THE USE OF HYDROMETEOROLOGICAL DATA IN DROUGHT MANAGEMENT: POTOMAC RIVER BASIN CASE STUDY

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ABSTRACT: Development and implementation of a drought management system for the Potomac River basin are discussed in this paper. The drought management system is comprised of hydrologic models which are used for streamflow forecasting and models of the regional water supply system. It is shown that the hydrologic models, especially the Sacramento model, are particularly well suited for representing streamflow characteristics in the Potomac River basin. An important component of the streamflow forecast system is the Extended Streamflow Prediction (ESP) procedure, which is used to produce long-range water supply forecasts. The streamflow forecast system and water supply models are linked to form a drought management system which is used for allocating water supplies in the Washington, D.C., metropolitan area during drought periods.
(KEY TERMS: streamflow forecasting; drought management.)

INTRODUCTION

Three topics pertaining to the development and implementation of a drought management system for the Potomac River basin are discussed in this paper. First of all the physical characteristics of low streamflow in the Potomac River basin are discussed. Spatial variation of low streamflow is shown to be closely related to geologic features of the basin and a map of hydrologic provinces is presented. Our second topic concerns the hydrologic models that are used for streamflow forecasting. The main components of the streamflow forecast system are the Sacramento Soil Moisture Accounting Model and the Extended Streamflow Prediction (ESP) procedure, both of which are components of the National Weather Service River Forecast System (NWSRFS). The relations between the physical characteristics of low streamflow in the Potomac River basin and the form of the hydrologic models are discussed. Our final topic concerns linking the streamflow forecast system with a model of the Potomac River basin water supply system. This combined system is used for allocating water supplies during drought periods.

HYDROGEOLOGY OF LOW STREAMFLOW IN THE POTOMAC RIVER BASIN

Streamflow data for water years 1950-1979 from gages within the upper Potomac River basin along with geologic maps of the states of Maryland, Virginia, West Virginia, and Pennsylvania were used in developing the map of hydrologic provinces presented in Figure 1. Streamflow data for the upper Potomac River basin are summarized in Table 1. Following Olmsted and Hely (1963) the statistic Q_{90}/Q_A is used as the primary measure of low flow regimen, where Q_A represents the mean daily flow (in cfs/drainage area in square miles) and Q_{90} represents the daily flow that is exceeded with probability 0.9.

The central features in the relationship between low flow and geology can be summarized as follows:

1) Regions underlain by shale are the poorest sources of baseflow in the basin.

2) The Piedmont metasedimentary rocks have uniformly high baseflow.

3) The metavolcanic rocks of the Piedmont and Blue Ridge have uniformly poor baseflow.

4) In the folded sedimentary rocks of the Valley and Ridge, the presence of carbonate rocks is necessary for high baseflow conditions.

5) The region with highest baseflow in the Potomac River basin is located in the eastern portion of the Great Valley at the western slope of the Blue Ridge (Antietam Creek and the South Fork of the Shenandoah River).

6) Flat-lying sedimentary rocks of the Allegheny Plateau have poor baseflow even when carbonate rocks are present.

The physical basis for the sharp contrasts between hydrologic provinces is best illustrated in the Piedmont of Virginia, Maryland, and Pennsylvania. Figure 2a shows flow duration curves for three streams in the Virginia Piedmont. Bull Run and Cedar Run drain Triassic shale; Difficult Run,

