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HYDROLOGIC IMPACT STUDIES OF ALTERNATIVES TO MEET WATER NEEDS IN SOUTH - CENTRAL PENNSYLVANIA

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ABSTRACT

This paper presents the use of several interrelated models to investigate the potential hydrologic impacts of several proposed water supply alternatives for the South Central Pennsylvania area. The area contains major demand centers in Harrisburg,York, Lancaster, Lebanon, Manheim, Elizabethtown, Ephrata, New Holland, Lititz, Carlisle, and Mechanicsburg, which for the most part depend on local surface waters for their water supply with supplemental withdrawals from the Susquehanna River and from groundwater. Withdrawals from all of these sources could have an impact on the flows in the Susquehanna itself. Since this river is the main source of freshwater to Chesapeake Bay, it was important to assess the relative impact of each of the proposed alternatives on the outflow distribution to the Bay. The scope of the study was limited to the hydrologic aspects of the problem. The models used to evaluate the impacts of the alternatives were:

1. A synthetic streamflow augmentation and generation model to first augment the existing records up to a full 80-years, and second generate a set of 200-year synthetic records which resembled the historical records in their statistics.

2. A linear regression model relating monthly rainfall and evapotranspiration to streamflow in the tributaries was used to evaluate the impact of groundwater withdrawals on surface water flows.

3. A simulation model used as an accounting device to show the impact of the alternatives on the monthly flows at several locations in the area including the outflow of the Susquehanna to Chesapeake Bay.

INTRODUCTION

The objective of this paper is to describe the methodology used in hydrologic investigations carried out on a series of water supply alternatives for the South Central Pennsylvania area (Resource Analysis, Inc., 1974b). The area contains major demand centers in Harrisburg, York, Lancaster, Lebanon, Manheim, Elizabethtown, Ephrata, New Holland, Lititz, Carlisle and Mechanicsburg, Pennsylvania as shown in Figure 1. In general, these communities depend on local surface water for their water supplies, with additional supplies coming from the Susquehanna River and from groundwater. With continuing increases in population in the area, major capital investment in new facilities and water sources will be necessary. Withdrawals from groundwater or local surface water storage may have a different impact on flows in the Susquehanna and its tributaries than withdrawals from the Susquehanna itself. While the area is itself relatively water rich, different withdrawal patterns will lead to changes in the flow characteristics of the local tributaries and to different distributions of outflows from the Susquehanna to Chesapeake Bay. Since a change in the outflow distribution for the main freshwater input to the Bay could have major ecological impacts, this outflow is of significant interest.

Objectives of Study

The primary objective of the study was to assess the relative impact of the proposed alternatives for water supply development on the distribution of monthly outflows from the study area. In addition, estimates of the impacts on low flows in local tributaries were made. Other parts of the study conducted by other contractors dealt with institutional, ecologic, and engineering feasibility considerations. Our study dealt only with hydrologic considerations, i.e., the distribution of outflows from the system and on the tributaries as they are affected by the different alternatives.

Study Area

The study area is shown in Figure 1 and contains all or parts of Cumberland, Adams, York, Dauphin, Lebanon, and Lancaster Counties in the south central part of the Commonwealth of Pennsylvania. Major tributaries to the Susquehanna River in the study area are Swatara, East Conewago, Chickies, and Conestoga Creeks on the east side; and Conodoquinet, Yellow Breeches, West Conewago, and Codorus Creeks on the west side. Present water supply usage and future water demand (year 2020) are shown for each major municipal area in Table 1. The major demand areas include surrounding water companies as well as the new municipalities. In general, Harrisburg (East) presently depends on Clark, Stony, and Swatara Creek sources; Harrisburg (West) on Yellow Breeches, and Conodoquinet Creeks; Mechanicsburg on Yellow Breeches; Elizabethtown and Manheim on Chickies Creek; Lebanon on the Swatara; Lititz and New Holland on groundwater; Ephrata on Conestoga Creek; and York on the Codorus. Only Lancaster presently draws major supplies from the Susquehanna.

