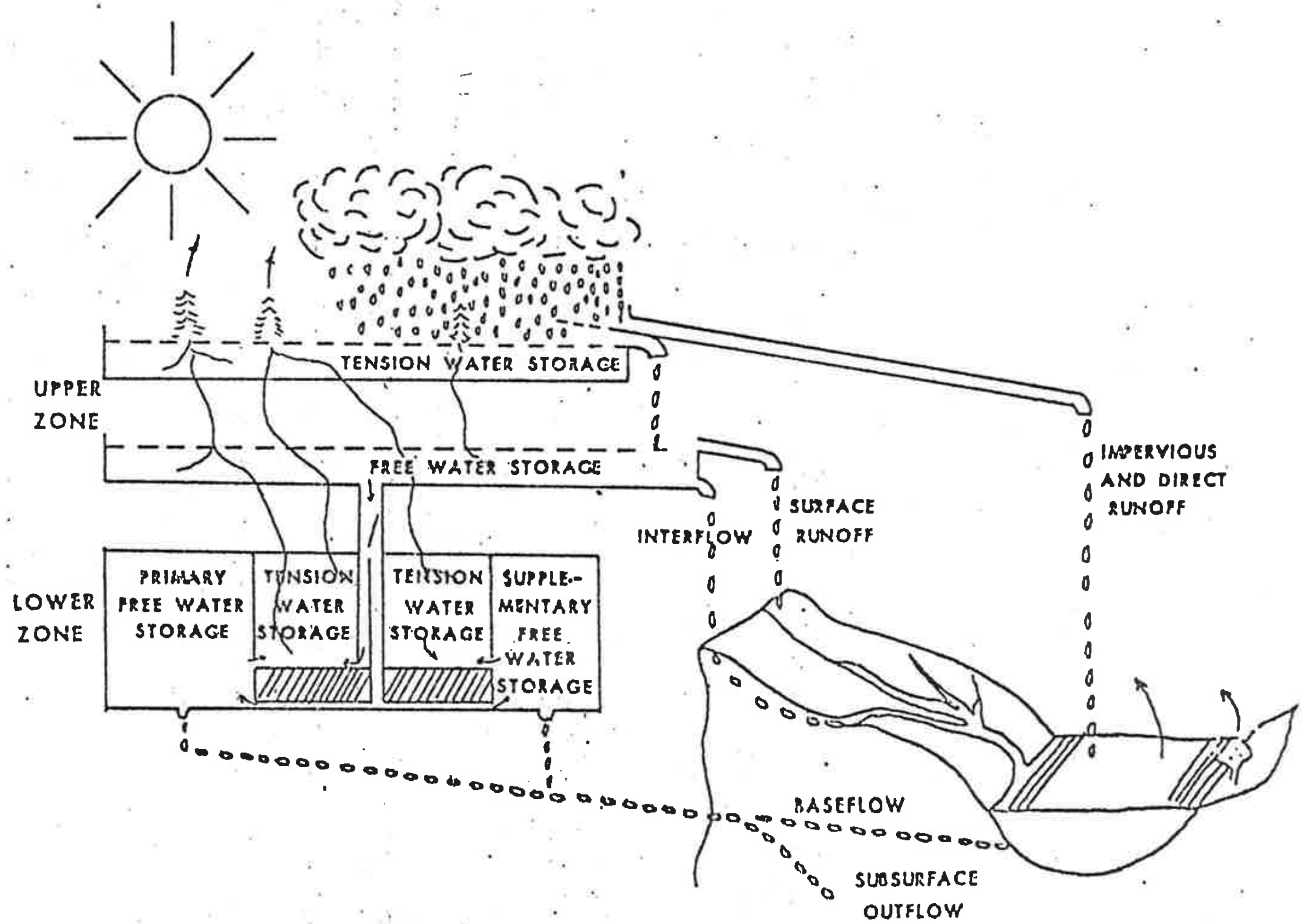