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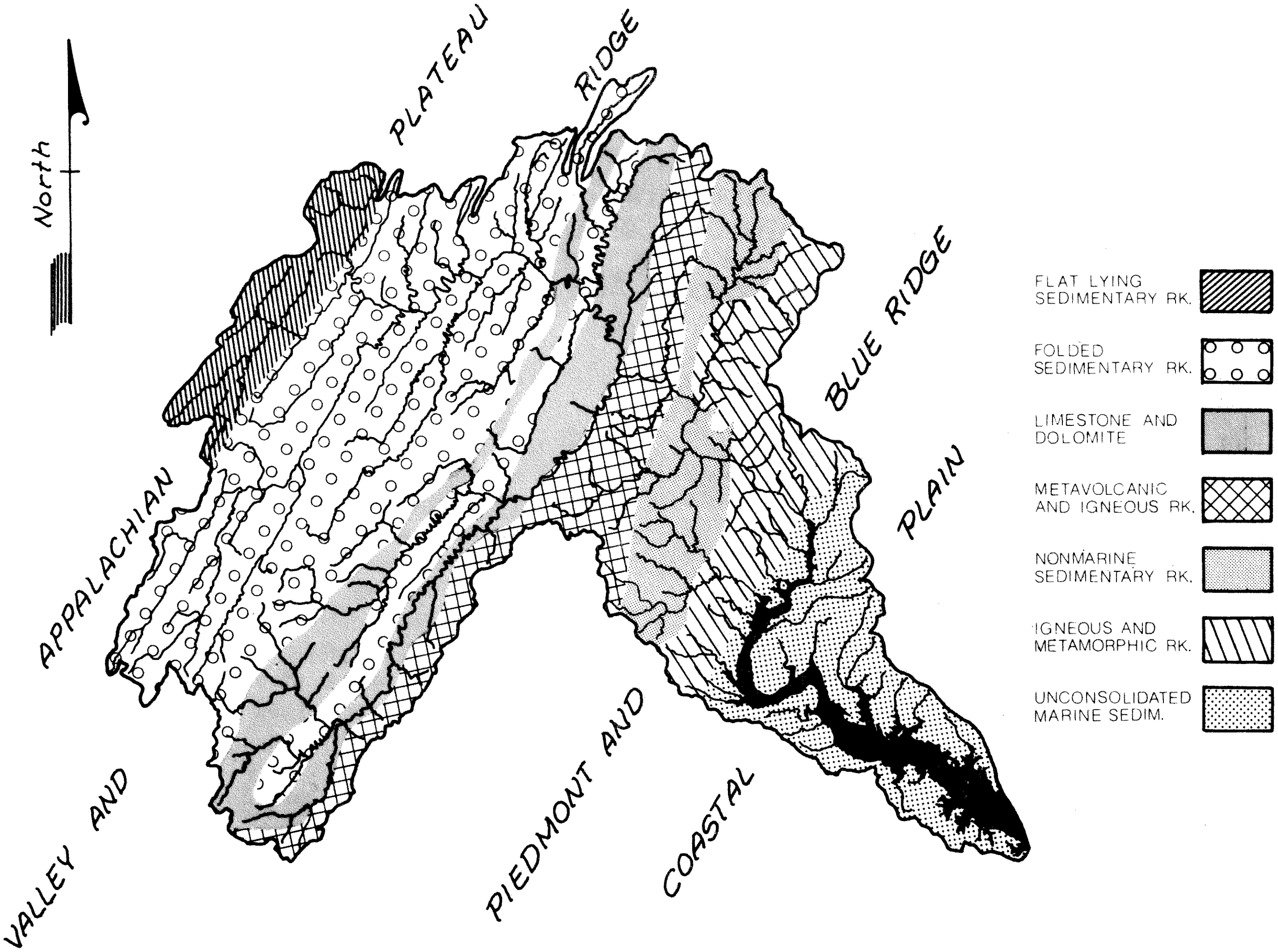

Figure 1. Hydrologic Provinces of the Potomac River Basin.

which borders Bull Run, drains Paleozoic metasedimentary rocks. Figure 2b shows flow duration curves for Monocacy River, Senaca Creek, and Patuxent River. Monocacy River, which drains Triassic shales in Pennsylvania, has flow duration values nearly identical to those of Bull Run and Cedar Run, while Seneca Creek and Patuxent River, which drain Paleozoic metasedimentary rocks in Maryland, have flow duration values similar to Difficult Run.

