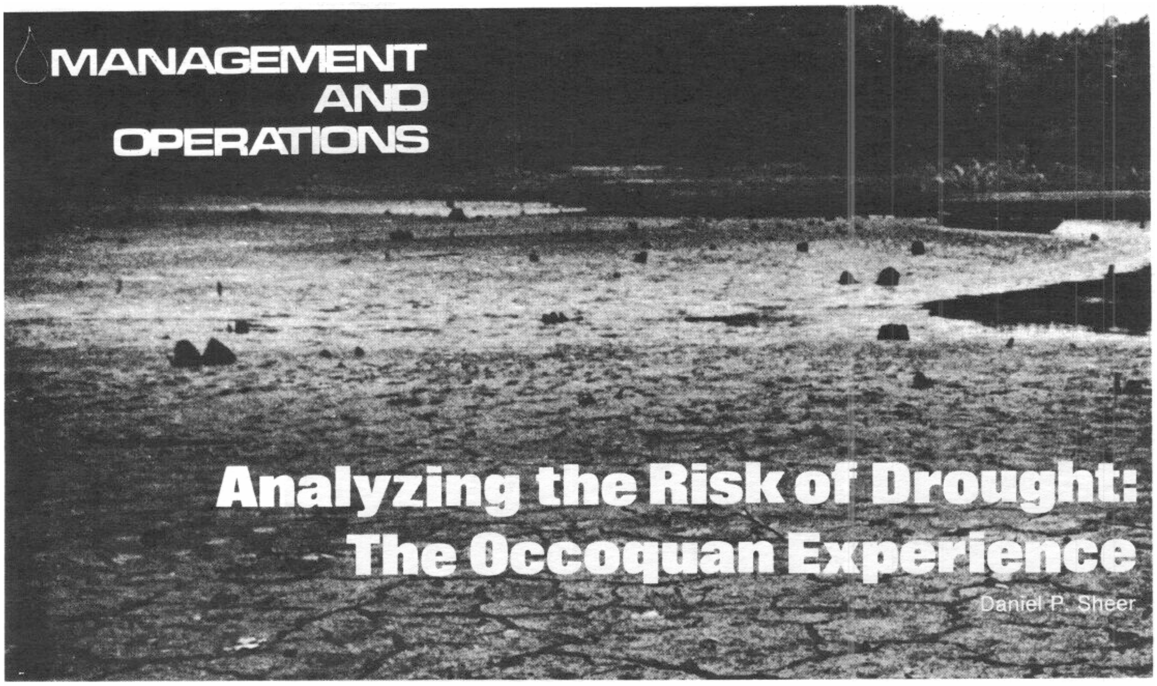

Analyzing the Risk of Drought: The Occoquan Experience

Daniel P. Sheer

During a recent drought in Fairfax County, Va., two practical risk analysis techniques were developed to determine the possibility of extreme water shortages and to evaluate the policies necessary for reducing those risks to acceptable levels.

The Fairfax County Water Authority (FCWA) is the sole water purveyor supplying some 650 000 people in Fairfax County, Va., a suburb of Washington, D.C. The primary source of water is a small dam and reservoir on the Occoquan Creek, a local tributary of the Potomac River (Fig. 1). In 1977 the reservoir had been dropping steadily throughout the summer, and by the end of August had receded to a record low level. Worried that the drought would continue, the FCWA and local governments instituted bans on nonessential water use, such as lawn watering and car washing. More drastic measures, such as the closing of schools and businesses, were actively being considered. It was under these circumstances that the author organized a technical effort to analyze the risk of extreme water shortages and to evaluate the policies necessary to reduce those risks to acceptable levels.*

This paper describes the development and implementation of the risk analysis techniques, the subsequent interaction between technical and political decision makers, generation of the required information, and the application of these techniques and procedures to future drought problems.

*The team that undertook this effort was composed of Robert Hirsch, hydrologist with the USGS, and John Schaake, Eric Anderson, and George Smith of the National Weather Service.

Background

In 1976, the year prior to the drought, the FCWA had commissioned a study to determine the safe yield of the Occoquan reservoir. This report pegged the safe yield at 247 ML/day (65 mgd).[1] By August 1977 the FCWA was averaging about 266 ML/day (70 mgd) withdrawal from the reservoir, with the expectation of reducing demand to 209 ML/day (55 mgd) by October as a result of normal seasonal reduction in water use. The average demand should have been below the safe yield, but during August the reservoir level fell precipitously.

