Systematic Development of Methodologies in
Planning Urban Water Resources for Medium Size Communities

PHASE I
FINAL REPORT

by
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PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
WEST LAFAYETTE, INDIANA
Water Resources Research Center
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West Lafayette, Indiana

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ABSTRACT

The principal objective of the research is the development of methodologies in comprehensive planning of the water resources of medium size communities (100,000 - 200,000 inhabitants), and in extending the planning to a 25 to 30 year horizon. The approach is that of systems analysis involving interaction between several research disciplines and with community groups. The disciplines represented in the research are sociology, geology, surface and groundwater hydrology, water quality, economics and land use planning.

The project is divided into two phases. The first phase, reported herein, addresses the methodologies of models for estimating population growth, water demand, quantity and quality of surface runoff, and availability of ground water sufficient to supply increasing demand and for determining economic trade-offs between alternate drainage systems. In the second phase these models will be integrated and the role of population distribution and of community policy decision will be evaluated. The test area used is principally the Lafayette, West Lafayette community, in Tippecanoe County, Indiana. Other sites in Indiana, Oklahoma and Illinois are used for specific purposes.

Life tables for Indiana and for the 14 economic areas of the state were developed as an important component for making population projections, which, in turn, are one of the basic ingredients for the projection of water demand. A regression equation is proposed which relates the water consumption in a city block to size and value of houses, rental values and age distribution of the population.

A detailed geologic and hydrogeologic investigation of the aquifers is required for those communities which depend in part or completely on groundwater. A systematic procedure for the development of aquifer maps is presented and applied to Tippecanoe County, Indiana. Recommendations are made for improved monitoring of the levels and the quality of ground water in view of possible pollution due to land disposed wastes.

A mathematical model of the ground water aquifer was developed which gives the response of the aquifer under different pumping stresses corresponding to possible future land use and future demands. Stochastic models of the monthly rainfall and of the stages of the principal river in the test area were used as inputs in the ground water model.

Deterministic and stochastic models of the urban runoff which accept stochastic rainfall inputs were developed. The models are of the lumped nonlinear type. Their performances have been found to be superior or equal to the linear instantaneous unit hydrograph model. The methods developed successfully model the rainfall-runoff process and appropriately quantify the effects of urbanization on runoff.

Rainfall, runoff and water quality data were acquired at two sites in West Lafayette, Indiana. A procedure was developed for obtaining water quality from watersheds of varying degrees of urbanization. It is recommended that suspended solids and BOD be analyzed and, if possible, that total and fecal coliform counts, total solids, COD, and phosphorus be included in the analysis.

Techniques were developed for evaluating the economic feasibility and effectiveness of a wide range of alternate methods of conveying the surface runoff using open channels, subsurface sewers (with or without detention basins) and with different treatment levels. For flood prone areas, techniques were developed to determine the benefits resulting from providing adequate drainage and to compare the benefit-cost relationship of providing this drainage system before the urbanization has begun and after the urbanization has been completed.
ACKNOWLEDGEMENTS

The research leading to this report was supported by the Office of Water Research and Technology, Department of the Interior under Title II grant C-3277. The authors wish to express their appreciation to Dr. Dan Wiersma, Director of the Purdue University Water Resources Research Center for his assistance in the administration of the project and for his encouragements during the many sessions he attended with the principal investigators. The authors also wish to recognize the help they received from many individuals in private, Federal, State and City agencies. Their names are listed in sections 1.3a and 1.3b.
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CHAPTER 1

SYLLABUS

1.1 PROBLEM IDENTIFICATION

Urban planners have developed several land use and city planning models. Most of these have been designed around the transportation systems and have neglected the interaction of land development and urban water resources. In contradistinction many water models for quantity and/or quality of urban drainage, or for water supply and distribution have proceeded somewhat independently of the urban development models. The planning, design and management of water supply, sewage collection and water for recreational uses often are in the hands of different institutions with different goals. It is not uncommon to see, as in West Lafayette, Indiana, that the water supply is operated by a private concern, the sewage collection is municipally operated and the recreational aspects are under the jurisdiction of a Park Commission. There is thus a pressing need for the integration of water related activities with the urban planning functions and for the development of appropriate methodologies in comprehensive planning of urban water resources.