The contrasts in flow properties between shales and crystalline rocks of the Piedmont are most readily explained in terms of soil moisture storage and permeability properties. The Piedmont crystalline rocks are covered by a thick mantle of saprolite. Nutter and Otton (1966) report that depth to bedrock averages 45 feet in the crystalline Piedmont of Maryland. Nutter and Otton also note that a region of high permeability occurs at the base of the saprolite. Conversely, soils forming on the Triassic shales are thin (Roberts, 1928) and, due to the high clay content, have low permeability.

Storage and permeability are also the key features in producing the region of high baseflow at the western border of the Blue Ridge. Surficial deposits on the west slope of the Blue Ridge in Virginia were reported by Hack (1965) to range from 100-300 feet. Similar values were reported for the corresponding region in the Antietam Creek basin to Maryland (Nutter, 1976). This region of high groundwater storage is underlain by intensely folded carbonate rocks. Joint planes in the carbonate ocks, which are especially numerous due to the intense folding, have been enlarged by solution to produce the most extensive caves in the Potomac River basin (Nutter, 1976). Storage in the carbonate rocks is hydraulically connected with stream channels largely through joint planes. This region is thus similar to the crystalline Piedmont in that it has high ground water storage capacity and zones of high permeability.

Thin soils provide the primary explanation for low baseflow conditions in the metavolcanic rocks of the Blue Ridge

TABLE 1. Summary Statistics for Streams in the Potomac River Basin.

	DA (sq. mi.)	Q_A (cfsm)	Q_{90}/Q_A
1) Flat-Lying Sedimentary Rocks			
North Branch	225	2.00	0.10
Abram Creek	47	1.62	0.06
Crabtree Creek	17	1.72	0.08
Savage River	49	1.52	0.05
2) Folded Sedimentary Rocks			
A) Shales and Sandstones			
Patterson Creek	219	0.78	0.05
Back Creek	243	0.85	0.06
South Fork South Branch	102	0.98	0.07
N.F. Shenandoal River	210	0.93	0.02
Passage Creek	88	0.76	0.07
B) Carbonate Rocks			
South Branch	182	0.88	0.18
Opequon Creek	272	0.84	0.24
Antietam Creek	281	1.04	0.33
Middle River	375	0.81	0.26
South River	127	1.09	0.22
S.F. Shenandoah River	1642	0.93	0.25
3) Metavolcanic Rocks			
Catoctin Creek	67	1.13	0.07
Goose Creek	332	0.97	0.06
Owens Creek	6	1.61	0.07
Hunting Creek	18	1.45	0.10
4) Metasedimentary and Igneous Rocks			
Seneca Creek	101	1.06	0.24
Patuxent River	35	1.14	0.22
Difficult Run	58	1.06	0.21
Big Pipe Creek	102	0.96	0.21
5) Nonmarine Sedimentary Rocks			
Bull Run	148	1.08	0.02
Broad Run	51	1.03	0.08
Cedar Run	93	0.95	0.02
Monocacy River	173	1.08	0.04

and Piedmont, the noncarbonate folded sedimentary rocks of the Valley and Ridge, and the flat-lying sedimentary rocks of the Allegheny Plateau (see Trainer and Watkins, 1975). Thin soils form on metavolcanic rocks due, in large part, to the lack of quartz in the parent material. The shales which predominate in the noncarbonate regions of the Valley and Ridge and Allegheny Plateau have similar hydrologic properties to the shales of the Piedmont described above. The contrast in hydrologic properties between flat-lying carbonate rocks and folded carbonate rocks is, in our opinion, related to the relative importance of bedding (high in flat-lying carbonates) and joint planes (high in folded carbonate ocks) in determining storage and permeability characteristics. A different perspective on this problem is presented by White (1977).