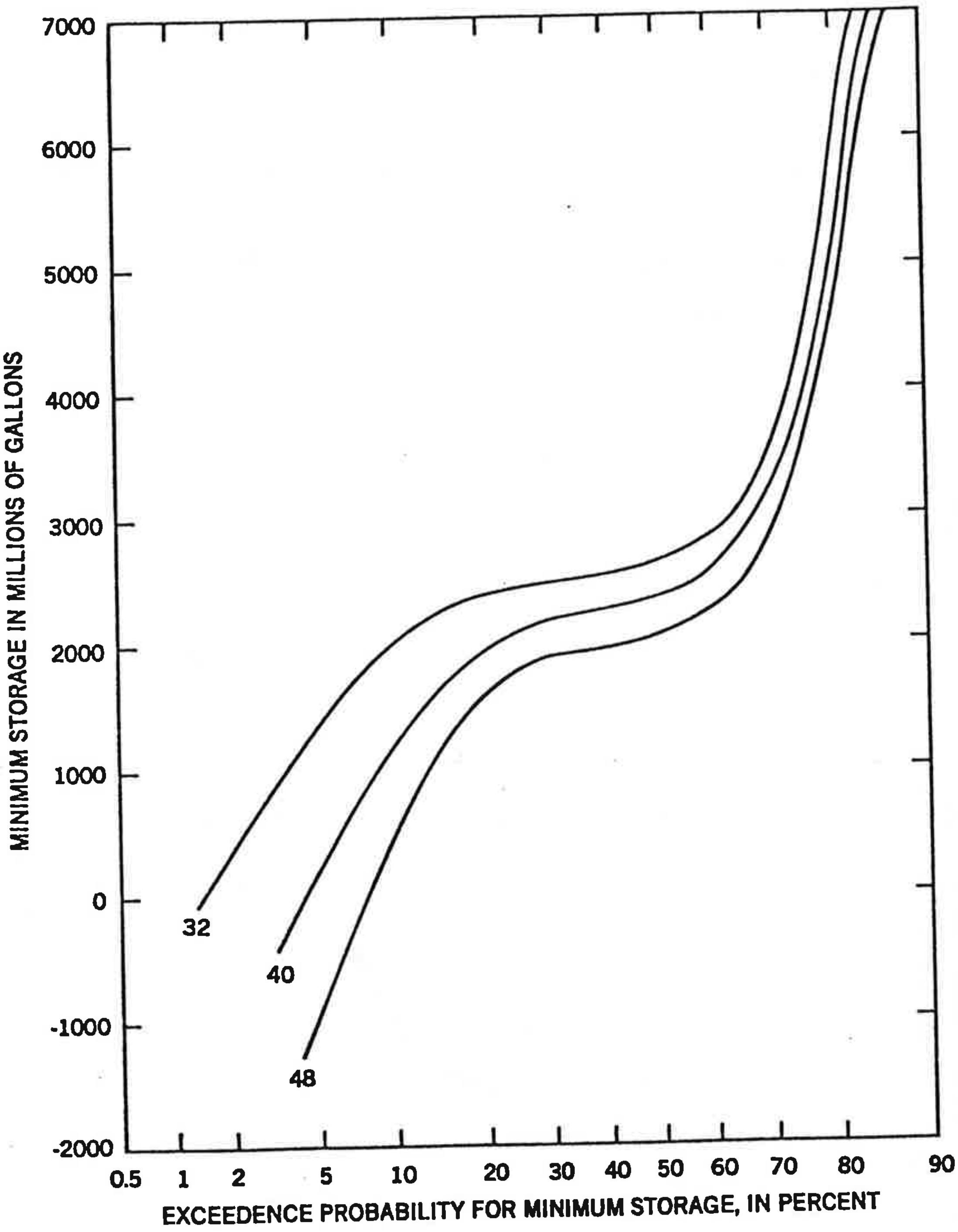