Early in August the FWCA decided that voluntary conservation measures were prudent, and mandatory measures were instituted by September 14. That these measures were taken as early as they were is a tribute to the insight of the FCWA personnel. In late August, largely because of the publicity and controversy that accompanied the beginning of the restrictions, an independent analysis* of the safe yield was undertaken using readily available, computerized USGS streamflow data. It was believed that the results of that analysis would support the contention that the prevailing restrictions in water use were very conservative.

On the contrary, the analysis showed a historical safe yield of only 205 ML/day (54 mgd) over the 26 years of records available at that time. The discrepancy between the earlier report and the new analysis was due to the selection of the critical period used in the 1976 analysis. The difference of 42 ML/day (11 mgd) was critical.

Although it was significant, the historical safe yield analysis provided information only on the year that

*By the author and R.M. Hirsch.

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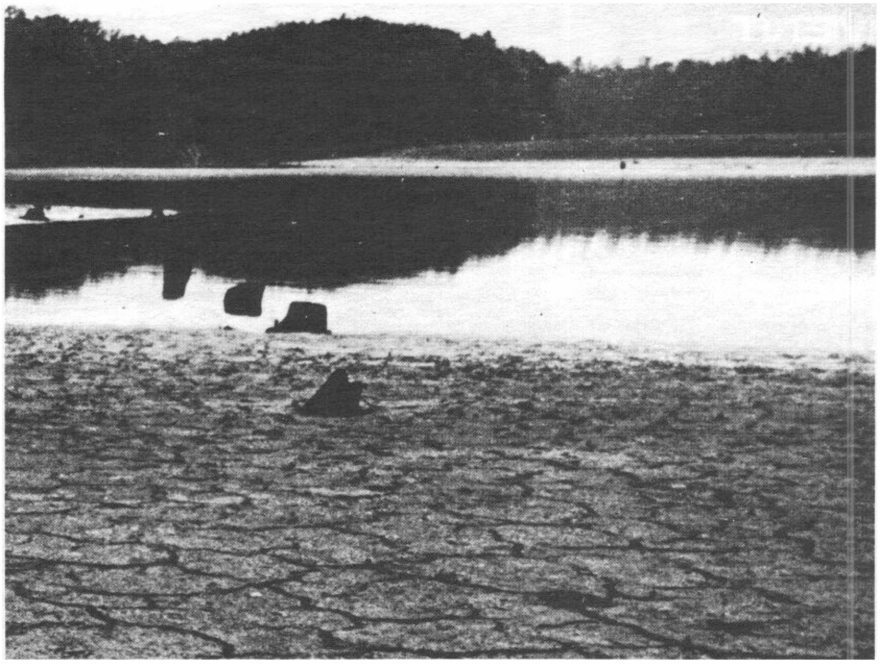
Michael Ford Parks



Alarmingly low water levels in Fairfax County's Occoquan reservoir, shown here at a point 0.6 km (1 mi) below the dam, prompted a detailed analysis of the risk of extreme water shortage as a guide to instituting appropriate conservation measures.

produced the most severe water supply problems (critical period) and on maximum yield from the start of the critical period to the end of the critical period. The fact that the current average withdrawal exceeded the historical safe yield implied that in at least one year in the historical record the reservoir would have gone dry if the FCWA had attempted to meet the current demand.

While this was important information, it did not relate directly to the problem at hand. No use was made of available data concerning the level of water in the reservoir or the relative severity of the existing drought as compared to the worst historical drought.

Genesis of the Techniques

A simulation very closely related to the simulation used to determine historical yield was developed to incorporate information about the current situation. The new simulation was designed to answer the question of what would have happened if the demands had been as high as they were in 1977, the reservoir as low as it was in 1977, and the date were Sep. 1, 1965 (one of the worst drought years), instead of Sep. 1, 1977. The current storage was added to the inflows for September 1965, and the expected water use for September of the current year and an allowance for evaporation were subtracted. The result was the storage that would have remained on Oct. 1, 1965. The calculation was then repeated for each subsequent month until the end of the 1965-66 drought. Table 1 shows the results of this simulation, indicating that the reservoir would have been dry during parts of the following January and February.

To determine in how many years in the historical record the reservoir would have gone dry, the simulation was repeated for each of the 26 years of record then available. In four of those years the reservoir would have been empty. Thus the risk of a dry reservoir was four in 26 years, or $\frac{4}{26}$—approximately 15 percent. The consequences of such a breakdown in the public water supply, particularly loss of fire protection and sanitary facilities, would have been disastrous.

This analysis was called the "position analysis" because it described the current position of the water supplier with respect to the risk of encountering a critical situation in the near future.