The relations between low streamflow and geology outlined above are not peculiar to the Potomac River basin. Table 2 summarizes streamflow data at selected sites in the Central and Southern Appalachians. It should be noted that two of the classifications listed in Table 1 are missing from Table 2. Metavolcanic rocks of the Central and Southern Appalachians, similar to those exposed along the Blue Ridge in the Potomac River basin, are restricted to a small area of southwestern Virginia. Nonmarine sedimentary rocks are prominent in the Piedmont of New Jersey, Delaware, Pennsylvania, and Virginia. Unfortunately, historical streamflow records that are unaffected by regulation are scarce. A detailed discussion of the relations between low streamflow and geology in the Central and Southern Appalachians is in preparation.

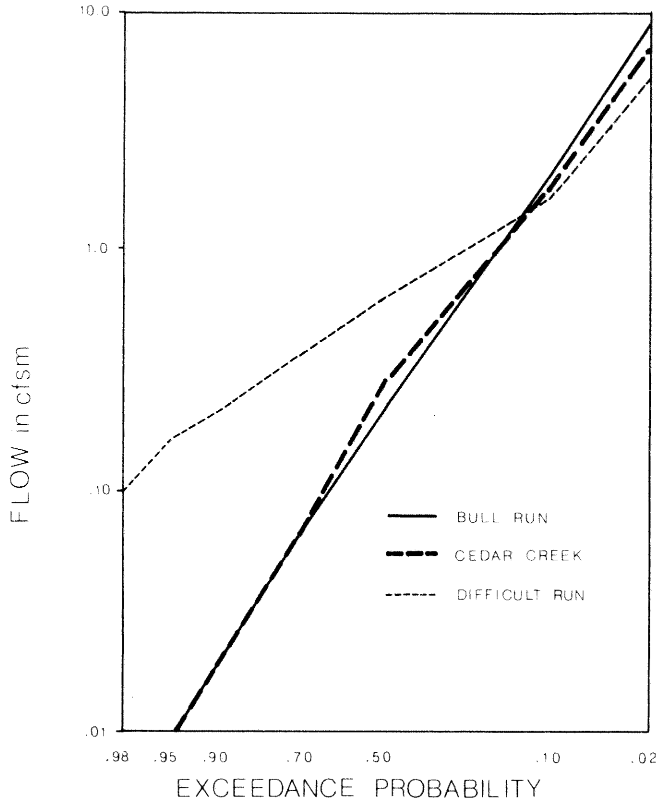

Figure 2a. Flow Duration Curves for Piedmont Streams – Virginia.

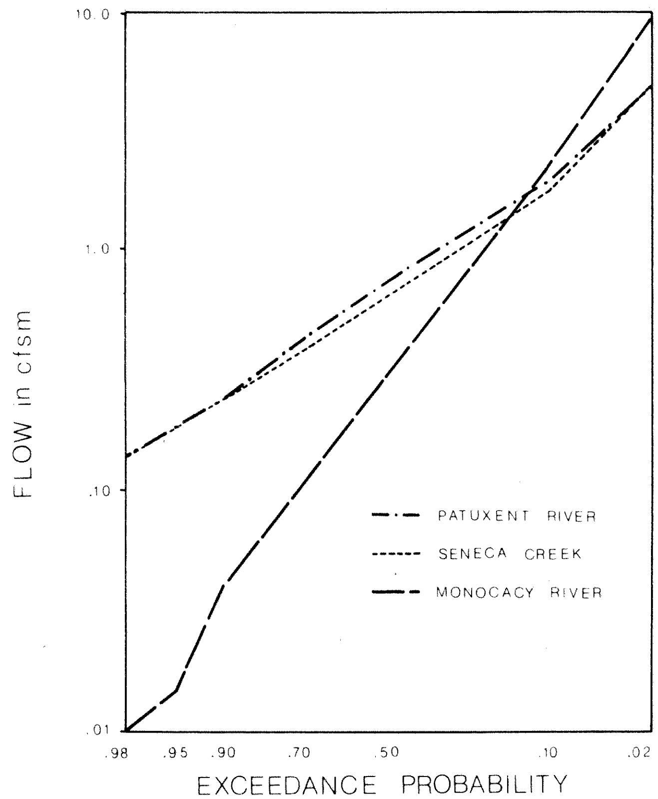

Figure 2b. Flow Duration Curves for Piedmont Streams – Maryland, Pennsylvania.