Alternatives for Water Supply

A variety of different water supply options exists for the area ranging from all ground and local surface water to all Susquehanna water, as well as combinations of the two. As there is a relatively large amount of water available in the area, the question of importance is which sources should be developed rather than whether it is possible to find the water. For example, Harrisburg (East and West), Mechanicsburg, Lebanon, Elizabethtown, York, Lancaster, and New Holland could go directly to the Susquehanna for additional sources. Alternatively, new or improved impoundments on the Conodoquinet, Swatara, E. Conewago, and W. Conewago Creeks; and the South Branch of Codorus Creek could also be used to supply future water needs. Groundwater in areas like York, Lebanon, Elizabethtown, Ephrata and New Holland could serve their new water needs. To consider the options available a series of alternatives were conceived by the U.S. Army Corps of Engineers and the Commonwealth of Pennsylvania, and developed by the Anderson-Nichols Co. to consider

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combinations of these possibilities. A brief discussion of the alternatives is shown in Appendix A.

Table 1

Water Supply Service Areas and Demands for 1970 and 2020

Major Demand Areas	Municipalities Included	Demand (MGD) 1970	2020
Carlisle	Carlisle Boro and Suburban	3.7	6.9
Mechanicsburg	Millsburg, Grantham, Mechanicsburg W.C.	1.8	6.2
Harrisburg (West)	Riverton W.C.	7.7	19.8
Harrisburg (East)	Harrisburg W.C., Dauphin, Hershey, Middletown, Steeltown	22.4	32.7
Lebanon	Lebanon City, Keystone, Cornwall, Meyerstown, Heidelburg	8.2	16.8
York	Red Lion, Dover Boro, Dover Twp., West Manchester, York W.C.	21.0	40.2
Elizabethtown	Rheems, Elizabethtown, Mount Jay	0.8	3.6
Manheim	Manheim	0.5	0.7
Lancaster	Columbia, Mountville, E. Hempstead, E. Petersburg, Lancaster, Millers	17.4	40.1
Lititz	Lititz	1.0	3.0
Ephrata	Akron, W. Earlham, Ephrata	1.1	2.2
New Holland	Leola, New Holland, Blue Bell	0.7	2.7
Total		86.3	174.9

Outline of Methodology

The information available for this study was the following:

1. Estimates of future demands from municipal and industrial (M&I), agricultural, and consumptive powers cooling users.

2. Monthly gauging records for several locations in the area including the Susquehanna River, Codorus, Conodoquinet, Swatara, W. Conewego, and Conestoga Creeks.

3. Monthly precipitation records at York, Harrisburg, Lancaster, and Lebanon.

4. Configurations for each water supply alternative including reservoir capacities and allocation of demands to sources.

Given this data base, the objective was to assess the hydrologic impacts of each alternative through a simulation study. The following tasks were carried out to evaluate the alternatives:

1. Process the rainfall and streamflow data into the RAI Hydrologic Data Management System (Resource Analysis, Inc., 1974a).

2. Augment the streamflow records to produce a "full" set of records of consistent length to be used for parameter estimation purposes.

3. Estimate the statistical parameters of these records, and generate a set of 200-year synthetic records.

4. Develop a linear regression model relating the effect of groundwater withdrawal on future streamflows. This relation was to be used to assess impacts of groundwater development on local surface water flows.

5. Simulate the operation of the system under both the historical and synthetic streamflow records for each alternative plan in order to assess its reliability and the resulting hydrologic impacts.

The following sections briefly describe each of the above steps. A full discussion of the methodology and results is contained in the final project report, Resource Analysis, Inc. (1974b).

GENERATION OF SYNTHETIC STREAMFLOW RECORDS

Available Streamflow Data

Historical records at eleven gauging sites in or near the study area were available. The length of these records is shown on Figure 2. All stations had at least 40 years of observations except for Station 5755 which had 32 years, and Stations 5745 and 5765 which had some small gaps.

An improvement in the parameter estimates was obtained by extending or "filling-in" the shorter records by correlation with nearby stations. Regression analysis has been frequently used to carry out the augmentation of records. The theory on which these procedures are based has been discussed by Fiering (1962), Matalas and Jacobs (1964), and Gilroy (1970), and will only be briefly summarized here.

