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**A NUMERICAL INDICATOR  
OF WATER CONDITIONS  
FOR NORTHERN DELAWARE**

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INTRODUCTION

Numerical indicators, or indices, are widely used to measure the status of complex relationships. As such, indices have become accepted by researchers and the public in such disparate fields as economics, air quality, and weather. In this paper we explore the formulation of an indicator of water conditions in northern Delaware, propose formulas that may be applicable, and test those proposals against long-term records of basic data.

The need for a simple indicator of water supply conditions in Delaware, and especially in New Castle County, has become increasingly apparent. The Delaware River Basin Commission (DRBC) has applied an index to the Delaware River Basin, which includes a portion of Delaware. The Governor's Drought Advisory Committee has sought an objective means of determining when water supply conditions might warrant conservation measures. Discussions of the subject have also been held within the State Comprehensive Water Management Committee. We are pleased to acknowledge the constructive comments of these groups and of other colleagues with whom we have discussed this work. George R. Phillips of the Delaware Department of Natural Resources and Environmental Control (DNREC) was especially helpful in analyzing the practical implications of using the index presented in this paper. John R. Mather, Delaware State Climatologist, provided Palmer Drought Severity Index values with the cooperation of the National Weather Service. This report was reviewed by Richard N. Benson and John H. Talley of the Delaware Geological Survey (DGS).

## WATER OCCURRENCE AND USE IN DELAWARE

Water is generally abundant in the State, but supply is restricted by natural geologic conditions in some areas, by contamination in others, and is dependent on precipitation. Because of geologic conditions and heavy usage, water is generally less abundant in New Castle County than elsewhere in Delaware.

Water supply is used here to refer to water available for private, public, and commercial use. Lack of adequate precipitation can also result in serious negative effects on agriculture because of reduced soil moisture. Agricultural conditions tend to relate directly and rather immediately to rainfall through soil moisture. It is possible to have an agricultural "drought" that does not as seriously affect general water supplies. It is the condition of the general water supplies that is considered here.

Delaware's water supplies come from precipitation within the boundaries of the State, except for the contribution to stream flow from nearby Pennsylvania and Maryland. Some ground-water supplies are also common to both Maryland and Pennsylvania. The precipitation is captured by man from the streams generally by surface impoundments and from subsurface storage in aquifers by means of wells. Surface water is used primarily within the Piedmont Province of northern Delaware. Ground water is the principal source of supply elsewhere in the State.

The surface water occurring in streams consists of (1) overland runoff from precipitation and (2) a base flow component that is contributed by water seeping from subsurface storage (ground water). The long-term flow of a stream is generally sustained by the base-flow or ground-water runoff component.

Ground water, on the other hand, represents that portion of rainfall that seeps into the ground and occurs in the pore spaces between grains of rock material and within fractures and voids in massive rocks. Because large quantities of water can be stored in the small openings in rocks beneath the surface, the effects of fluctuating precipitation are dampened. When rain is not falling or has not fallen in the immediate past, water may still be obtained by means of wells from the supplies that are stored in the rocks. Changes in the amount of water in storage in the subsurface reservoirs, or aquifers, are indicated by

the fluctuations in height to which water will rise in a well tapping that aquifer. The height of the column of water, which is called the "head," is generally measured as a vertical distance from the land surface immediately surrounding the well. The actual quantity of water available depends also on the saturated volume of the rock mass, the porosity, and the permeability.

In most of the eastern United States the amount of water available to an aquifer from precipitation commonly exceeds the amount withdrawn by wells or which naturally flows away from the point of recharge. Excess water from storage in near-surface aquifers runs into streams to provide base flow. If a stream flows over an aquifer that is not saturated, water from the stream may seep into storage in the aquifer. In these ways the waters occurring on the surface and in the ground are interrelated. Nevertheless, because their supply characteristics differ and because the means of obtaining supplies from water occurring above and within the ground are also different, surface water and ground water are considered for many practical purposes to be separate entities.

The amount of water flowing in a stream is measured by determining the velocity of its flow through a measured cross-sectional area. Where velocity and cross-section are known for a variety of flow conditions, the volume is related to the height of the water in the stream by graphs or tables. Stream heights, and therefore the amount of water being discharged, are continuously recorded for thirteen streams in Delaware. The installations used to make these measurements are known as gaging stations.

Ground-water conditions are, in part, assessed by means of observation wells dedicated to that purpose, in which heads are measured either continuously or on a periodic basis. Twenty-eight observation wells are operated by the DGS and the U. S. Geological Survey (USGS) to evaluate water conditions in ten aquifers throughout Delaware. From the analysis of records from these relatively few stream gages and from observation wells it is possible to reliably extrapolate water conditions for other, unmeasured, aquifers and streams in the State.