DESCRIPTION OF THE STREAMFLOW FORECASTING SYSTEM

Low summer streamflow in the Potomac River is the product of low summer rainfall combined with dry antecedent soil moisture conditions. This is illustrated by comparing summer streamflow records from 1951 and 1966 (Figure 3). During the period July-September nearly identical rainfall totals were recorded in 1951 and 1966, yet in 1966 (following three *years* of abnormally low rainfall) Potomac River streamflow at Point of Rocks reached a daily minimum of 547 cfs while in 1951 (following a wet Fall and Winter) the minimum daily flow was 1170 cfs. Streamflow forecasting, used as a drought management tool, must consider information concerning soil moisture conditions as well as uncertainty in future precipitation. The approach taken for streamflow forecasting in the Potomac River basin relies on a conceptual hydrologic model, the Sacramento Soil Moisture Accounting Model, which is a component of the National Weather Service River Forecast System (NWSRFS). The Sacramento model can accurately reproduce historical streamflow using historical meteorological data as input. The model uses parameters which are surrogates for the physical structure of the drainage basin. It provides the forecasting flexibility required for water supply management.

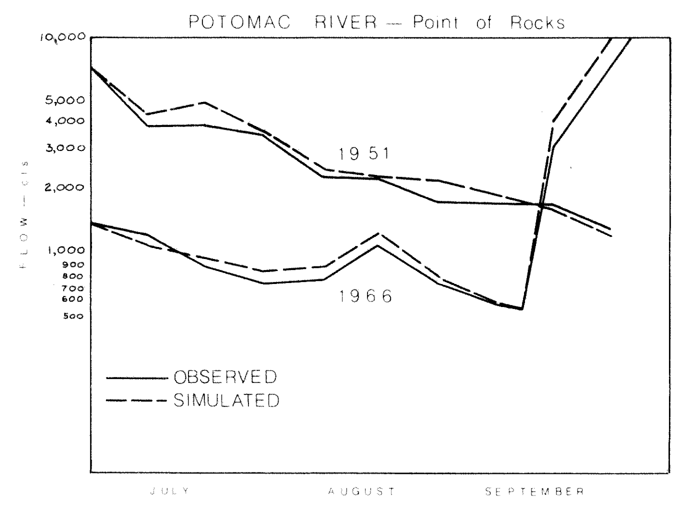

Figure 3. Potomac River Streamflow – 1951 and 1966.

The Sacramento model, illustrated in Figure 4, provides a conceptual accounting of the precipitation input to a drainage basin. The model represents the storage and movement of water beneath the surface, the transmission of ground water to stream channels, and the evaporation and transpiration of water from the soil and stream channel.

TABLE 2. Summary Statistics for Central and Southern Appalachian Rivers.

	DA (sq. mi.)	Q_A (cfsm)	Q_{90}/Q_A	Drainage
1) Flat-Lying Sedimentary Rocks				
East Branch Delaware River	163	1.92	0.09	Delaware River
Pine Creek	944	1.45	0.07	Susquehanna River
Youghiogheny River	295	2.23	0.07	Monongahela River
Allegheny River	550	1.71	0.08	Allegheny River
Greenbrier River	540	1.66	0.06	New River
S.F. Kentucky River	722	1.60	0.03	Kentucky River
Cumberland River	374	1.95	0.07	Tennessee River
2) Folded Sedimentary Rocks				
A) Shales and Sandstones				
Jordan Creek	76	1.50	0.09	Delaware River
Bald Eagle Creek	44	1.72	0.09	Susquehanna River
Aughwick Creek	205	1.25	0.06	Susquehanna River
Back Creek	134	1.37	0.06	James River
Calfpasture River	144	1.12	0.04	James River
B) Carbonate Rocks				
Little Lehigh River	81	1.21	0.37	Delaware River
Yellow Breeches Creek	216	1.34	0.38	Susquehanna River
Conodoquinet Creek	470	1.22	0.20	Susquehanna River
Little Juniata River	220	1.75	0.22	Susquehanna River
Kerrs Creek	35	0.95	0.21	James River
Reed Creek	247	1.13	0.27	New River
S.F. Holston River	301	1.50	0.23	Tennessee River
Nolichucky River	805	1.76	0.30	Tennessee River
3) Metasedimentary and Igneous Rocks				
Chester Creek	61	1.48	0.29	Delaware River
Deer Creek	94	1.36	0.34	Susquehanna River
South Branch Patapsco River	64	1.14	0.25	Patapsco River
North Mayo River	108	1.24	0.36	Roanoke River
S.F. New River	207	2.13	0.40	New River
French Broad River	68	3.59	0.38	Tennessee River
South Yadkin River	306	1.15	0.35	Pee Dee River
Chattooga River	207	3.28	0.37	Savannah River