Almost as soon as the first analysis was complete it was apparent that additional information could be used to refine the estimate of risk. The historical streamflow record could be extended by using statistical techniques and records of long duration from nearby gauges. Serial correlation of streamflows, a measure of the persistence of previous droughts, could be taken into account by excluding from the analysis those historical years in which summer flows were high. Which years to exclude was the difficult question. The US Geological Survey agreed to develop techniques to answer this question using historical stream flow data.

Much of the persistence in droughts is caused by the lack of soil moisture and its impact on runoff from rainfall. For this reason, the assistance of the National Weather Service (NWS) hydrologic research laboratory was requested so that the NWS rainfall runoff model and statistical analysis program (the NWS river forecast system, or NWSRFS) could be applied to simulate streamflows using historical meteorological data. The streamflows simulated were those that would have occurred, given the current soil moisture conditions. These simulated streamflows were then used in the position analysis instead of the historical streamflows, thereby providing a method of accounting for soil moisture conditions in the position analysis. A comparison of historical and simulated streamflows is given in Table 2.

In nearly all cases the simulated flows were lower than the historical flows. This was the result of the low soil moisture conditions used to initiate the model runs. It illustrates the dramatic impact that soil moisture can have on runoff, and thus the importance of considering soil moisture in establishing the risk of drought.

Starting the Technical–Political Interaction

The political climate eased the way for an independent evaluation of the seriousness of the drought. The question of how much additional development should occur in Fairfax County was and is a very hot political issue. The FCWA is charged with the responsibility of serving whatever growth does occur, but because its present facilities are running at their capacity, the FCWA was seeking approval (since granted) for the construction of a new water treatment plant on the Potomac River. Unfortunately, political groups opposed to further development viewed the control of provision of additional water and sewer service as the most effective way to control growth. In this context, warnings from the FCWA concerning the seriousness of the drought were seen as a ploy by the pro-growth forces to justify the need for additional treatment capacity. With the 1976 safe yield report as a backup, the arguments of the anti-growth forces that the drought was a sham carried some weight.

The FCWA staff had been applying the best techniques at its disposal to attempt to predict the course of the drought. US Department of Agriculture Soil and Conservation Service rainfall–runoff curves were used with long-range weather forecasts to predict runoff.[2] The curves plot runoff as a function of rainfall, given soil type and soil moisture conditions.

With this information, long-range weather forecasts were broken down into six-day periods. Starting with the first period, rain runoff was calculated from the curves, and the change in soil moisture conditions was estimated. The process was continued for ten periods (two months) to produce a predicted streamflow trace, and this trace was then used to predict the contents of the reservoir.

When the FCWA staff contacted the NWS to obtain long-range forecasts suitable for use in this manner, the NWS refused to provide them on the grounds that such forecasts could not be made accurately. The FCWA then contracted with a private weather forecasting firm for the forecasts. The FCWA staff was acutely aware of the dependence of the streamflow predictions on weather forecasts of doubtful accuracy, and the ability of the risk analysis technique to deal with this uncertainty was perceived to be advantageous.

The simplicity of the technique was also an advantage, as the results had to be explained to a nontechnical audience. FCWA staff formed an advisory group of

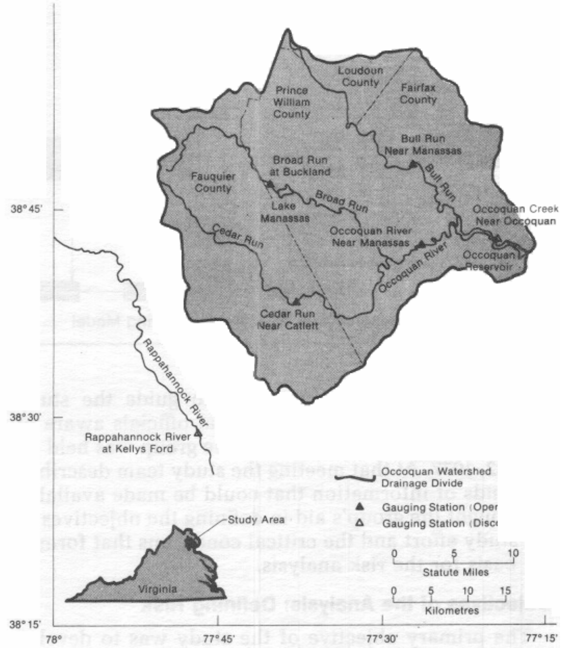


Fig. 1. Map of the Occoquan Watershed Showing Location of **Streams, Gauges, and Reservoirs**