Illustration of the Sacramento Soil Moisture
Accounting Model of the National Weather Service River Forecast System

FIGURE 9



Cumulative distribution functions for S_{min} at 32, 40, and 48 Mgal/d production rates, from Position Analysis based on 22 years with dry-late summer periods.

FIGURE 10

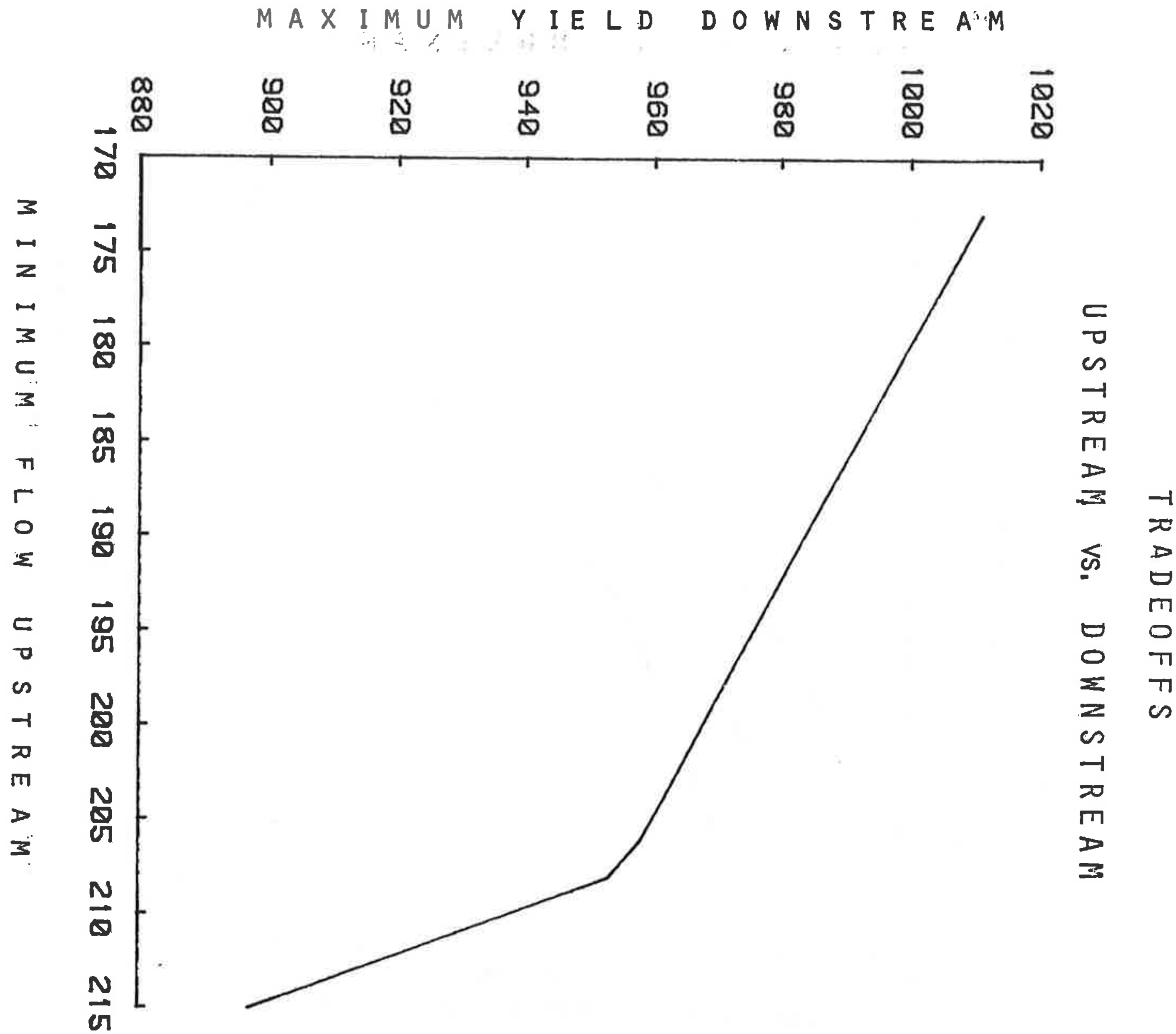

TRADEOFFS
UPSTREAM VS. DOWNSTREAM
MAXIMUM YIELD DOWNSTREAM
MINIMUM FLOW UPSTREAM
880
900
920
940
960
980
1000
1020
170
175
180
185
190
195
200
205
210
215