Soil moisture storage is represented in the model by upper zone and lower zone storages. Each of these zones is further subdivided into tension water and free water storages. Traditional components of hydrograph separation can be interpreted as drainage from specific storages in the model. Output from the lower zone free water storages can be interpreted as baseflow. Output from upper zone free water into the stream channel can be interpreted as interflow. Precipitation in excess of the storage and drainage capacity of the upper zone, which is transmitted directly to the stream channel, can be interpreted as overland flow. A detailed description of the Sacramento model can be found in Burnash and Ferral (1972) and Peck (1976).

The main parameters of the Sacramento model are maximum storage capacities and drainage rates. It will be recalled that a conclusion of the previous section was that spatial variability of low streamflow in the Potomac River basin could be explained largely in terms of ground water storage capacity and permeability. The form of the Sacramento model is thus attractive in terms of its consistency with physical features of the Potomac River basin.

The Potomac River basin was segmented into 24 subregions for which the Sacramento model was calibrated. A hydrologic routing model, lag/K (Linsley, *et al.*, 1972), is used to route the outflow from one basin to downstream segments. Segmentation of the basin was based in part on the location of streamflow gages. Another goal of segmentation was to provide regions of homogeneous hydrologic properties. This was done by utilizing the results discussed in the section concerning hydrologic provinces. As an aside, we note that an important potential application of a hydrologic province map such as the one presented in Figure 1 is obtaining "good" initial estimates for Sacramento model parameters for uncalibrated areas. For example, the results presented in Figure 1 and Tables 1 and 2 (along with the geologic map of Pennsylvania) suggest that the calibrated