## INDICATORS OF WATER CONDITIONS

The principal factors in determining the availability of water are precipitation, streamflow, and ground-water levels in aquifers. Data from rain gages, stream gages, and observation wells have been collected for many years, resulting in massive compilations of basic data that have served well in allowing experts to evaluate water availability. The purpose of this study is to attempt to reduce these data to simple indicators that will summarize water conditions in northern Delaware at any given time.

Other methods or indices for measuring water availability have been developed. One such method is the Palmer Drought Severity Index (PDSI) (Palmer, 1965). This index is routinely calculated for northern and southern Delaware by the National Weather Service. The index reflects, among other variables, the soil moisture value for any given time period (Appendix). As farming is the prime industry in much of Kent County and most of Sussex County, the PDSI appears to be an adequate indicator of water conditions for these areas. During summer months the index is available weekly from the National Weather Service and would probably serve well as an overall indicator of water conditions in Sussex County and most of Kent County. If the PDSI is to be used by management agencies as an action tool then some discretion is needed to avoid general alarm when only crops may be affected. In New Castle County an indicator that reflects overall water availability appears to be preferable to the Palmer Index.

### DESIRABLE PROPERTIES OF A WATER CONDITIONS INDEX

The Delaware Geological Survey sought an index satisfying the following conditions:

1. Calculable from existing data. Much information has been compiled over many years about factors influencing water availability. Ideally, an index should utilize this existing information so that new field installations to collect data will not be necessary and so that comparisons can be made throughout the historic period of record.
2. A simple, numerical expression. An index should be a numerical value readily understood by all disciplines concerned with water and should also be

useful to the general public. The value should be capable of being computed readily at frequent intervals.

3. Applicable to varying conditions. Sensitivity over a wide range of conditions is important if the index is to accurately reflect the wide variations in water availability that, through experience, are known to occur.
4. Need for water. In order to be valid an index should reflect the demands for water within the area that it is used to characterize. The relationship between natural availability (as modified by storage) and demand determines the adequacy of supply.
5. Verification by testing. A reliable index must, when calculated for past periods of record, agree with trends indicated by other long-term water data. An index may be tested by comparing it with actual records of rainfall, streamflow, and ground-water conditions.
6. Agreement with past experience. A further test of the validity of an index can be made by comparing it to actual experience. A valid index will indicate, for example, when there has been general agreement that drought conditions have existed as indicated by failures in water supply.

The factors then that appear to be applicable to the formulation of an index are: (1) precipitation, (2) streamflow, (3) ground-water levels, and (4) the demand for water. The index proposed here is designed specifically for New Castle County because of the intensive use of both ground and surface water and because of the variety of water users.

#### DERIVATION OF A WATER CONDITIONS INDEX FOR NEW CASTLE COUNTY

On the basis of the considerations stated it is proposed that water conditions in New Castle County be characterized by precipitation, streamflow, ground-water level, and the population of the area. The first three factors indicate water availability and the last the demand for water.

The factors can be related in the following expression:

$$\text{Precipitation} \times \text{Streamflow} \times \text{Water Level} \div \text{Population} \\ = \text{An Index Number}$$

The precipitation factor proposed is the cumulative six-month antecedent precipitation as measured by the U. S. Weather Service at the Greater Wilmington Airport. Rainfall in a given storm is unevenly distributed, but over a period of record including many storms a single point of measurement may suffice to characterize the amount of water from this source for an area the size of New Castle County. The National Weather Service station at the Greater Wilmington Airport was used because it is a permanent and reliable source of long-term data. Because precipitation fluctuates considerably in short periods of time, the accumulated amount during a period of time should be utilized. The six-month period represents one-half of a water-year and integrates relatively wet and dry seasonal periods.

Seven stream gages are operated in New Castle County, but the use of a single station is advocated in order to comply with the criterion of simplicity. Comparisons of records indicate that trends in streamflow conditions are similar throughout New Castle County. The stream gage on Brandywine Creek at Wilmington was used because (1) the gage has supplied reliable long-term records (35 years of record), (2) Brandywine Creek is the largest stream in the County and less subject to wide variations in streamflow than smaller streams, and (3) the largest surface water withdrawals in New Castle County are from Brandywine Creek. The monthly average flow of the Brandywine as gaged at Wilmington is used to reasonably reflect antecedent conditions and to dampen variations in flow due to a single precipitation event.