The larger metropolises such as New York, San Francisco, Detroit, Chicago and Los Angeles have sufficient resources to operate their own planning groups and eventually to develop their own methodologies. However, if one observes the population distribution of the Standard Metropolitan Statistical Areas (SMSA), it is apparent that the mode of the distribution corresponds to medium size communities of the order of 100,000 to 200,000 inhabitants. Communities of this size can, in general, afford only a limited amount of planning effort and do not have the resources to develop their own methodologies. It therefore appears that the need for the development of methodologies in comprehensive planning of urban water resources is greatest for these medium size communities. Because of their large number relative to the amount of expertise available it is not practical or economically feasible to develop new methodologies for each metropolitan area. Although some medium size communities are new cities, such as Columbia, Maryland and Reston, Virginia, most of the medium size communities already are in existence and have varied but generally limited advanced planning. There is a need to extend the planning for these existing communities to a 25 or 30 year horizon.

The problem identified is thus the lack of general methodologies in comprehensive planning of the urban water resources for medium size communities.

1.2 GENERAL OBJECTIVES OF THE RESEARCH

The principal objective of the research is the development of methodologies in comprehensive planning of urban water resources in medium size communities (about 100,000 to 200,000 inhabitants), and in extending the planning to a 25 to 30 year horizon. The approach is that of systems analysis involving interactions between several research disciplines and with community groups. The interdisciplinary team represents the different interests involved in the planning of the components of urban water resources developments. In addition to the obvious technical competence requirements in hydraulics, hydrology and geology, it must be recognized that the water related facilities are developed for the people who are to use them. Therefore, an understanding of the community needs, wants and constraints is essential. Sociologic competence is thus necessary to analyze the demographic and socio-economic characteristics of the community. Eventually, alternate plans may be presented to the decision making bodies. The evaluation of these alternatives is usually based on an economic comparison as well as on the environmental and ecological impacts of the proposed developments, thus requiring competence in the areas of economics and of the environment. The minimum research group should thus include at least experts in the areas of hydrology, hydraulics, geology, environmental engineering, sociology and economics.

This team of researchers has to work in close relationship with community groups. It is assumed
that a community of the size considered will have some land planning organization; this could be under the form of a city development commission, a county wide area planning commission, a council of governments or some combination thereof. This group can usually provide a substantial input regarding current land uses and alternative future land uses. It is also essential to maintain a liaison with other city, county and state agencies as well as with citizens’ groups representing the community.

Because of the size of the task it was proposed to approach this problem in two consecutive phases. During Phase I (1971-1975), specific problems in the sociologic, geologic, hydrologic, water quality and economic aspects would be investigated, and specific methodologies or models in each of these disciplines would be tested and evaluated.

The first phase addresses the methodologies of models for estimating population growth, water demand, quantity and quality of surface runoff, and availability of ground water sufficient to supply increasing demand, and for determining economic trade-offs between alternate drainage systems.

During the second phase (1975-1977) these models would be integrated, and placed in an overall urban planning framework which would include the effect of local policy decisions on the hydrological and ecological systems, and the subsequent influence on urban and water resources planning. An attempt will be made to evaluate the role of population distribution and community policy decisions as related to the stresses placed on the local ecological and hydrological systems and the resultant impacts on environmental quality. Consideration will also be given to means of evaluating acceptance of alternatives by the decision makers and the public at large.

The models will be general in nature, and the methodologies will be "transferable", that is, they are not specific to a particular location. This class of models would then be generally applicable to a large number of medium size communities in a broad geographical area.

For the purpose of testing some of the methodologies data from the Lafayette - West Lafayette Communities in Tippecanoe County, Indiana, were used. It should be stressed that it was not the objective of this research to develop specific plans for Lafayette or West Lafayette. Data from other communities were used when more convenient or when appropriate information was not available in Lafayette - West Lafayette. Data from Anderson, Indiana; Tulsa, Oklahoma, and Cook and DuPage Counties in Illinois were used for specific purposes.

The specific objectives of the research are discussed in Chapter II.

1.3 STUDY MANAGEMENT

A) THE RESEARCH TEAM

The research team consisted of a project director and seven principal investigators. The role of the project director was to serve as a coordinator, to provide the linkages between the several principal investigators, and to provide some guidance and uniformity of purpose for the research.

Each principal investigator was assisted by one or more Graduate Research Assistants. Each Research Assistant was an advanced degree candidate in one of the disciplines represented in the project, using the research done on the project as a thesis for a specific degree. One difficulty encountered in the academic environment is that the Research Assistants and the Principal Investigators each have to satisfy two requirements which may be contradictory:

1) the need of producing a thesis or publishing papers pertinent to the granting unit of the university and to the specific profession.

2) the need of producing a usable contribution to the overall research project.