TABLE 1

Position Analysis Simulation Using 1965–1966 Inflows

Position Analysis	Date	Calculation of Reservoir Storage ML	Calculation of Reservoir Storage *mil gal*
Actual reservoir storage	9/65	13 900	3650
Inflow		+1900	+507
Withdrawals and evaporation*		−5700	−1500
Simulated reservoir storage	10/65	10 100	2657
Inflow		+4500	+1192
Withdrawal and evaporation*		−5900	−1550
Simulated reservoir storage	11/65	8700	2299
Inflow		+1600	+433
Withdrawal and evaporation*		−5700	−1500
Simulated reservoir storage	12/65	4600	1232
Inflow		+1900	+493
Withdrawal and evaporation*		−5900	−1550
Simulated reservoir storage	1/66	600	175
Inflow		+2900	+753
Withdrawal and evaporation*		−5900	−1550
Simulated reservoir storage	2/66	0	0
Inflow		62 000	16 246
Withdrawal and evaporation*		−5900	−1550
Simulated reservoir storage	3/66	37 200†	9800†

*At 190 ML/day (50 mgd)
†Maximum reservoir capacity

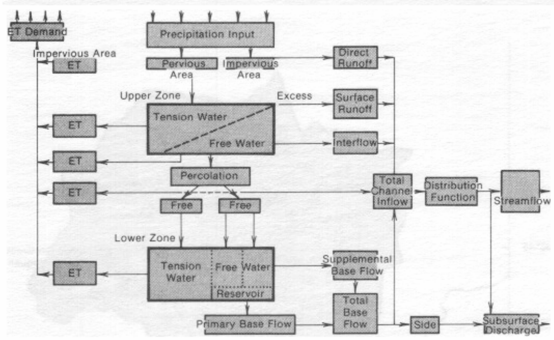


Fig. 2. Sacramento Soil Moisture Accounting Model

local government staff members to guide the study effort and to keep responsible local officials aware of its progress. The first meeting of the group was held on Sep. 22, 1977. At that meeting the study team described the kinds of information that could be made available and sought the group's aid in defining the objectives of the study effort and the critical conditions that formed the basis for the risk analysis.

Objectives of the Analysis: Defining Risk

The primary objective of the study was to develop useful information concerning the future availability of water. As local governments are responsible for making and enforcing decisions concerning water use, it was appropriate that the local government representatives be consulted at the first meeting concerning what information would be most useful in the decision-making process. Following the explanation of the techniques and the presentation of the preliminary results, the immediate question asked by the local officials was "How likely are we to run out of water?"

The study team responded to this question by saying that the chance of running out of water was highly dependent on policy decisions as to when and how much to further cut consumption. It was pointed out that as the available storage fell further, progressively more stringent water use restrictions would be imposed in order to preserve the remaining storage. This kind of operation would reduce the likelihood of exhausting the reservoir storage.

Prior to the meeting, the FCWA and the local governments had agreed on an operating policy to deal with the drought which called for the imposition of increasingly severe water use restrictions keyed to water levels in the reservoir.[3] Stage 1 of the restrictions called for voluntary restrictions on outside uses of water, including car washing and lawn irrigation. Stage 2A called for mandatory restrictions on the same uses. Stage 2B called for loosely defined restrictions on water use within the home, and stage 3 imposed the shutdown of schools and businesses. At the time of the first meeting stage 2A restrictions had just been imposed, and much discussion followed on what would be required in stage 2B and how such restrictions could be enforced. Stage 3 was thought of as a last resort, even though the risk of the reservoir's dropping low enough to trigger stage 3 restrictions was unknown.

In this context, the local officials decided that the risk of the reservoir's falling to the level requiring stage 3 restrictions was the risk to be controlled. The decision to be used to control this risk was the decision as to the severity of the stage 2B restrictions to be imposed. Developing information on the implications of implementing stage 3 restrictions was indeed possible; however, in the interest of developing the most pertinent information in the shortest time, all effort was directed to determining appropriate stage 2B restrictions.