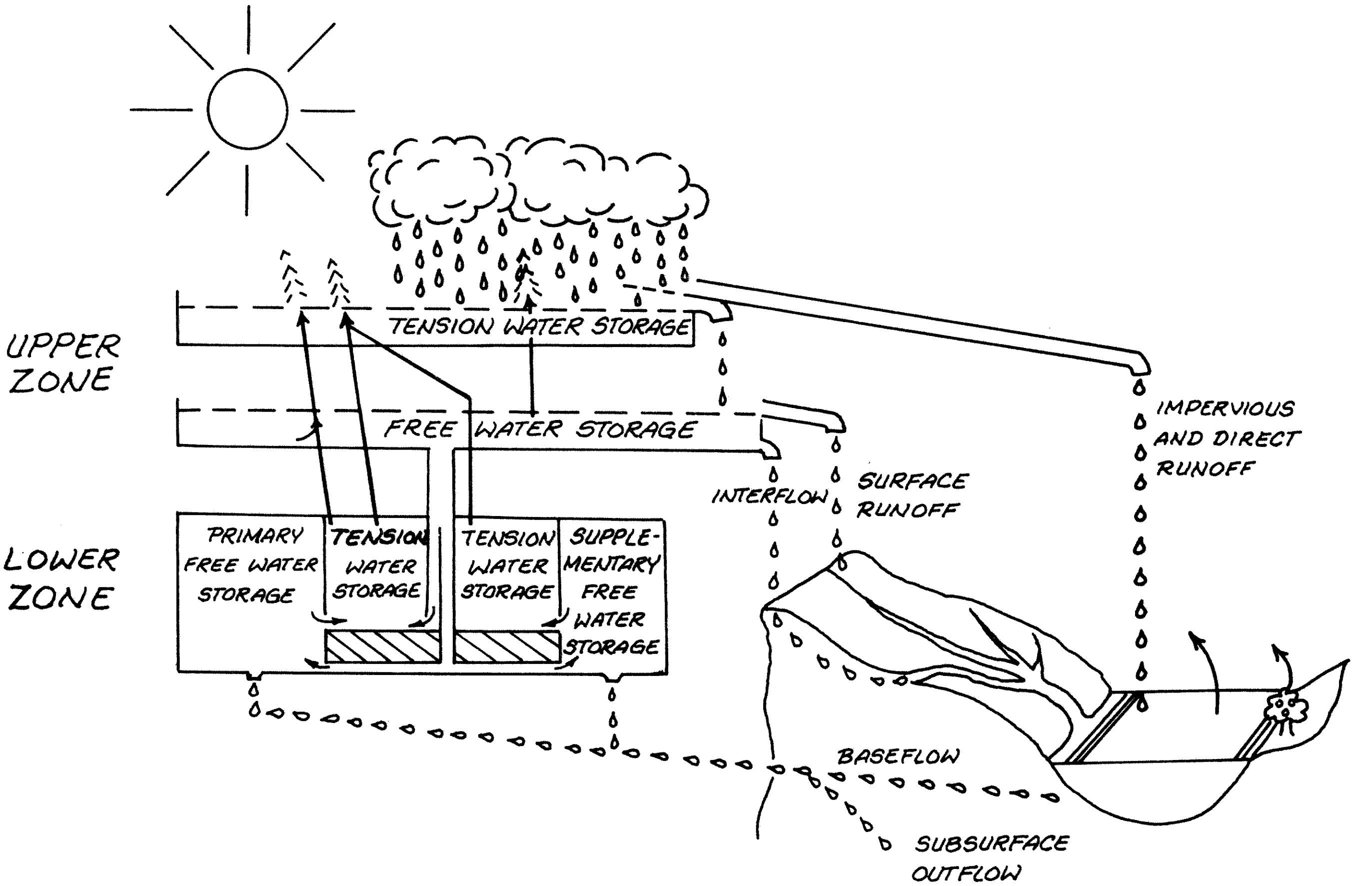

Figure 4. Illustration of the Sacramento Model.

parameters for Antietam Creek in the Potomac River basin would be good initial estimates for the parameters of Yellow Breeches Creek in the Susquehanna River basin and Little Lehigh Creek in the Delaware River basin.

The procedure which is used to convert the hydrologic models discussed above into a forecast system is the Extended Streamflow Prediction (ESP) component of NWSRFS. The ESP procedure, as applied to the Potomac River basin, incorporates current information pertaining to soil moisture conditions by using "current" storages in the Sacramento model as the starting point in a simulation of streamflow (thus storages in the Sacramento model must be regularly updated with observed precipitation). In simulating future streamflow the ESP procedure uses historical precipitation data.

Table 3 illustrates the main features of the procedure. This table is produced from an ESP forecast of minimum mean daily flow of the Potomac River for the period May 1, 1982 to October 1, 1982. Twenty-four Years (1951-1974) of historical precipitation data (restricted to the period May 1-October 1) are used to simulate 24 streamflow sequences. The minimum values for each year are listed in Table 3 under "Conditional Simulation." Each simulation begins with the same Sacramento soil moisture storages, namely the storages of May 1, 1982. Comparison of the simulated values with the observed values indicates that the risk of streamflow falling to the levels of the mid-1960s in 1982 is small.