FIGURE. 11

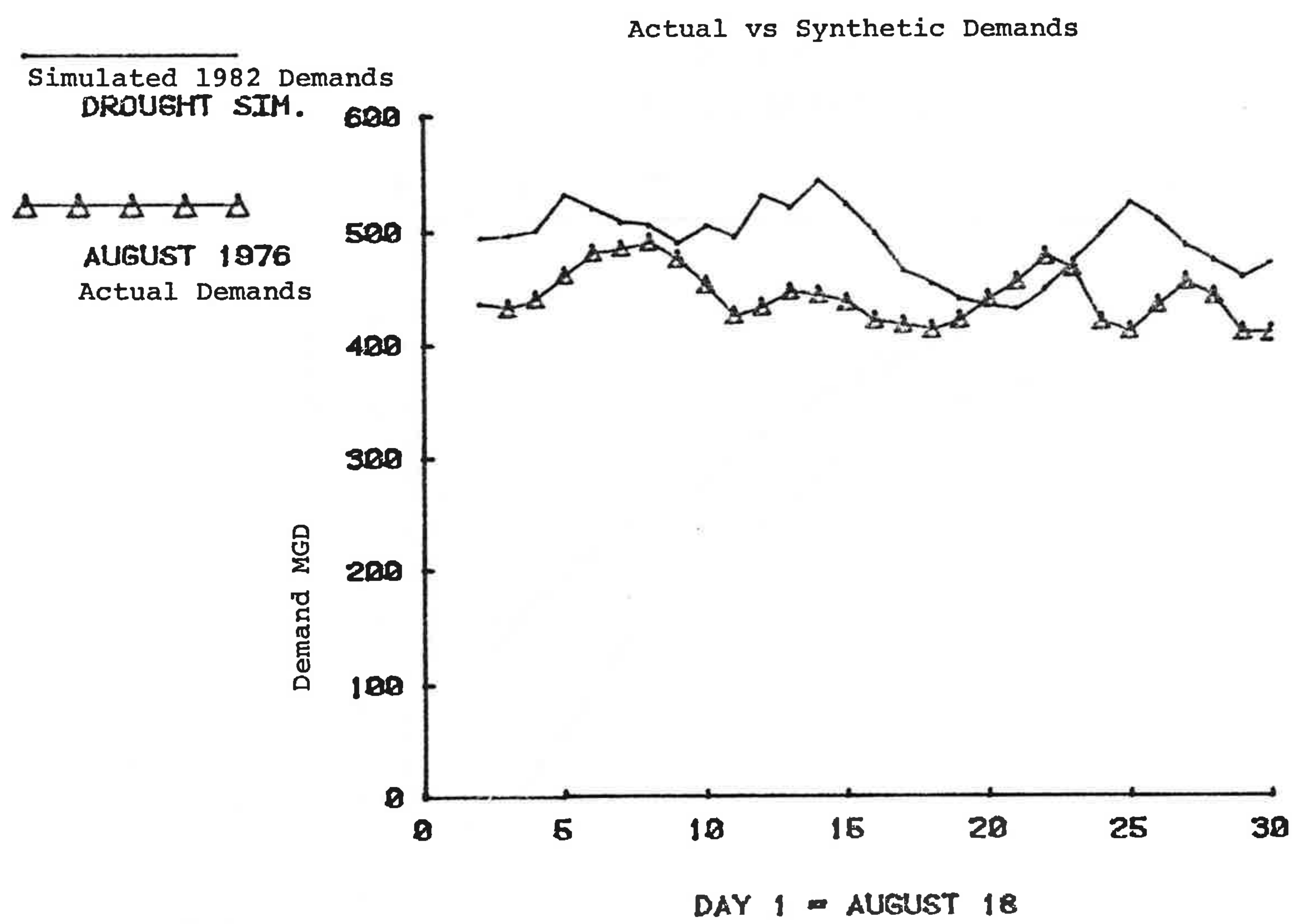

Actual vs Synthetic Demands
Simulated 1982 Demands
DROUGHT SIM.
AUGUST 1976
Actual Demands
Demand MGD
600
500
400
300
200
100
0
0
5
10
15
20
25
30
DAY 1 = AUGUST 18