TABLE 2
Simulated Conditional Streamflow Versus Historical Streamflow† for the Occoquan Reservoir in November*

Year	Simulated Flow		Historical Flow	
	ML	*mil gal*	*ML*	*mil gal*
1949	12 574	3309	80 058	21 068
1950	5890	1550	10 682	2811
1951	13 361	3587	39 683	10 443
1952	10 617	2794	9633	2535
1953	55 415	14 583	87 632	23 061
1954	7323	1927	3029	797
1955	3876	1020	2922	769
1956	3203	843	9435	2483
1957	4636	1220	48 613	12 793
1958	3743	985	15 743	4143
1959	2956	778	3386	891
1960	3728	981	13 864	3648
1961	2736	720	4951	1303
1962	3397	894	9853	2593
1963	24 426	6428	23 100	6079
1964	38 008	10 002	31 380	8258
1965	3245	854	7638	2010
1966	2223	585	1645	433
1967	2899	763	10 591	2787
1968	3359	884	5491	1445
1969	4393	1156	18 122	4769
1970	3276	862	8767	2307
1971	34 717	9136	89 334	23 509
1972	5977	1573	55 203	14 527
1973	71 254	18 751	4366	1149
1974	3200	842	5586	1470
1975	3051	803	2660	700

*Soil moisture conditions as of 11/25/77
†Reconstructed from Hirsch[4]

Techniques Used by the USGS

The techniques used in the USGS analysis have been fully described by Hirsch.[4]* They are essentially a refinement of the position analysis method. The initial work by the USGS focused on extending the streamflow record as far back into the past as possible. Longer flow records on nearby drainage basins were available. Linear regression of flows at gauges in the Occoquan basin with flows in these other basins formed the basis for the extension of the historical record. The record produced by this technique had less variability than the actual historical record, a fact that tended to reduce the severity of historical droughts as represented in the extended record. Nevertheless, the record did represent a best estimate of past streamflows. Using the regression techniques, a sequential streamflow record of 49 years was generated.

To account for the persistence of low streamflows, the autumn and winter flow series from the 49-year record were divided into two groups, those which

*This publication is available from the author upon request.

followed dry Septembers (DS) and those which followed wet Septembers (WS). The dividing flow for determining whether a September was wet or dry was arbitrarily set at an average of 190 ML/day (50 mgd). Twenty-two years in the 49-year record met the DS condition, and these were used in the position analysis techniques to determine risk.

The choice of 190 ML/day (50 mgd) as the dividing flow was made as a compromise of two conflicting objectives. The first was to keep the number of years used in the analysis as high as possible to account for the inherent variability of streamflow. The second was to eliminate from the analysis those years dissimilar to the current year. A statistical procedure, the Mann-Whitney rank sum test,[5] was employed to determine the similarity between the DS and WS flows. With the division set at 190-ML/day (50-mgd) average flow, the hypothesis that both groups came from the same sample population was rejected at the 1 percent level. While 190 ML/day (50 mgd) was not the largest dividing flow that still produced this level of confidence, it provided an appropriate balance between sample size and sample similarity. Because the DS group included all the worst drought years but excluded many high flow years, the risk estimates were approximately twice as great as the estimates generated using the entire historical record.

National Weather Service Techniques

During the course of the NWS study effort, existing NWS techniques were combined with the position analysis to produce risk estimates. Like the USGS effort, the major focus of the NWS effort was to produce a set of streamflow records that were more representative of what could happen in the future than the historical streamflow record. This record would then be used in a position analysis to determine risk. The NWS used the NWSRFS model[6] along with historical meteorological data to produce the streamflow records. The NWSRFS is an integrated system of forecast models including the Sacramento soil moisture accounting model,[7] streamflow routing models, reservoir operations models, procedures for estimating average precipitation and temperatures over large areas, and statistical analysis techniques. The Sacramento soil moisture accounting model is the basis of the NWSRFS (Fig. 2). This is a conceptual hydrologic model for the movement of water through the soil, through groundwater systems, and over the surface to the stream network. It accounts for evapotranspiration and maintains a detailed water balance in time increments of six hours.

Because the entire 1560-km² (600-sq mi) drainage area of the reservoir was treated as a single catchment, the flow routing routines available in the NWSRFS were not used. NWSRFS also contains a snow accumulation and ablation model[8] (Fig. 3) to account for the influence of snowmelt. Calibration of the model was performed using 26 years of historical streamflow and meteorological information. The object of the calibration was to adjust the model parameters to achieve the best match between flows predicted by the model using historical meteorological data and the observed streamflows for the same period.