APPLICATION OF THE FORECAST SYSTEM TO DROUGHT MANAGEMENT

The principal sources of water for the Washington Metropolitan Area (WMA) are the Potomac River, two local reservoir systems, and two upstream reservoirs (for which the travel time to the WMA is approximately five days). Palmer, *et al.* (1982), concluded that the WMA water needs could be met (beyond the year 2000) without constructing new reservoirs if available resources were jointly operated. The efficiency of joint operation of WMA water supplies is due in part to the regional variability of supplies. For example, the two local reservoir system, although separated by a short distance, have very different supply characteristics due to the fact that one is underlain by Triassic shales, which are flashy and have very low baseflow, while the other is underlain by high baseflow metasedimentary rocks. One of the conclusions reported by Palmer, *et al.* (1982), was that streamflow forecasting should play a central role in drought management.

TABLE 3. Sample ESP Output From Forecast of Minimum Daily Flow of Potomac River – May 1, 1982 to October 1, 1982.

ESP Forecast: Minimum Daily Flow for Potomac River – May 1, 1982 to October 1, 1982		
Water Year	**Conditional Simulation in CFS**	**Observed in CFS**
1951	1290	1310
1952	1823	2110
1953	1385	1200
1954	1569	1080
1955	2196	1460
1956	1806	1860
1957	1121	806
1958	1420	1810
1959	1208	787
1960	1871	1660
1961	1403	1310
1962	1173	1050
1963	982	880
1964	974	665
1965	1125	734
1966	890	547
1967	1928	1640
1968	1621	1010
1969	1854	885
1970	1405	1480
1971	2183	1810
1972	1989	2160
1973	1640	2270
1974	1560	1740
Mean	1517	1344
Standard Deviation	373	498

As indicated in the previous section, the forecast system that has been developed for drought management in the Potomac River basin is based on the ESP procedure. Operating rules for reservoirs, however, are not based directly on probabilistic forecasts of minimum daily flow (such as shown in Table 3) but rather on the probability of meeting demands and refilling reservoirs. The transition from an ESP forecast involving flow related variables such as minimum daily flow or total flow volume to an ESP forecast of meeting demands is accomplished by linking ESP to a model which simulates the water supply system of the basin. This is done by using the simulated streamflow sequences of ESP as input to the water supply model. Thus for the forecast period used in Table 3, 24 sequences of May 1-October 1 streamflow for five sites (Potomac River and inflow to four reservoirs) are used as input to a water supply model producing, for example, 24 values of total shortages. The 24 values of shortages are then used to produce a probability distribution of shortages for the period May 1, 1982 to October 1, 1982.

The CO-OP model, which simulates daily water supply operations in the Potomac River basin, is used in conjunction with ESP to form a drought management system. CO-OP has as its predecessor the PRISM model developed by Palmer (Palmer, *et al.*, 1981). PRISM has been extensively used as a water supply planning tool. The CO-OP model serves both as a planning tool and, through its link with ESP, as an operational model.

SUMMARY AND CONCLUSIONS

Low streamflow regimen in the Potomac River basin is shown to be strongly associated with geologic features of the basin. The sharp hydrologic contrasts between regions draining shale, metasedimentary rocks, and carbonate rocks are not peculiar to the Potomac River basin, but are generally valid for the Central and Southern Appalachians.

The Sacramento Soil Moisture Accounting Model is the central component of the streamflow forecasting system developed for the Potomac River basin. The Sacramento model is especially appealing in that its parameters have physical interpretations which are consistent with the results discussed in the section on "Hydrogeology of Low Streamflow in the Potomac River Basin." As an extension of this observation, we suggest that hydrologic province maps such as presented in Figure 1 may be useful in obtaining good initial estimates of Sacramento model parameters for uncalibrated areas from the calibrated Potomac River basin parameters.

Our final topic concerns application of the streamflow forecasting system to water supply management. The CO-OP model simulates, on a daily time step, the principal water supply and demand features of the Washington Metropolitan Area. The CO-OP model is linked with the ESP procedure to produce a forecasting tool for water supply management during drought periods. In particular the system produces probabilities of water shortage and refilling reservoirs.

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