FIGURE 12

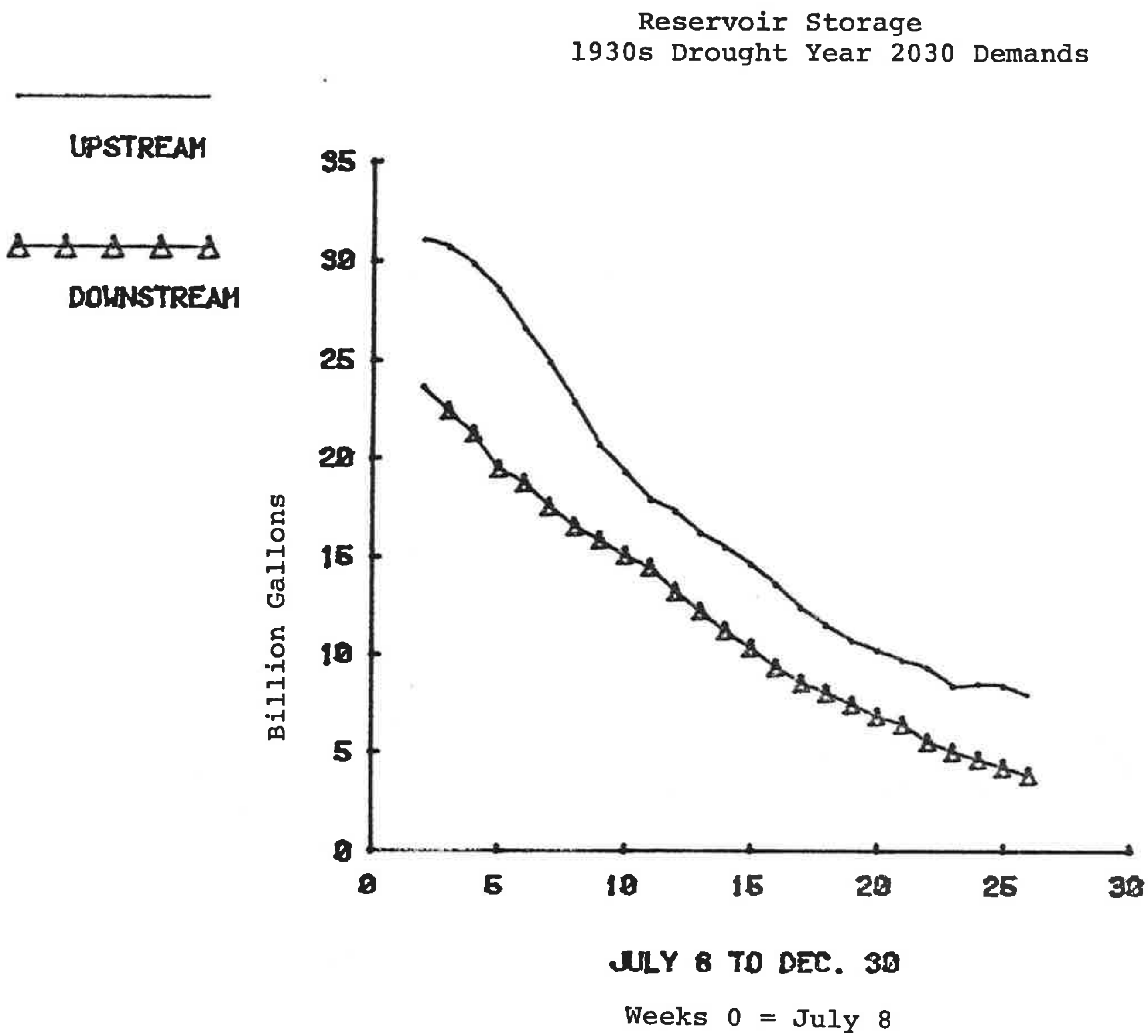

Reservoir Storage
1930s Drought Year 2030 Demands
UPSTREAM
DOWNSTREAM
Billion Gallons
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
JULY 8 TO DEC. 30
Weeks 0 = July 8