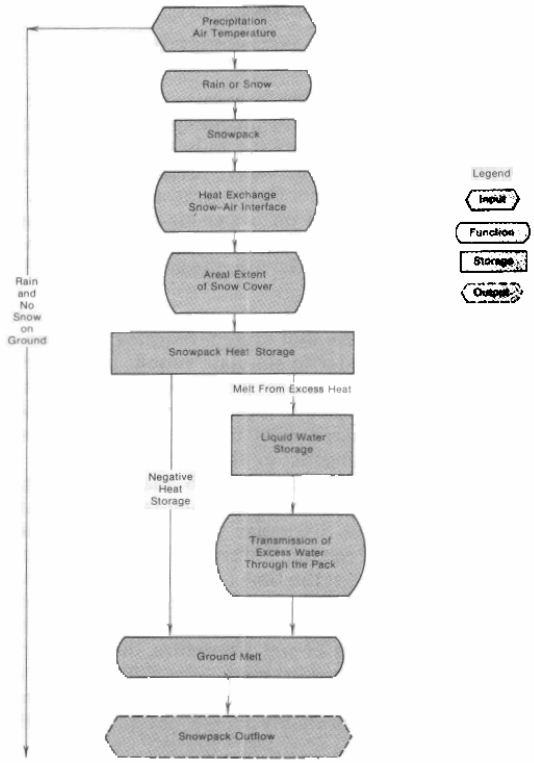


Fig. 3. Snow Accumulation and Ablation Model

The meteorological data used in the analysis are stored on magnetic tape by the NWS. The data represent six-hour averages for precipitation and temperature readings at NWS stations. Those readings for stations in and around the basin were converted to mean aerial temperature and precipitation for the basin by routines contained in the NWSRFS model.

Once the model was calibrated, the current values of the model's soil moisture parameters were estimated by running meteorological data for the preceding six-month period through the model. With the model parameters set to these estimates, meteorological data beginning at the current data and for one year in the historical record were run through the model. This produced the streamflow trace that would occur if the historical meteorological data repeated themselves in the immediate future. Running the simulation for every year in the historical record produced a set of 26 historical "conditional" streamflow records, each conditioned on current soil moisture conditions in the basin. It is important to note that although the streamflows generated were conditioned on soil moisture conditions, no actual soil moisture or groundwater level measurements were taken.

These streamflows were used in a position analysis to estimate the risk of encountering a critical condition.

Statistical techniques used in the extended streamflow prediction program[9] of the NWSRFS were used to further refine estimates of risk.

Attempts to Incorporate Long-Range Weather Forecasts

NWS long-range weather forecasts are updated every fifteen days and cover the forthcoming month. They are intentionally imprecise, stating only that temperature and precipitation will be above normal, normal, or below normal for the month for large areas of the US. The forecasts are based on upper air circulation patterns expected for the next 30 days and the weather that has been associated with those patterns in the past.

These forecasts cannot be directly incorporated into the NWSRFS because that system requires input on a six-hour basis in order to simulate runoff. Instead, the approach taken was to use the forecast to eliminate from the historical record those years that had upper air circulation patterns most unlike the forecast patterns. This is analogous to the techniques used to eliminate WS years from the USGS analysis. Because of the great uncertainties in the long-range forecasts, only the three most dissimilar years were eliminated from the historical record. Unfortunately, the upper air circulation patterns at the time of the analysis were not generally associated with either drought or wet periods, and none of the record years chosen as most dissimilar were particularly dry or wet. Therefore, the incorporation of long-range forecasts made little difference in the estimate of risk. Had the long-range forecast shown a definite trend, this probably would not have been the case.

No attempt was made to use the long-range forecast provided to the FCWA by the private forecasting service mentioned earlier. However, these forecasts were made for six-day periods, an interval much more suitable for direct use in the NWSRFS models. The forecasts are compared to the actual rainfall in Table 3. Although the monthly totals seem to agree fairly well, the regression line of the predictions on the actual rainfall is negative for the ten forecast periods. The correlation coefficient is not significant. This tends to support the NWS contention that such forecasts cannot be made accurately. Certainly, such forecasts should not be the basis for decisions crucial to the protection and well-being of large numbers of people.

TABLE 3
Private Weather Predictions Versus Actual Rainfall

Date	Predicted Rainfall		Actual Rainfall	
	cm	in.	cm	in.
September				
2–7	1	0.4	2.5	0.99
8–13	1	0.4	0.6	0.24
14–19	1	0.4	1.6	0.65
20–25	1.75	0.7	1	0.4
26–Oct. 1	1.25	0.5	0.4	0.16
Total	5.85–6.15	2.25–2.55	6.1	2.02
October				
2–7	3.8	1	0.17	0.07
8–13	4	0.6	1.85	0.74
14–19	3.8	1	2.77	1.11
20–25	2.25	0.9	0.37	0.15
26–Nov. 1	1	0.4	5.75	2.3
Total	14.65–15.05	3.7–4.1	10.7	4.28

Continuing the Technical-Political Interaction

The second meeting of the advisory group was held on Oct. 7, 1977. By this time, preliminary risk estimates were available from the USGS effort. Because withdrawals from the reservoir had been reduced by mandatory restrictions on outside water use, by public cooperation in conserving water, and by purchasing as much water as practicable from surrounding utilities through small existing interconnections, the risk of reaching the critical level in the reservoir had been reduced to about 10–15 percent despite the continuing drought. This risk level was still unacceptably high. The preliminary analysis indicated that the risk level could be reduced threefold by a reduction of only 30 ML/day (8 mgd) in reservoir withdrawals, or a 46-Lpcd (12-gpcd) reduction in water use.