Comparisons of levels in water-table observation wells throughout New Castle County indicate that a single well, strategically placed, reasonably represents ground-water storage conditions. Artesian (confined) aquifer measurements are not used because they vary relatively little under short-term natural conditions and because heads are influenced by pumpage occurring over wide areas. Observation well Db24-10, located east of Newark, records water-table levels in the Columbia Formation and has about a 24-year period of record. The values of ground-water level measurements increase when water levels decline because in this case the levels are referred to land surface. This is opposite to

the numerical trends for the other factors utilized and, therefore, must be converted in numerical sign by subtracting the head measurement from an arbitrarily selected value, in this case, 100.

Some factor reflecting the demand for water is incorporated in the formula in order to indicate the availability of supply relative to requirements. Water demand in northern Delaware is roughly proportional to the population, suggesting that population itself may be used to characterize the demand for water. Per capita consumption of water has increased, but not markedly so, over the 30-year period of record considered desirable for the purposes of calculating an index. Moreover, per capita demand appears to be leveling off due to public consciousness of the need to conserve water. Population figures from census data (Office of Management, Budget, and Planning, 1980) are also more readily available than are measurements of the actual amount of water used over long periods.

A formula initially considered was:

$$\frac{\text{PPT} \times \text{S} \times (100 - \text{L})}{\text{POP}} = \text{I} \quad (1)$$

Where: PPT = Six-month antecedent precipitation, in inches.

S = Current monthly average streamflow of Brandywine Creek, in cubic feet per second.

L = Level of water in observation well Db24-10, in feet (single reading).

POP = Population of New Castle County during the year for which calculation is made.

I = Index of water availability (units ignored).

Substituting reasonable figures yields:  $20 \times 200 \times (100 - 10) \div 350,000 =$  approximately 1. Thus, coincidentally, these nominal values equal approximately unity, suggesting that a value significantly less than unity would indicate adverse supply conditions whereas a value significantly greater than unity would indicate abundant supplies.

This formula yields values satisfying the conditions set forth above; however, the index values tend to rise to unduly high numbers when streamflow, which varies through several orders of magnitude, is also high. That is, the

formula is overly sensitive to high streamflow conditions. In order to correct this the square root of streamflow is used. In the final form of the equation the resulting value is multiplied by 100 to give simple whole numbers:

$$\frac{\text{PPT} \times \sqrt{\text{S}} \times (100-\text{L})}{\text{POP}} \times 100 = \text{I} \quad (2)$$