One of the functions of the project director was to ascertain that this second requirement was fulfilled. In order to maintain an impartial attitude, the project director did not have a Graduate Research Assistant.

The research team was structured as shown in Table A.
TABLE A
RESEARCH TEAM

<table>
<thead>
<tr>
<th>Area</th>
<th>Principal Investigator</th>
<th>Research Assistant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Director:</td>
<td>J. W. Delleur</td>
<td>E. Cooper (9/71 - 8/74)</td>
</tr>
<tr>
<td>Sociology:</td>
<td>L. Z. Breen</td>
<td>M. Malgar (9/74 - 12/74)</td>
</tr>
<tr>
<td></td>
<td>H. R. Potter</td>
<td>G. Grossman (6/75 - 7/75)</td>
</tr>
<tr>
<td>Geology:</td>
<td>W. N. Melhorn</td>
<td>R. Woodfill (9/71 - 1/72)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A. Maarouf (1/72 - 12/74)</td>
</tr>
<tr>
<td>Surface Hydrology:</td>
<td>A. R. Rao</td>
<td>B. T. Chenchayya (9/72 - 9/74)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R. G. S. Rao (1/73 - 8/73)</td>
</tr>
<tr>
<td>Ground Water Hydrology:</td>
<td>J. A. Spooner</td>
<td>B. T. Chenchayya (9/74 - 8/75)</td>
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<tr>
<td></td>
<td>A. R. Rao</td>
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<tr>
<td></td>
<td></td>
<td>C. F. Mattox (1/73 - 8/74)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D. Hartman (9/74 - 6/75)</td>
</tr>
<tr>
<td>Economics:</td>
<td>W. L. Miller</td>
<td>S. Erickson (9/71 - 8/73)</td>
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<tr>
<td></td>
<td></td>
<td>K. M. Naber (9/73 - 8/75)</td>
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The group met regularly, at intervals of about three weeks on the average. Dr. Dan Wiersma, director of the Purdue Water Resources Research Center also attended the meetings. Formal minutes of the meetings were prepared by the project director. These included the record of attendance and a summary of the discussions. Except for those meetings concerned with budgetary and management problems, the graduate research assistants were in attendance. The research assistants held additional meetings among themselves, which they felt helped in understanding the several facets of the research and their interrelationships.

It took a certain time, perhaps a year, for the team to develop an "esprit de corps", but the team has learned to work as a unit. There is a strong spirit of cooperation among all the participants.

8) INTERACTION WITH COMMUNITY GROUPS AND AGENCIES

In an attempt to interact with community groups and with potential users of research results, working relationships were established with the following agencies and their respective officers.

Tippecanoe County Area Planning Commission:
Mr. J. Fletcher, Director through Summer 1973;
Dr. A. Schilling, Director starting fall of 1973.

Indiana Department of Natural Resources, Water Division, State Water Resources, Planning Section:
Mr. M. Furman, Mr. J. Russell.

Indiana State Board of Health:
Director of Environmental Engineering: Mr. Oral Hert
Dept. of Hospital and Nursing Home Facilities,
Mr. Arthur Hasse; Medical Licensing Div.; Mr. Joseph O'Brien

Indiana State Medical Association:
Miss Jane Leeds

Indiana Health Careers, Inc.;
Mrs. Dee Manna

City of Lafayette:
Mr. J. F. Riehle, Mayor; Mr. M. Callahan, City Engineer

City of West Lafayette,
Mr. W. Kashner, City Engineer

Lafayette Redevelopment Commission:
Mr. K. Schuette

Greater Lafayette Chamber of Commerce:
Mr. A. Riley

Tippecanoe County
Indiana Stream Pollution Control Board
Ohio River Basin Commission
Agricultural Stabilization and Conservation Service:
Mr. W. Lowe
Soil and Water Conservation District:
Mr. M. Ice, W. Martin
U. S. Geological Survey:
Mr. J. Cook
Indiana Law School
Allen County, Surveyor's office:
Mr. W. Sweet
West Lafayette Water Co.,
Mr. O'Connor
Tippecanoe County Sanitarian:
Mr. L. Ade
Tippecanoe County Drainage Engineer:
Mr. Dan Ruth

A general meeting was held with representatives of the above agencies and further consultations were continued privately with many of these persons. Their help is gratefully acknowledged. A particularly constructive relationship was established with the directors of the Tippecanoe County Area Planning Commission. However, the contacts decreased in 1974 because some staffing problems developed which slowed the completion of the land use maps by the Area Planning Commission.