The average water use was then about 330 Lpcd (87 gpcd), and no member of the advisory committee or the study team felt such reduction was unachievable.

Although the NWS results were not yet available, a decision had to be made as to whether or not the USGS information should be made public in its preliminary form. The probable results of delaying the implementation of the proposed water reduction program were analyzed. Delaying a 30-ML/day (8-mgd) reduction for two weeks would mean the use of an additional 425 ML (112 mil gal) of water. This represented only a three- to four-day supply, or at the most an additional week of time to wait for rain should the drought continue through the winter. The advisory group decided to wait the additional time to be certain that the further reductions were necessary. The study group supported this decision, knowing that the additional 425 ML (112 mil gal) of storage would not have a significant impact on risks.

The discussions at this second meeting also centered on what information could be made available to assist the local governments in deciding when it was safe to lift restrictions, should the level in the reservoir begin to rise. If the risk of reaching a critical level fell to less than 1 percent with normal consumption, it was decided that restrictions could be lifted. The task of finding the reservoir level at which risks fell to 1 percent as a function of time was then undertaken.

Results

The agreement between the final NWS and USGS results was very good. This was encouraging, since the two techniques are quite different. The study group met and resolved the small differences that did occur.

The final results of the study effort were presented in a short report,[10] and are given in part in Tables 4 and 5 and Fig. 4 and 5. The report recommended immediate implementation of water conservation to achieve an 30-ML/day (8-mgd) reduction in demand.

Implementation

These results were presented to the advisory group at its third and final meeting on October 18. It was decided to implement the recommended 30-ML/day (8-mgd) demand reduction by voluntary measures rather than through enforcement. The members of the advisory group felt that, given adequate publicity, the public would understand the implications of the risk analysis and respond favorably to a request for a moderate reduction in water use. Much more severe reductions in water use were then being achieved in California, which was also in the midst of a drought.

Briefings were immediately arranged for the leaders of the affected jurisdictions to produce a unified call by all responsible officials for the appropriate reduction in demand. This unified front was deemed necessary if the voluntary reductions were to be effective, given the existing political situation.

A televised press conference was arranged, and the story was leaked to a *Washington Post* reporter the night before. Unfortunately, there was no chance to see if the publicity would work. On October 27 it began to rain—in torrents.

Postmortem

By November 8, when restrictions were formally ended, the reservoir level had risen 5 m (17.5 ft) and was about 1.5 m (5 ft) above the level specified as safe in the target storage curve. The reservoir was filling so fast that the restrictions certainly would have been lifted in any case. However, in the two-month period between September 1 and October 31, the risk analysis techniques had been brought from conception to operation, their use had produced results, and these results had been implemented as a part of the operating policy of the FCWA and the local governments. Since then, the FCWA has implemented the streamflow-based technique on its own computer system and performs a position analysis at the beginning of each month, or more often as necessary. An excessive level of risk is taken as an indication that a drought may be imminent, although no formal mechanisms have been developed for integrating operational policy with the position analysis. The FCWA is continuing to upgrade its ability to use position analysis; for example, weekly instead of monthly flow records are being obtained from the USGS for use in the simulation.

Comparison of the USGS and NWS Techniques

The USGS technique is by far the simpler of the two techniques developed. It requires considerably less data to implement than the NWS technique, and can be performed without the aid of a computer. For sources like the Occoquan Creek, where snowmelt is not a major factor and groundwater conditions are not influenced by events either outside the basin or totally independent of streamflow, the results produced are likely to correspond to those produced using the NWS techniques. In cases where snowmelt or groundwater is a factor, the analysis may be improved by the considered input of persons familiar with local conditions. Research is continuing on methods to incorporate serial correlation and other statistical properties of the historical record into streamflow-based position analysis.[11] The author believes that streamflow-based position analysis should be the technique of first resort in estimating the risk of streamflow-induced drought.