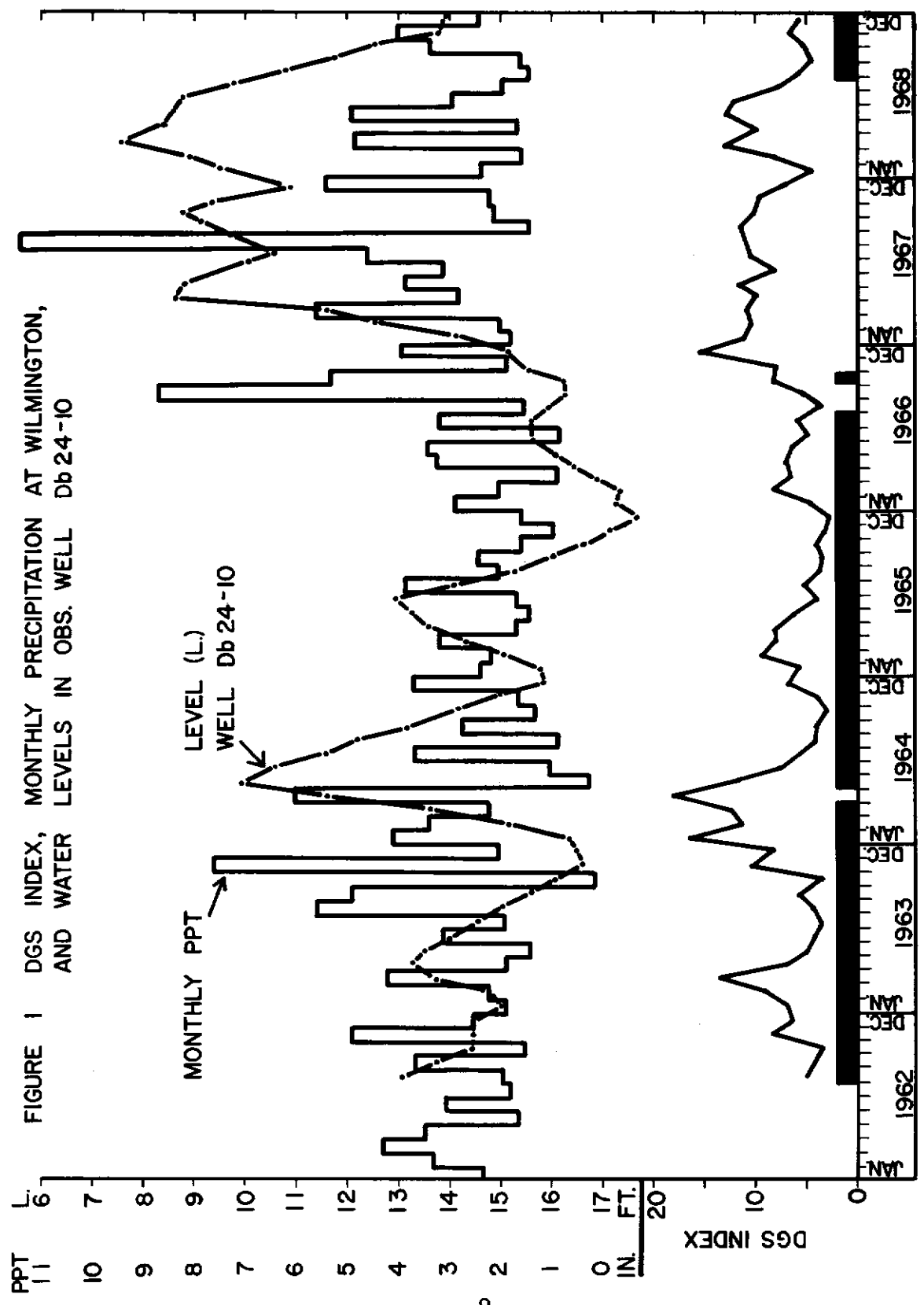
#### RESULTS OF INDEX CALCULATIONS

The final equation (2) was used to calculate the monthly index for three test periods known to be, respectively, "wet," "dry," and "normal." The results show satisfactory agreement with the known hydrologic conditions. Monthly indices were then calculated for the period August 1962 through July 1981 (observation well data were not available before 1962). This longer record period spans a variety of hydrologic conditions, including at least two periods when water supply was considered deficient. The results are shown in Figure 1.

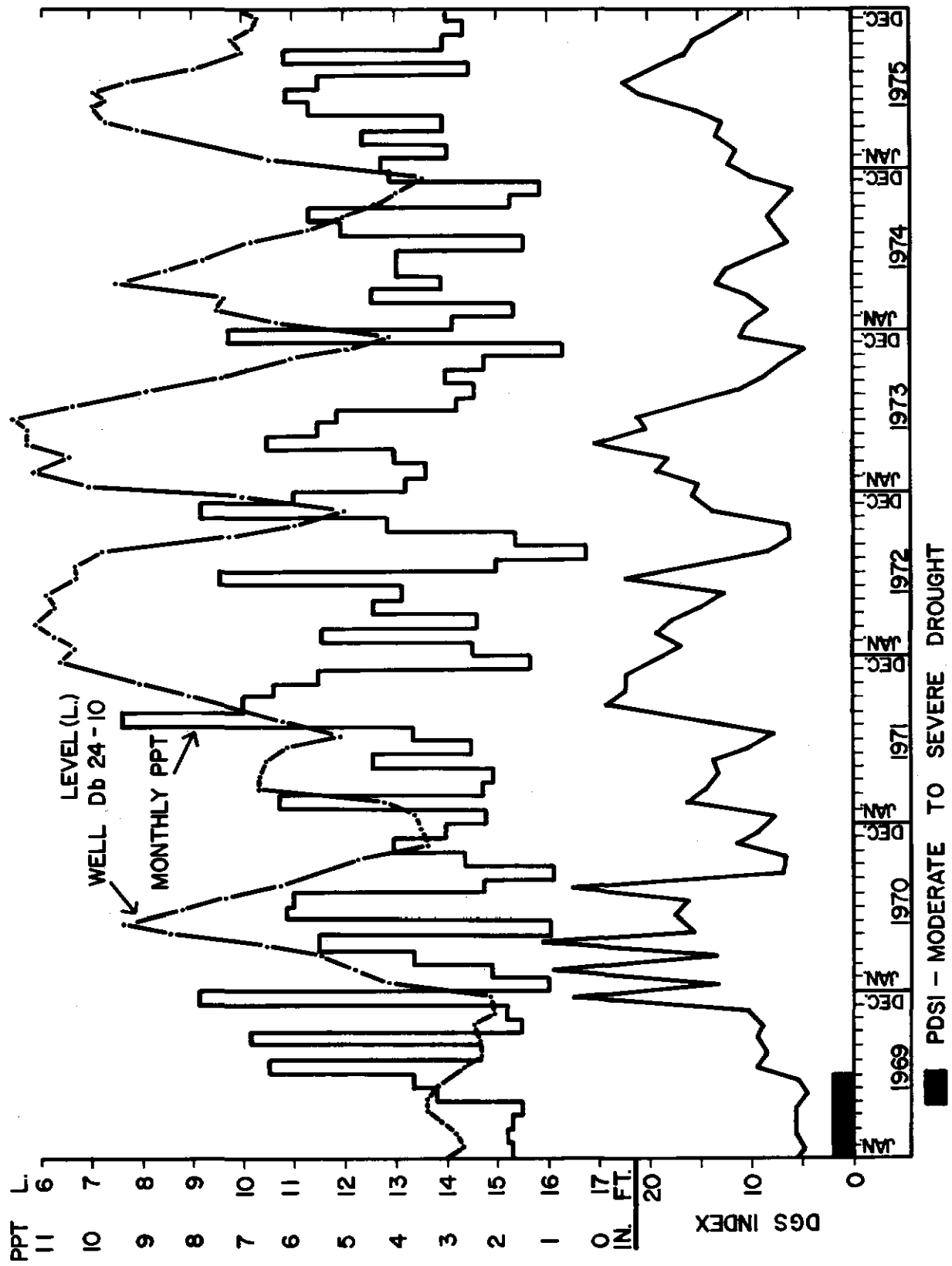
For the time period indicated in Figure 1, the index appears to roughly track ground-water levels on a seasonal basis with shorter variations imposed on the curve by streamflow and precipitation (streamflow not plotted on Figure 1). The selection of an index value below which local water supplies can be termed deficient is somewhat arbitrary. Figure 2 shows that an average index tends to fall approximately between about 7.5 and 11. The drought of 1962-1966 produced indices as low as 3 during late summer and early fall months. The summer of 1980 and winter of 1981 were generally considered to be water deficient throughout Delaware and the entire Delaware River Basin. In October 1980 the DRBC issued a "drought warning" and in January 1981 declared that a "drought" condition existed. These actions were based on available storage in New York City reservoirs located in the Delaware River Basin (the "rule curve"). Indices derived by the method described herein were approximately 4.5 at the time of the warning and approximately 2.5 at the time of the drought declaration.