FIGURE 13

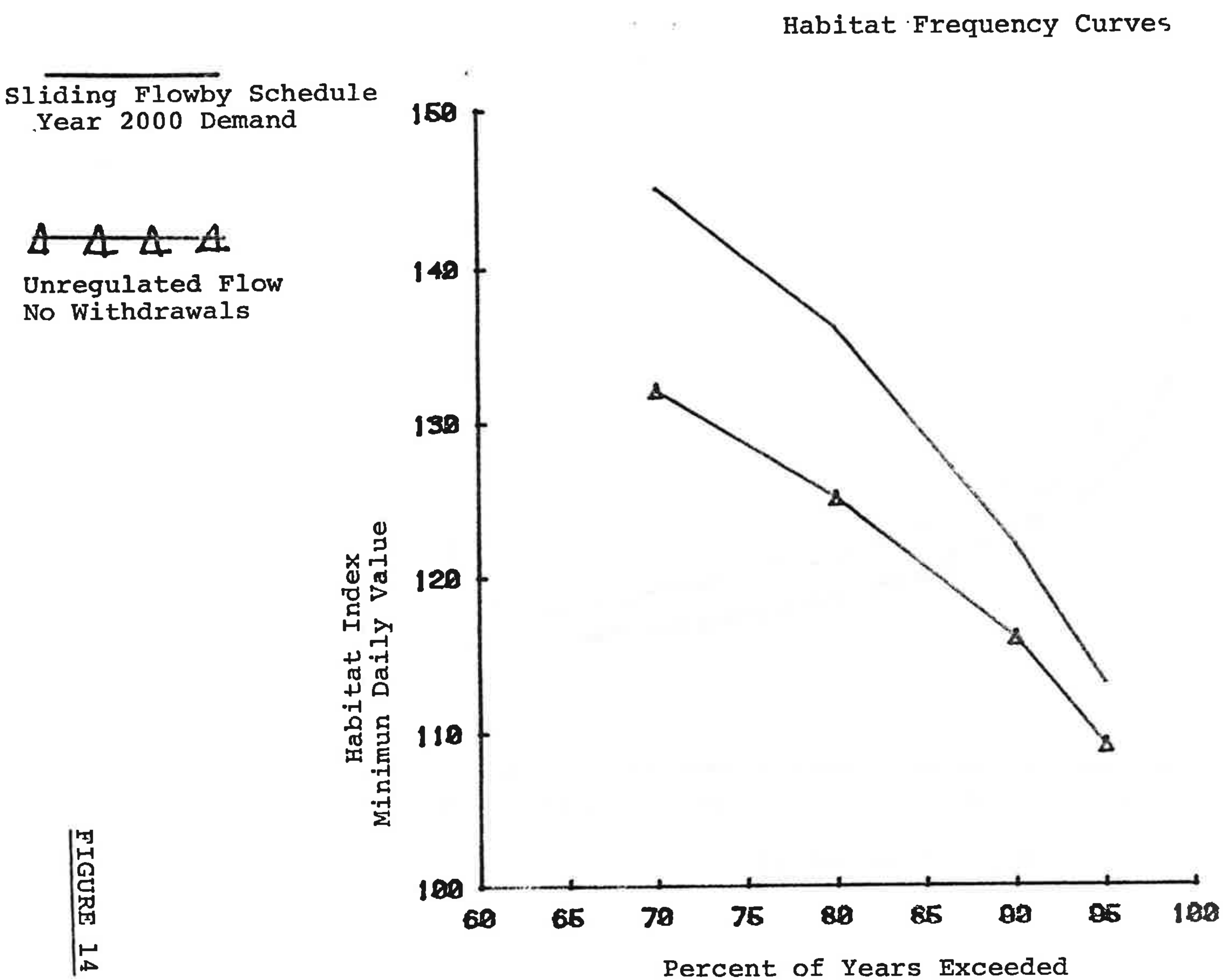

Habitat Frequency Curves
Sliding Flowby Schedule
Year 2000 Demand
Unregulated Flow
No Withdrawals
150
140
130
120
110
100
Habitat Index
Minimun Daily Value
60
65
70
75
80
85
90
95
100
Percent of Years Exceeded