The streamflow data at the gauging stations with the shorter record y_t, are related to the data at other sites x_{1t}, x_{2t}, ..., x_{pt}, through a linear regression model given by:

$$y_t = a + b_1 x_{1t} + b_2 x_{2t} + \dots + b_p x_{pt} + e_t \qquad (1)$$

where e_t is a standardized normal random deviate. The parameters of this model: a, b_1, b_2, ..., and b_p are computed from the available data through standard least square procedures for regression analysis. These values are then used in the model to estimate the streamflow at station y where these values are missing. Similarly, in the case of shorter records, the record at station y is extended by this same procedure from the longer observed nearby or related records.

Three data augmentation runs were carried out. These are described in Table 2. The objective of the first run was to obtain a full forty years. Run No. 2 extended the 8 stations to 73 years. Finally in Run No. 3, the nine shorter records were extended an additional seven years by regression from the longest record. The final output was a set of 80-year records at all eleven stations.

Table 2

Data Augmentation

Run No.	Stations Augmented	Other Stations	Period Augmented	Period of Estimation
1	5145 5755 5765	5730 5705 5700 5750 5740	10/1932 to 9/1972	*10/1932 to 9/1972
2	5700 5730 5745 5750 5760 5765 5740 5755	5670 5705	10/1899 to 9/1972	10/1932 to 9/1968
3	5670 5700 5745 5750 5760 5765 5730 5255	5705	10/1891 to 9/1972	10/1932 to 9/1968

*Includes only extension of record length, not monthly gaps.

Synthetic Streamflow Generation

A 200-year synthetic streamflow record was generated based on the procedures described in Valencia and Schaake (1972, 1973). Briefly, the procedure is first to generate a series of annual flows at the selected stations. These annual flows are then disaggregated into seasonal flows. Finally, a similar procedure disaggregates seasonal flows into monthly flows. This scheme preserves the means and variances of the seasonal and monthly flows, the correlation between monthly flows at the same site or different sites, and the correlation between any monthly flow and any seasonal flow, and between the seasonal flow and the annual flow. The generated monthly values at any site will add up to the corresponding annual value, which guarantees the preservation of annual statistics.

GROUNDWATER MODEL

A simple model of the impacts of groundwater withdrawals on surface water flows was developed. This model was based on a theoretical analysis of the range of potential impacts to be expected, as well as a statistical analysis of rainfall and streamflow data to evaluate the dynamic properties of the aquifers in the study region.

The historical rainfall and streamflow records available for this region were used to determine the time delay characteristics of the natural groundwater system. A mathematical description of this system was created, based on the following assumptions. First, the average streamflow in each month consists of groundwater and direct runoff components. Second, the amount of direct runoff is assumed to depend upon the current month's precipitation. Finally, the amount of groundwater is assumed to depend upon the current and previous months' precipitation in excess of evapotranspiration. An equation representing this is:

$$Q_t = a_0 + a_1 P_t + \sum_{i=0}^{6} b_i (P_{t-i} - E_{t-i}) + V_t \quad (2)$$

where Q_t represents streamflow in month t, P_t and E_t denote the rainfall and evapotranspiration in month t, and the values of a_0, a_1, b_0, ... , b_m are to be evaluated for each sub-basin. The precipitation variables P_t should be basin average values which can only be estimated from point values. Likewise, the evapotranspiration variable, E_t, should be the basin average value. The disturbance term V_t accounts for the errors introduced by using point measurements instead of the "true" basin average values.

The effects of groundwater withdrawals on surface flows was then assumed to be similar in response to the rainfall-runoff relations derived above. Thus the streamflow depletion in month t denoted as D_t was related to the groundwater withdrawals for the six previous months, W_t through W_{t-6}, by:

$$D_t = \sum_{i=0}^{6} c_i W_{t-i} \quad (3)$$

where the coefficients C_i are computed from:

$$c_i = \frac{b_i}{\sum_{i=0}^{6} b_i} \quad (4)$$

A similar formulation was used by Nieswand and Granstrom (1971) to model the Mullica River Basin in New Jersey.