C) Interaction with Technical Groups
A close contact was maintained with Mr. M. B. McPherson, Director of the ASCE Urban Water Resources Research Program. On two different occasions, Mr. McPherson spent two days on the campus with the principal investigators.

Consultations were also held with Mr. W. Sweet, Allen County Surveyor, who played a leading role in the development of the master plan for the Fort Wayne - New Haven - Allen County Metropolitan Area. Discussions were also held with Mr. Frank Dalton, Assistant Chief Engineer of the Metropolitan Sanitary District of Greater Chicago and with Mr. R. Zimmerman, Resource Specialist of the U.S. Soil Conservation Service.

1.4 Publications
The publications prepared as part of this research fall under four categories: (a) technical reports, (b) graduate students' theses, (c) journal publications, and (d) other publications. Within each category the publications are grouped by area of research.

A) Technical Reports (Purdue University Water Resources Research Center Series)

i) Sociology Area

ii) Geology Area

iii) Hydrology Area

iv) Water Quality Area

v) Economics Area
B) GRADUATE STUDENT THESIS

i) Sociology Area


ii) Geology Area


iii) Hydrology Area


iv) Water Quality Area


v) Economics Area

"Economic and Environmental Impacts of Alternate Methods of Surface Runoff Disposal" by S. Erickson, M.S. Thesis, Purdue University, August, 1973, 113 pp. Major Professor W. L. Miller.


C) JOURNAL ARTICLES

i) Hydrology Area


ii) Economics Area


D) OTHER PUBLICATIONS


1.5 SUMMARY OF THE REPORT AND CONCLUSIONS

This report summarizes the research accomplished under Phase I of the project entitled "Systematic Development of Methodologies in Planning Urban Water Resources for Medium Size Communities". This research attempts to outline a number of methodologies for the comprehensive planning of the water resources in communities with populations in the range of 100,000 to 200,000.

Comprehensive planning deals with a variety of physical, social, economic and other types of facilities and institutions. Comprehensive planning also considers the hydrologic, ecologic, environmental and sociological impacts of water developments related to urban areas. Comprehensive planning includes a wider area than the city limits of a given community under study. For the hydrologic studies, the watershed or subwatershed(s) boundaries are more appropriate than the political boundaries. For the geologic investigation of ground water the study boundaries are governed by the location of the aquifers and of their recharge areas. For demographic and economic studies the area includes a grouping of jurisdictions that comprise a large, articulated economic area centered around the urbanized area. Thus comprehensive planning not only recognizes the many functions and the many areas involved in the planning process but also considers the interrelationships between the functions and areas.

The present study also recognizes the interrelationships between urban land uses and water resources developments. For the size of communities considered it seems reasonable to assume that the community would have some kind of planning organization. Typically, such an organization would provide current land use maps and would have some projected land uses developed primarily around transportation studies. Typically the planning of urban water resources would be either lacking or inadequately developed. Thus, this report attempts to systematically introduce models involving the geology and hydrogeology of ground water supply, the hydrology and water quality of urban runoff, the economic aspects of alternate urban drainage systems, and of drainage improvements in flood prone areas and the socio-economic aspects of populations and water demand projections.

Population projections form one of the basic ingredients for the projection of water demands. An important component for making population projections is the life table. These tables relate deaths to an enumerated population in corresponding age categories. These tables provide prerequisite data for population estimates and projections since the estimate of the probability of dying is necessary for the calculation of survival ratios. Life tables were developed for Indiana and for the fourteen economic areas of the state.

Residential water consumption can be projected using tract and block data which are available from the Bureau of the Census. This method is particularly attractive for medium size communities which do not have the planning staff to undertake a massive data acquisition task. (For both tracts and blocks substantial differences in residential water use are shown by indicators of socio-economic status, with only minimal differences by housing size and age distribution.) A regression relationship is proposed which relates the water consumption in a city block to size, values of houses, rental values and age distribution of the population.

A detailed geologic and hydrogeologic investigation of the aquifers and of their responses under anticipated pumping demands is required. If ground water is a source of water supply, the geologic investigation is necessary to locate the principal sources of ground water in the vicinity of the urban area and to locate the zones of ground water inflow. A systematic procedure for the development of aquifer maps is presented. It is based on well records, seismic data, topographic maps and outcrop information. The methodology has been applied to Tippecanoe County, Indiana, and has resulted in the most comprehensive set of geologic maps available in this county. These include lithofacies maps, bedrock surface map, unconsolidated material thickness map, oenographic features map, map of infiltration properties, interglacial paleosurface maps and cross-sections and fence diagrams. Also included in this section is a detailed
surface drainage map of Tippecanoe County.