It appears that values of this index between 3.0 and 5.0 warn of potential water shortages. Values below 3.0 indicate that water supplies are inadequate to sustain normal use.

FIGURE 1 DGS INDEX, MONTHLY PRECIPITATION AT WILMINGTON,  
AND WATER LEVELS IN OBS. WELL Db 24-10



■ PDSI — MODERATE TO SEVERE DROUGHT



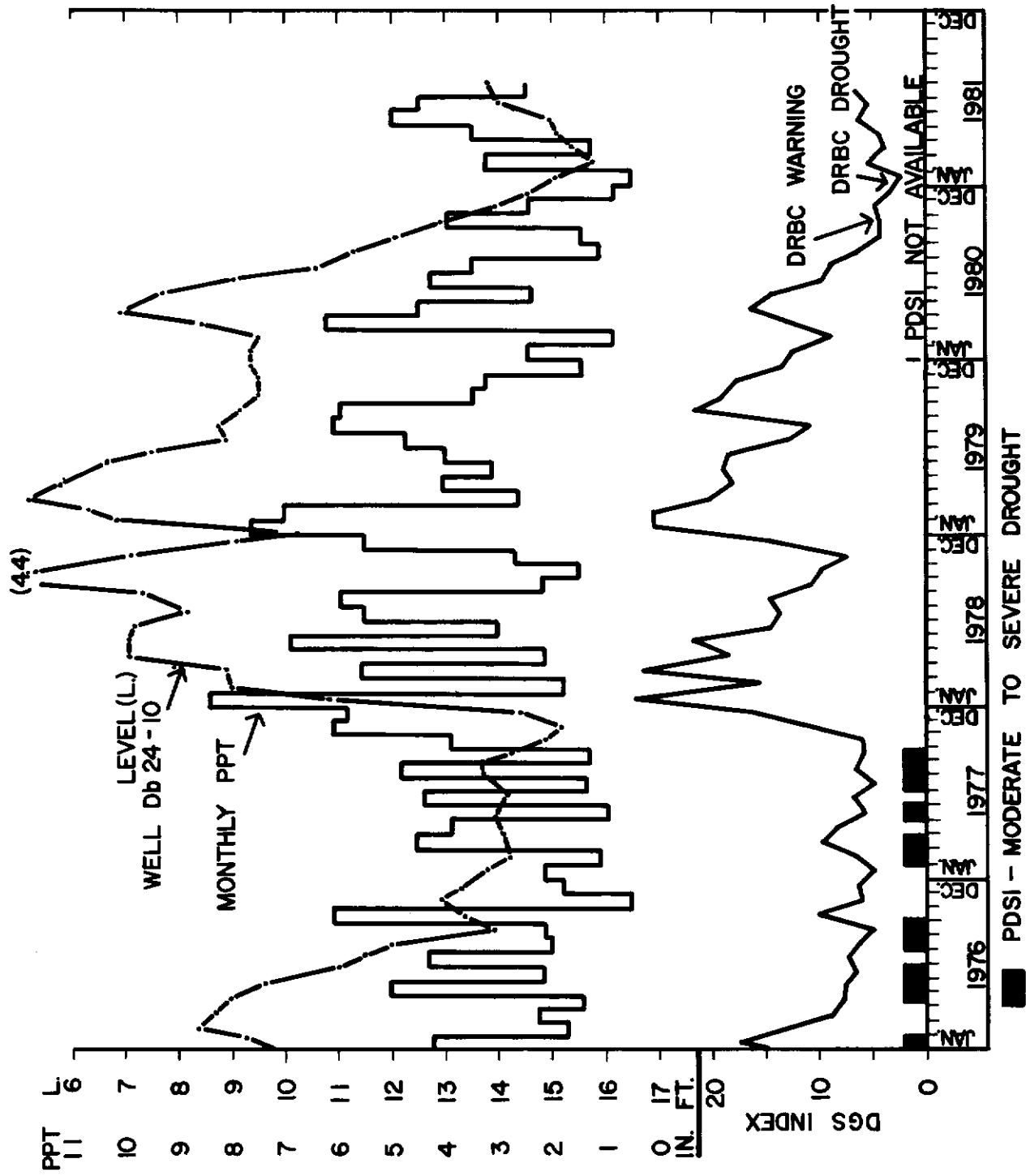
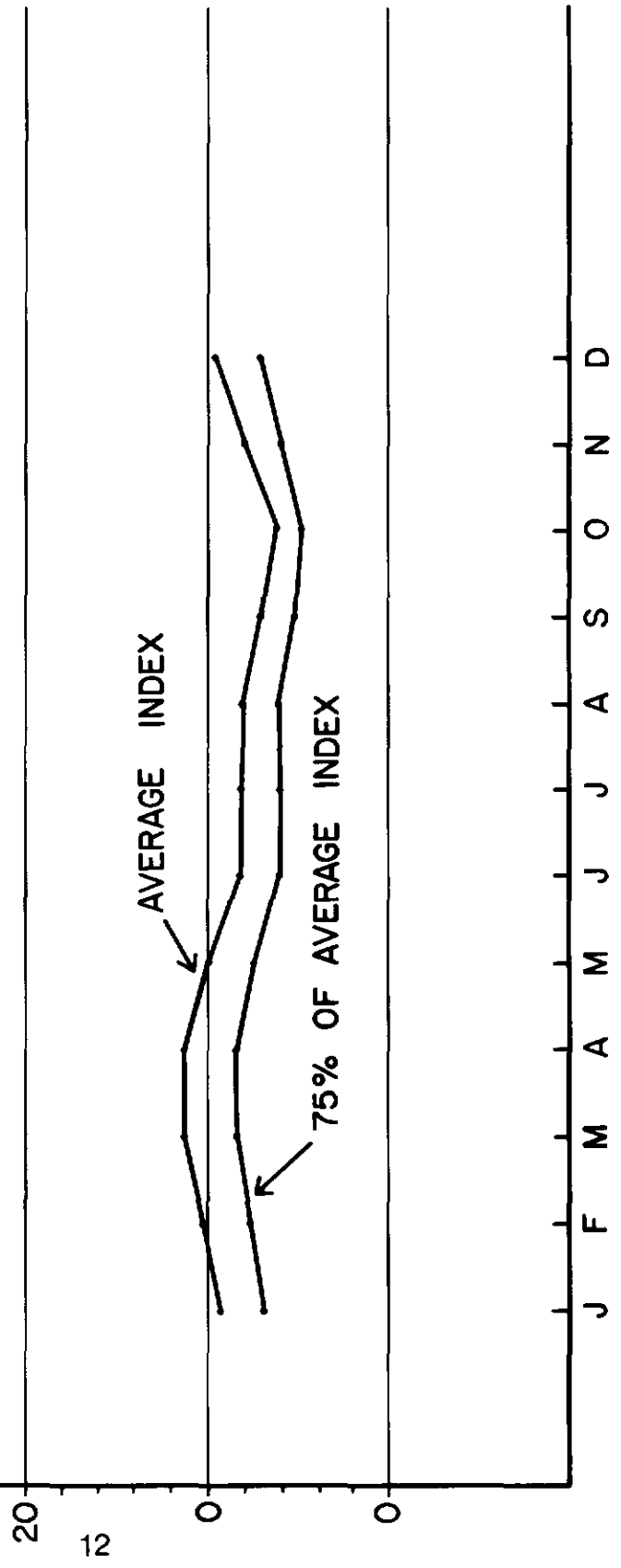


FIGURE 2. DGS INDEX BASED ON POPULATION, AVERAGE VALUES OF PRECIPITATION, WATER LEVELS, AND STREAMFLOW FOR BASE PERIODS INDICATED.