The coefficients obtained from the analysis of the Susquehanna data are shown in Table 3.

Table 3

Groundwater Withdrawal Impacts on Local Streamflows

BASIN	Streamflow responses in various months due to a unit groundwater withdrawal in month t						
	t	t+1	t+2	t+3	t+4	t+5	t+6
Codorus Creek	.147	.188	.237	.212	.151	.051	.014
Conodoquinet Creek	.178	.171	.225	.201	.153	.018	.054
Swatara Creek	.456	.207	.105	.087	.115	.030	0.00
Conestoga Creek	.165	.139	.175	.206	.165	.102	.048

SIMULATION MODEL

To assess the impacts of each of the alternatives on the distribution of flows in the Susquehanna and the low flows in the tributaries, and to evaluate the reliability of the proposed alternatives, a simulation study of the operation of the system was carried out. A modified version of the MIT River Basin SIMulation

Model (MITSIM) was used for this purpose (Schaake, et. al, 1974).

MITSIM was designed to generate and display both economic and physical information to aid in evaluating system response. The model is an accounting procedure that takes the synthetic or historical data developed, seasonal water demands and consumptive use, the groundwater response functions, the operating rules for the various reservoirs, pipelines, and groundwater systems, and operates them to find the monthly system flows at specified locations. The structure of the model is of nodes connected by branches with all water entering or leaving the system at the nodes. Typical nodes are:

1. Start nodes - nodes at which historic or synthetic streamflow data is input to the system. For the case study, a start node was used for all streams including non-gauged streams, and major overland flow areas to the Susquehanna. A special program was written to disaggregate data available at gauging stations (both historic and synthetic records) to input data for the start nodes.

2. Confluence nodes - the joining of two branches of the system used to show the connectivity of the activities.

3. Reservoir nodes - for each reservoir node, a capacity, seasonal target, and seasonal release schedule is given. Water may be removed from a reservoir node to meet demands provided enough water is in storage and release requirements are met.

4. Groundwater Nodes - represents the pumping of groundwater to meet a specified demand. A groundwater function relates seasonal withdrawal to impacts on local surface water in present and future seasonal withdrawal to impacts on local surface water in present and future seasons. A seasonal consumptive use coefficient shows how much of the groundwater is released to the surface water after use.

5. Irrigation Node - for each irrigation area, seasonal demands and consumptive use coefficients are combined to compute the portion of the specified demand in season that is returned to local surface waters in the present and future seasons.

6. M&I Node - a municipal and industrial demand and consumptive use coefficient is specified for each surface water demand in each season to calculate withdrawals and returns to streams.

   A typical schematic for a system is shown in Figure 3 and Appendix B describes the function of each of the nodes shown.

RESULTS

All of the alternatives described in Appendix A were simulated with the 200-year synthetic record. In addition, Alternatives 1,2 and 3 were simulated with the 80-year augmented historical record as inputs. The first question to be investigated was which of the records was more stringent or conservative. Comparison of the simulation results of Alternatives 1 through 3 for both the historic and synthetic records, showed that the 200-year synthetic record produced, on the average, lower monthly outflows from the study area even though two extensive drought periods were observed in the historic record. Since the relative impact of the alternatives on the distribution of the outflows from the system was of utmost importance in this study, the synthetic record was selected for detailed comparison of alternatives.

Monthly outflows were calculated at the lower boundary of the study area which was the intersection of the boundary of Lancaster County, Pennsylvania with the Susquehanna River. This line is slightly above the Conowingo pool,and thus our calculation of system outflow represents runoff from a slightly smaller drainage area than that supporting inflows to the Conowingo Pool, which other studies have focused on.

Table 4 presents a summary of the results obtained from the simulation runs. This table shows estimates of the annual and monthly 30-day low flow which occurs, on the average, once every twenty years (Q30-20) at the outflow of the study area. The results for each alternative plan with Year 2020 demands are shown, as well as a "Present" case for comparison purposes.

Table 4

Estimates of Q30-20 at the System Outflow 200-Year Synthetic Streamflow Trace and 2020 Demands. (Present Run Uses 200-Year Synthetic Trace and 1970 Data).