The location of the aquifers is an essential prerequisite for the development of a mathematical model of the ground water system. This model will give the response of the aquifer under different pumping stresses corresponding to possible future land use patterns and future water demands. The model developed in this study is a deterministic, digital computer model with stochastic inputs for the long range determination of the ground water supply capability under increasing demand due to population growth. The model is calibrated using historical input variables and pumping records. The model was applied to the aquifers in the vicinity of Lafayette and West Lafayette which had been identified by the geologic investigation. A 1000 foot square grid was used and the average piezometric levels during January were taken as the initial water levels for the digital model. Stochastic models were fitted to the monthly rainfall and stages in the Wabash River and the Wildcat Creek to be used as inputs to the ground water model. The accuracy of these mathematical groundwater models of relatively heterogeneous geologic formations such as the glacial aquifers underlying Lafayette and West Lafayette is limited by the data available, particularly observation wells for which histories of ground water levels are available.

Groundwater pollution is possible. The most likely sources of pollution are land disposed wastes. The monitoring of the chemical quality of ground water in the tested area appears to be unsatisfactory, and a network of observation wells which are monitored for water levels and water quality is recommended.

Urban developments are accompanied by an increase in impervious surfaces and by the construction of storm sewers. Both factors reduce the infiltration of surface flows into the ground and also reduce the evapo-transpiration of water back into the atmosphere. As a result the total runoff from urbanized watersheds is increased as compared to their pre-urban conditions, base flows become smaller and the stream flows become more variable. The peak discharge of surface runoff is increased and the time at which this peak occurs after the beginning of effective rainfall is shorter. The two key factors in increasing the peak flow and decreasing the time to peak are the percentages of the watershed that is impervious and the percentage of the area that is served by storm sewers. This disruption of the natural hydrologic processes by urban development contribute significantly to the deterioration of the quality of storm water runoff. These urban storm waters may have an increased biochemical oxygen demand (BOD) and contain rather high quantities of suspended solids, various other pollutants including lawn fertilizers and chemicals that are spread over paved areas to control snow and ice. In the more densely urbanized areas the pollution loads tend to occur early in the storm as the first flush of runoff picks up most of the dirt and other substances accumulated on the streets and paved surfaces.

In the investigation of the surface runoff hydrology, a deterministic model was developed which accepts stochastic rainfall inputs and is applicable to the determination of surface runoff from heavily urbanized areas and from surrounding sparsely urbanized areas. The classical linear unit hydrograph techniques often involve gross over-simplifications since the internal storage, the loss rate mechanisms and the motion of the surface runoff in the watershed are governed by nonlinear differential equations. Although somewhat more complicated than the linear unit hydrograph model, the lumped nonlinear model is superior or equal to the linear model. The necessary computer programs have been developed and tested using the daily rainfall-runoff records of the Salt Creek basin at Arlington in the Chicago metropolitan area.

The acquisition of rainfall and runoff data at four sites in West Lafayette was initiated in previous research projects and were continued as part of this project. As a part of a parallel research project, a probabilistic analysis of the short time increment rainfall process was made and a procedure for the synthetic generation of rainfall hyetographs was developed.

The surface runoff quality was monitored at two of these four sites in West Lafayette where the
rainfall and runoff were observed as part of the hydrologic study. A procedure was developed for obtaining the water quality from watersheds of varying degrees of urbanization. The procedure considers the limitations of the sampling equipment, the sampling frequency, the sample volume, the sample duration and the appropriate water quality analysis. It is recommended that suspended solids and BOD be analyzed, and, if possible, that total and fecal coliform counts, total solids, chemical oxygen demand (COD) and phosphorus be included in the analyses.

The storm runoff hydrograph was found to have a significant effect on the shape and magnitude of the pollutographs. A first flush of suspended solids and associated BOD was exhibited at the urban sampling station, but no initially high BOD and only a small first flush of suspended solids was evident at the semi-urban/rural sampling station.