PRECIPITATION BASE PERIOD, 1941 - 70.  
 GROUND - WATER LEVEL BASE PERIOD IN WELL Db 24 - 10, 1962 - 70.  
 BRANDYWINE STREAM FLOW BASE PERIOD, 1947 - 70.



20

12

0

0

## COMPARISON WITH PALMER DROUGHT SEVERITY INDEX

Monthly indices for selected time periods derived by the method described here were plotted against the PDSI in order to see what relationship (if any) exists between the two. Figure 3 seems to indicate a correlation between the two indices. However, it is apparent that the data have a broad scatter, particularly at the drought or low end of the scale. The PDSI can change rapidly from month to month, particularly in the summer, which accounts for some of the scatter in Figure 3. The DGS index is less sensitive to short-term changes in precipitation and, unlike the PDSI, is not dependent on soil moisture values. Correlation statistics could be calculated for the two indices, but this does not appear to be essential to the purpose of the present study.

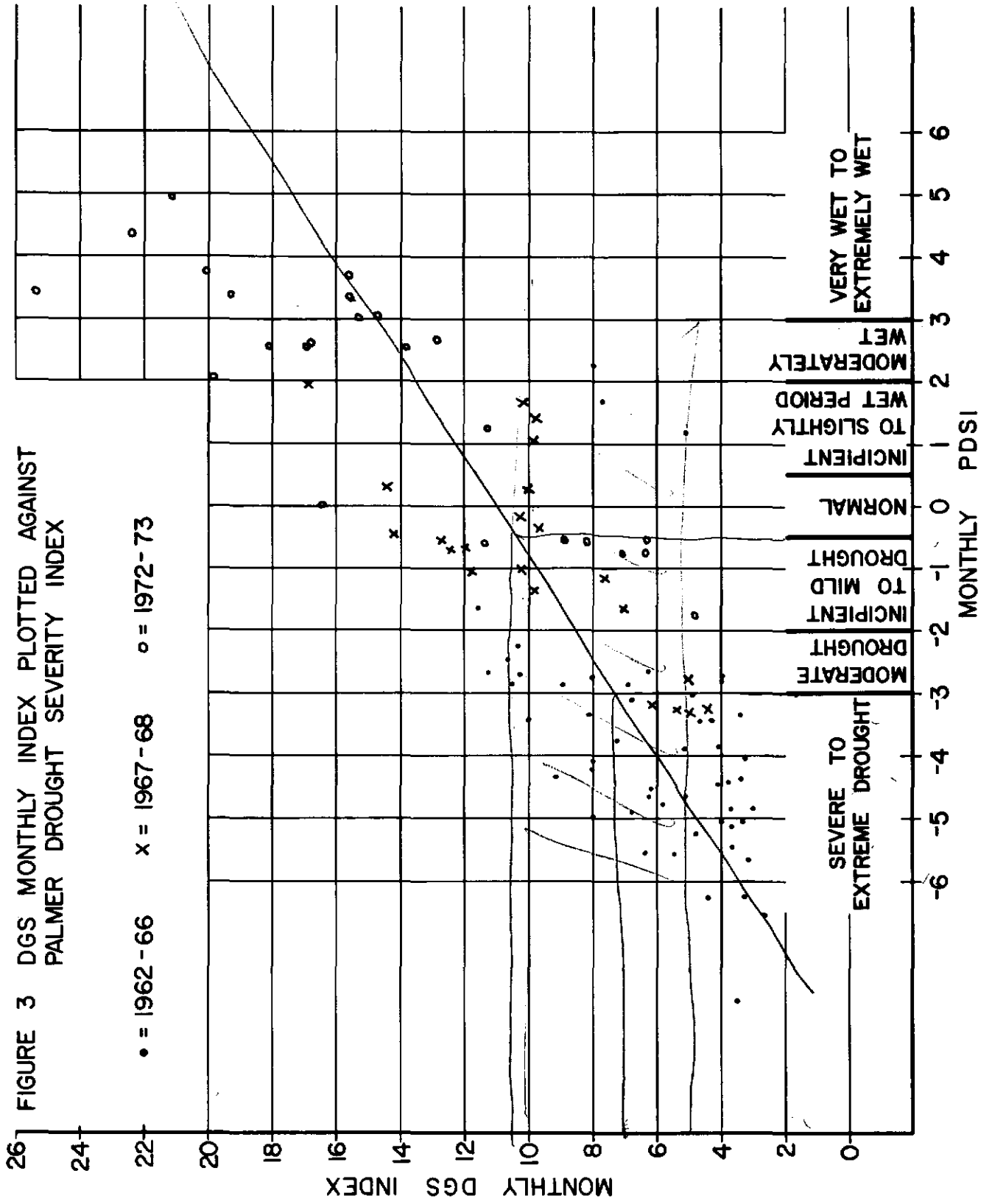
The PDSI is also broken into a number of classes of droughts and wet periods, and "normal" values occupy a rather limited range of index values (Figure 3). In the DGS index there is no corresponding emphasis on wet periods as the index was designed mainly to signal dry periods.