		Q30-20 (cfs)		
Altern.	Aug.	Sept.	Oct.	Annual
Present	3622	3266	3055	3075
1	3412	3051	2943	2840
2	3410	3050	2945	2820
3	3405	3048	2944	2818
4	3411	3052	2944	2840
5A	3411	3052	2944	2840
5B	3411	3052	2944	2840
5C	3405	3048	2944	2818
6A	3415	3056	2944	2853
6B	3425	3044	2944	2873
6C	3411	3052	2944	2840
7A	3422	3062	2946	2858
7B	3427	3065	2945	2879
7C	3407	3050	2945	2821

The overall results of the study were:

1. There is very little difference between alternatives in terms of Q30-20 or monthly average flows at the outflow of the study area. The values of annual Q30-20 for the alternatives range from 2818 cfs to 2879 cfs. The present case produces a value of 3075 cfs. Estimates of Q30-20 for August, September and October show similar results. Most of this decrease is due to a consumptive use increase in power cooling through 2020, which peaks at 345 cfs. The lower values are also due to increased groundwater and Susquehanna water usage, while the higher values are a result of reservoir storage in the tributaries.

2. From the viewpoint of flows in the tributaries, the alternatives with large groundwater usage decrease tributary flows slightly. However, all other alternatives tend to substantially increase tributary flows due either to diversions of Susquehanna water or larger reservoir impoundments.

3. Any reliability problems for M&I water availability are due to over estimates of present source capabilities and can be easily improved by increasing reliance on new sources. All alternatives are equally reliable.

SUMMARY

The use of several interrelated models to investigate the potential hydrologic impacts of several proposed water supply alternatives for South Central Pennsylvania has been presented. The objective of the study was to assess the relative impacts of the alternatives on the distrubution of the outflows to Chesapeake Bay. The methodology developed for this study consisted of several hydrologic models which processed the available hydrologic and water demand data to evaluate the impacts of the alternatives.

ACKNOWLEDGEMENTS

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Appendix A

DESCRIPTION OF ALTERNATIVES

Alternative #	Developments
1	Considers development each municipality would undertake without outside assistance. Harrisburg, Mechanicsburg, and Carlisle would draw from present sources with some additional groundwater development. Lebanon would develop new storage and improve existing storage on the Swatara, with some new groundwater development. York would go to the Susquehanna as a source and develop groundwater. Elizabethtown, Ephrata, New Holland, and Lititz would develop additional groundwater sources. Lancaster and Manheim would continue with present sources.
2	Considers major use of groundwater in the future, especially for York and Lebanon. No new impoundments or Susquehanna sources.
3	Considers Susquehanna as the major source of new water demands for Lebanon, York, and Elizabethtown, with no new impoundments built.
4	Considers new impoundment on Swatara Creek for Lebanon, and York water supply from Susquehanna.
5A	Considers impoundment on Swatara Creek for Lebanon and Elizabethtown, and York supply from Susquehanna.
5B	Same as 5A except reservoir development on E. Conewago Creek is considered for Elizabethtown.
5C	Susquehanna is used for Lebanon, Harrisburg, (East and West), York and for some additional needs in Carlisle and Mechanicsburg. Reservoir on E. Conewago Creek is used for Elizabethtown.
6A	Considers a new reservoir on the Swatara and groundwater for Lebanon. New reservoir on S. Branch of the Codorus for York.
6B	Lebanon impoundment retained, but Elizabethtown switched to Susquehanna and York to a W. Conewago reservoir.
6C	York, Lancaster, New Holland and Elizabethtown use Susquehanna, and new impoundments are developed on Conodoquinet Creek and Swatara Creek.
7A	Large groundwater development, Lebanon uses Susquehanna and York uses impoundment on W. Conewago Creek.
7B	Same as 7A except Lebanon uses a reservoir on the Swatara.
7C	Combines 5C and 6C and includes a reservoir on the Conodoquinet.