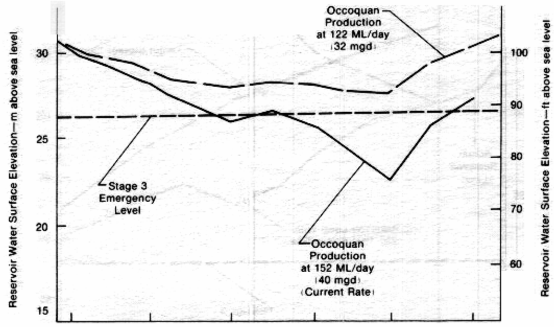


Fig. 4. Reservoir Levels at Various Production Rates

The NWS technique has the potential to be the more precise of the two techniques, at the expense of considerably more data and effort. Still, neither the data requirements nor the computational burden are really excessive if it is desirable to implement the technique for future use. If, as is often the case in the US, the data are available in digital form, the technique can be implemented with expediency.

In order to test the predictive ability of the NWSRFS model against the predictive ability of past streamflows, the author performed several multiple regressions using the Statistical Package for the Social Sciences program (SPSS).[12]

September flows were treated as the dependent variable, and two groups of variables—the values of three of the groundwater parameters in the NWSRFS model at the end of the preceding August and the preceding June, July, and August flows—were used as independent variables in two multiple regressions. The multiple regression coefficient for the model parameters was 0.39. For the flows in the three preceding months the multiple r was only 0.21, indicating that September flows were better related to modeled groundwater conditions than to previous flows.

Regressions were then run to test the ability of the two groups of parameters to predict droughts, again defining droughts as flows less than 190 ML/day (50 mgd) for the month of September. The dependent variable in these regressions was 190 ML/day (50 mgd), and 0 otherwise. Again the model parameters outperformed the previous flows, with multiple rs of 0.45 and 0.25, respectively. Transforming past flows by taking logarithms improved the correlation to 0.34, still lower than that achieved by the model parameters.

While these comparisons are far from conclusive, they indicate that even when snowmelt is not a factor, the model parameters may be a better predictor of future flows than past streamflows. When snowpack makes a significant contribution to future streamflows, the NWS technique has the tremendous advantage of

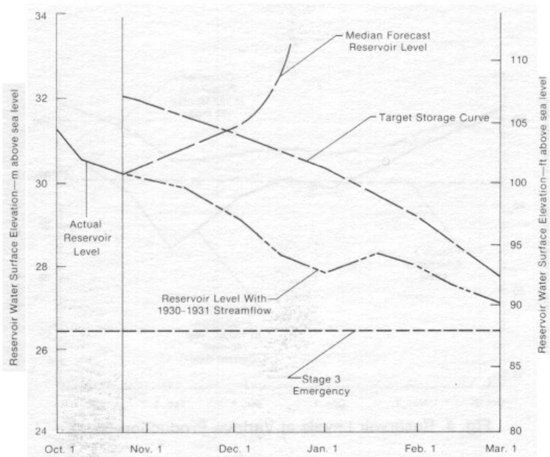


Fig. 5. Occoquan Target Storage Curve

accounting for the phenomenon explicitly.

The author also believes that techniques can be developed to effectively utilize long-range weather forecasts in the NWS technique. The attempts described here were crude, but nonetheless show great promise. As the precision of long-range forecasts improves, so will the precision of the risk estimates produced using the NWS technique.

The NWS technique attempts to account for soil moisture conditions without the need for field measurements of those conditions. (The information concerning soil type, soil depth, and other geologic data used in estimating the model parameters for calibration is generally available from the US Geological Survey.) Field measurements of groundwater conditions are often quite expensive. If the NWS technique is used, the value of such field data may be significantly reduced, obviating the need for such measurements.

TABLE 4

Probabilities of Occoquan Reservoir Falling Below Critical Storage Levels at 150 ML/day (40 mgd) Withdrawal

Storage Level		Volume of Storage Remaining		Probability
m	*ft*	*GL*	*bil gal*	*percent*
28	93	6.5	1.7	13
27	88	4.2	1.1	10
25	83	2.7	0.7	8

TABLE 5

Probabilities of Occoquan Reservoir Falling Below Critical Storage Levels at 122 ML/day (32 mgd) Withdrawal

Storage Level		Volume of Storage Remaining		Probability
m	*ft*	*GL*	*bil gal*	*percent*
28	93	6.5	1.7	5
27	88	4.2	1.1	3
25	83	2.7	0.7	2

Conclusions

The USGS risk analysis technique can be applied using only streamflow information, and should be the technique of first resort for assessing the likelihood of storage deficiencies. The NWS technique has the potential for being more precise, since it can explicitly incorporate snowmelt, long-range weather forecasts, and other factors. Furthermore, the groundwater parameters in the NWS model may be better predictors of future streamflows than are past streamflows. Both techniques provide information of great utility in public decision making.

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