FIGURE 14

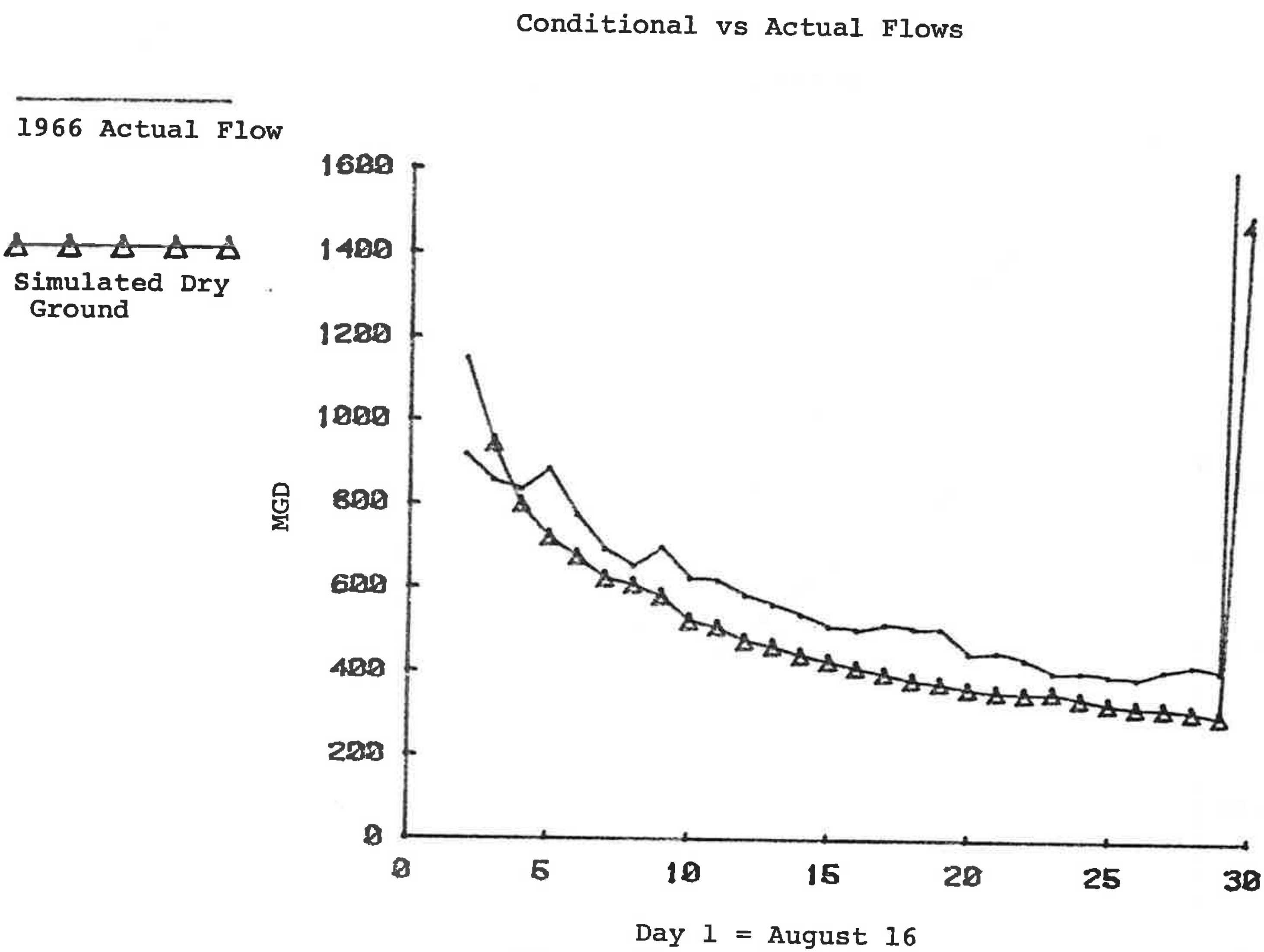

Conditional vs Actual Flows
1966 Actual Flow
Simulated Dry Ground
MGD
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
Day 1 = August 16

FIGURE 15