Appendix B Node Descriptions

Reservoir - CODRRES
M&I - CARLILMI, HARRWCDQ, MECHBGMI, HARRWYBC, YORKCODR, YORKCBC, YORKSUSQ, LANCSTSQ, EPHRTAMI, ELIZCHK, MANHMMI, LEBSWT, HARRESWT, HESUSQ, HARRESCL, SUSQMI
Groundwater - CARLILGW, MECHBGGW, YORKGW, LEBANGW, ELIZGW, LITITZGW, NEWHOLGW, LANCSTGW, EPHRTAGW
Irrigation - CDQIRR, WCONIRR, CODRIRR, CSTIRR, CONWIRR, SWTIRR

All others are start or confluence nodes.

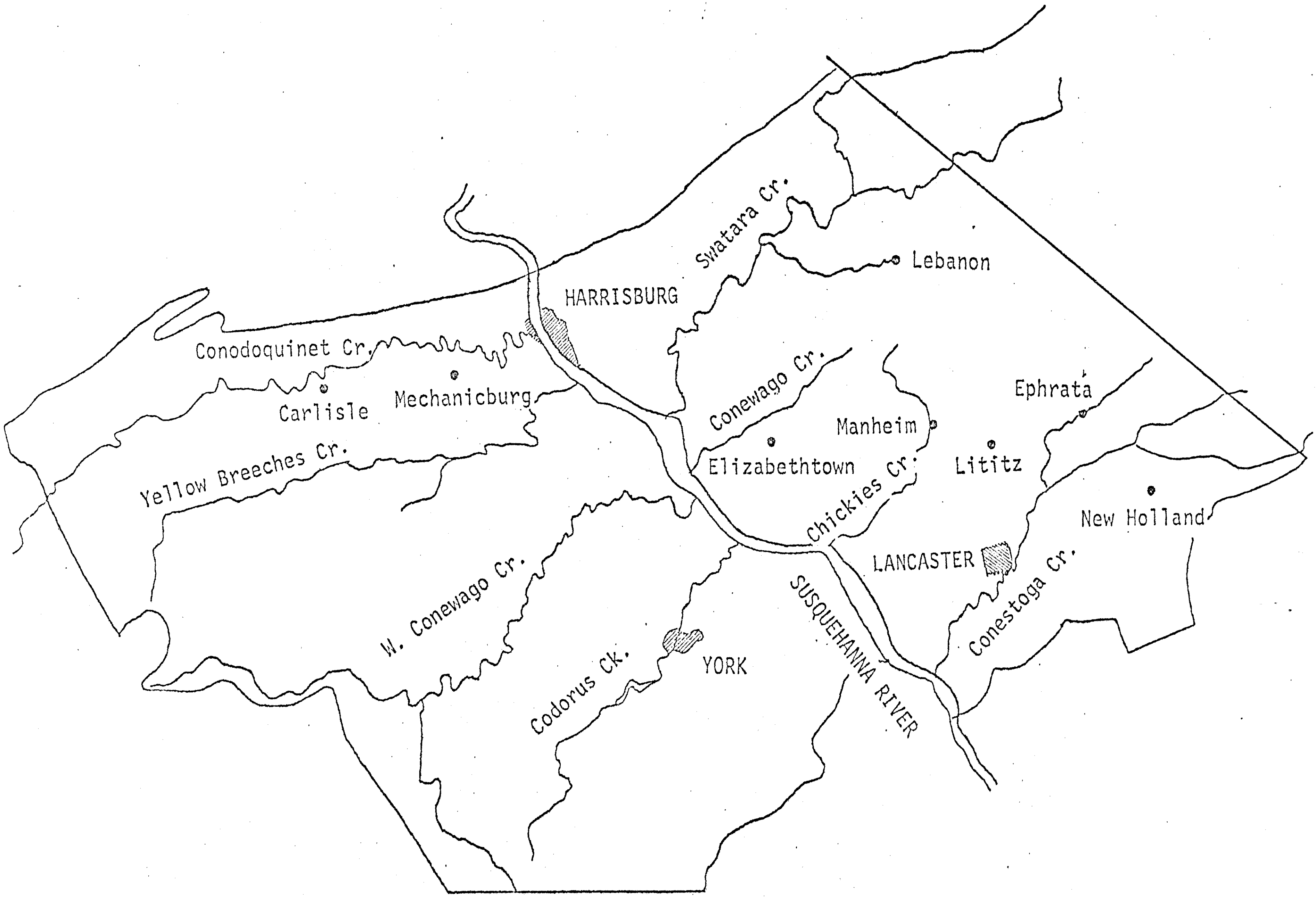

Figure 1: Study Area

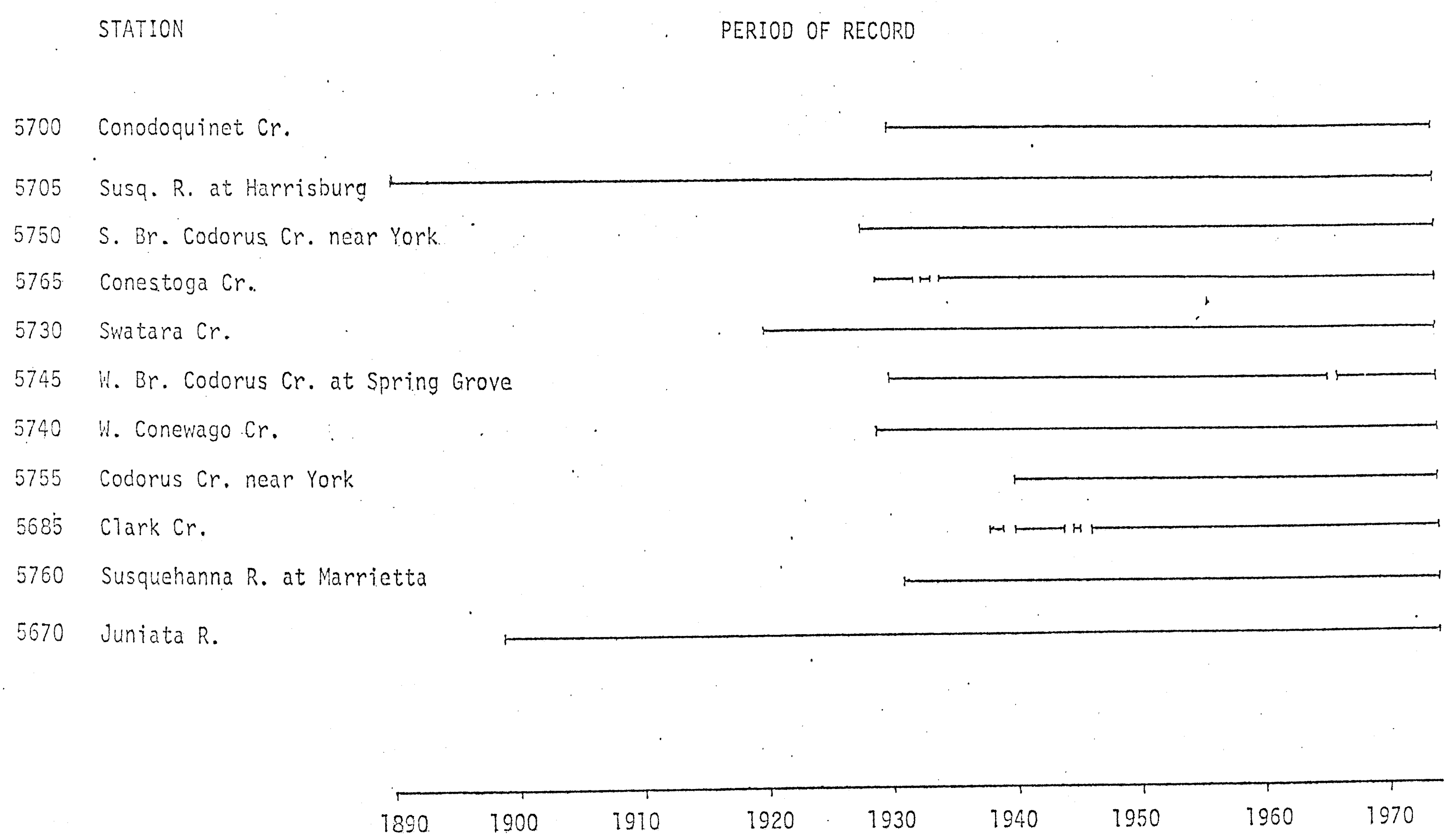

Figure 2: Available Streamflow Records

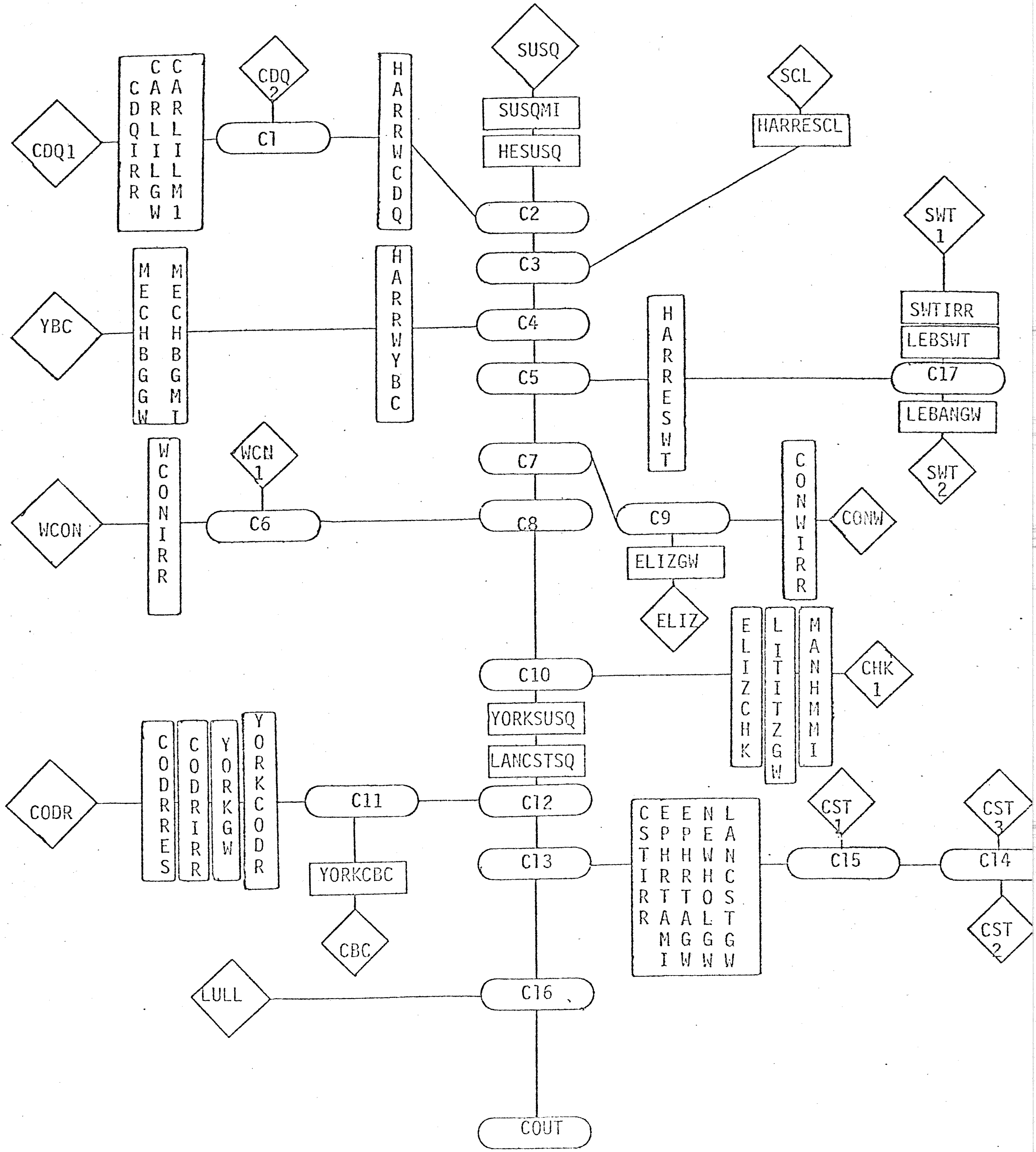

Figure 3: Typical Schematic