## QUALIFICATIONS AND REFINEMENTS

Further refinements may be made in the selection and use of data used in the index calculations. Rainfall could be averaged for two or, preferably, three stations. In some instances streamflow in the Brandywine may more accurately reflect conditions to the north of Delaware than conditions within Delaware. Therefore, some discretion is necessary in the use of these data. Per capita consumption of water may increase, which would decrease availability without changes in natural conditions. For the moment, the population of northern Delaware appears to be relatively stable, and a factor reflecting population might be omitted from an index calculation for a short-term comparison of water availability. However, population growth would be a key factor in long-term comparisons of available water supply.

Clearly, compromises and simplifications have been employed in deriving the water conditions index described herein. Specialists may prefer refinements. Any index must, however, be applied with good judgment. The method described is simple, the data used are easily obtained, and it reflects water needs.

FIGURE 3 DGS MONTHLY INDEX PLOTTED AGAINST PALMER DROUGHT SEVERITY INDEX



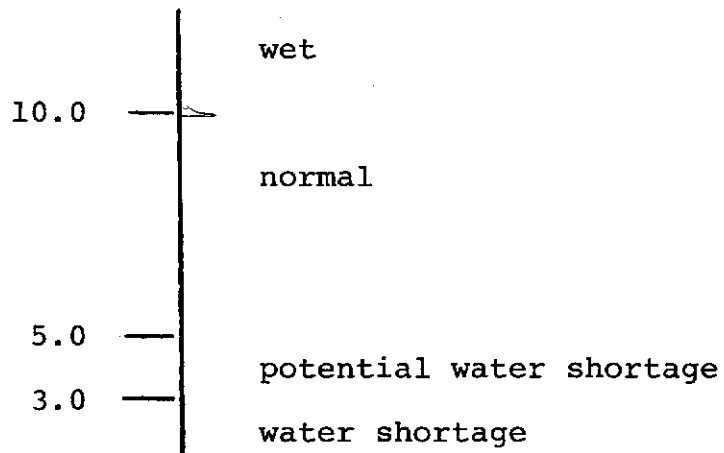
## CONCLUSIONS

The formula derived:

$$\frac{\text{PPT} \times \sqrt{\text{S}} \times (100-\text{L})}{\text{POP}} \times 100 = \text{I}$$

yields a water condition index number that agrees well with specific data for the period 1962-1981 and reflects actual experience with relatively wet and dry intervals. The index satisfies a variety of criteria and provides a useful general characterization of water conditions in northern Delaware.

The same index may be applied as an objective aid in identifying times of low water availability when drought warnings or a drought may be declared which would require institution of specific conservation measures. We suggest as a guideline the following table of index values, based on a qualitative preception of water availability:



Experience with the index may indicate the need for refinements in calculations and in the correlation of values with actual conditions.

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## APPENDIX

The Palmer Drought Severity Index (PDSI) for any month,  $i$ , is determined by:

$$PDSI_i = 0.897PDSI_{i-1} + \frac{1}{3} Z_i$$

where:

$$Z_i = k_j (P_i - (\alpha_j E_i + \beta_j G_i + \gamma_j R_i - \delta_j L_i))$$

- $i$  = a particular month in a series of months
- $j$  = one of the 12 calendar months
- $P_i$  = precipitation for month  $i$
- $E_i$  = potential evaporation for month  $i$
- $G_i$  = soil moisture recharge for month  $i$
- $R_i$  = surface runoff for month  $i$
- $L_i$  = soil moisture loss for month  $i$
- $\alpha_j$  = ratio of actual to potential magnitude for E
- $\beta_j^*$  = ratio of actual to potential magnitude for G
- $\gamma_j^*$  = ratio of actual to potential magnitude for R
- $\delta_j^*$  = ratio of actual to potential magnitude for L

\*based on standard 30-year climatic period.

and:

$$k_j = \frac{E_j + G_j}{P_j + L_j}$$

where:  $j$  = average values for standard 30-year climatic period.