A management technique often cited for reducing the storm water peak discharge and for reducing the storm water pollution is the detention of the water within the urban drainage basin before the runoff enters the sewage system and/or the receiving stream. An alternate technique of controlling the quality of the stormwater is its treatment before disposal in the receiving water body. The use of surface streams for architectural or aesthetic purposes has also been advocated. Techniques were developed for evaluating the feasibility and effectiveness of a wide range of alternate methods of conveying the surface runoff in open channels or subsurface sewers, with or without detention basins and with different treatment levels. These techniques were developed as part of the economic study. An integer programming model was designed to consider both system cost and water quality. This program was used to examine the effect of varying interest rates and varying levels of acceptable environmental pollution parameters on the total system cost. Tradeoffs between system costs and levels of water quality were generated for the Ross-Ade upper watershed in West Lafayette. Holding ponds were found to be a cost effective method to reduce pollution levels and have a low capital cost as also is the case for open channel conveyances.

For flood prone areas techniques were developed to determine the benefits resulting from providing adequate storm drainage and to compare the benefit-cost relationship of providing this drainage system before the urbanization has begun and after the urbanization has been completed. The methodology was tested using data from the city of Anderson, Indiana. For this particular instance the benefits of installing the drainage system prior to urbanization were found to be nearly equal to the costs.
CHAPTER 2

SPECIFIC OBJECTIVES OF THE RESEARCH

The specific objectives of the research are outlined by discipline and activity.

2.1 SOCIOLOGICAL ASPECTS

A study of the human use of any resource must begin with an estimate of the number of humans involved. Demographic concerns, population estimates, locations and projections thus become fundamental aspects of urban water resources development, and in a sense become the prior data for the research.

Fundamentally, the first objective is concerned with the numbers of persons and the socio-economic variables that seem crucial for understanding the utilization of urban water resources. This is to be achieved through the construction of life tables and by the investigation of population composition and location and land utilization.

The second objective is the estimation of the water demand in terms of the relevant socio-economic variables.

2.2 GEOLOGIC ASPECTS

Ground water as a resource is usually less understood and appreciated than surface waters and there is usually less information available about its quantity, quality and distribution. Thus emphasis is placed in this report on the study of subsurface waters. The principal purpose of the geological investigation is to outline and exemplify the methodologies of subsurface investigation that are necessary for the formulation of a mathematical model of the subsurface aquifers. Although such models have been developed and used in the arid Southwest, modeling has not been much attempted in the unconsolidated glacial drift region of the Midwest where there are more complicated boundary conditions, as is the case in the test area of Tippecanoe County, Indiana.

The objective of the geologic study is to investigate the hydrogeologic conditions that control the distribution and development of ground water. This is done in three steps:

1. locate areas of ground water recharge and inflow;
2. localize the distribution of water within the principal water-bearing formations; and
3. determine the quality of ground water and the possible relation to changing patterns of land use.

Some attention will also be given to surface waters, including:

1. the location and characteristics of surface streams and
2. the geologic characteristics of flood plains.

2.3 HYDROLOGIC ASPECTS

The hydrologic investigation is divided into two parts:

1. the problems associated with the prediction of the quantity and the time distribution of surface runoff and
2. the development of a ground water model.

The objectives of the runoff portion of the study are:

1. the development of a deterministic non-linear runoff model which will accept stochastic rainfall inputs to determine the surface runoff from heavily urbanized areas as well as the surrounding sparsely urbanized areas. This portion of the study includes the acquisition of rainfall and runoff data at four locations in the study area. (The establishment of the raingages and runoff gaging station was part of previous researches in urban hydrology.)

The objectives of the subsurface hydrology are:

1. to extend the geologic investigation in order to estimate the characteristics (transmissivity and storage coefficient) of the aquifers which are potential sources of water supply to the test community; and
2. to develop a deterministic model, which
will accept stochastic inputs, for the long range determination of the ground water supply under increasing demands due to population growth.

2.4 WATER QUALITY ASPECTS

This portion of the study coordinates with and extends the objectives of the surface hydrology section. The principal objective is the determination of the quality of stormwater runoff from typical urban, semi-urban and rural watersheds in the test area. This objective requires the following steps:

1. to develop a sampling methodology for economical procurement of representative samples and subsequent analysis
2. to analyze the samples for a number of quality parameters (total and suspended solids, volatile suspended solids, BOD, nitrogen, phosphorus, total coliforms and fecal coliforms);
3. to observe the variation of these parameters as a function of time; and
4. to relate the quality parameters to watershed and land use characteristics (e.g. land use, frequency of street sweeping, storm intensity and duration) in order to formulate a predictive model of stormwater quality. The water quality measurements are made at the same sites where rainfall and surface runoff are monitored.

2.5 ECONOMIC ASPECTS

The objective of the economic study is to identify and to quantitatively measure environmental and social benefits of alternative municipal drainage systems. This requires the following subobjectives:

1. to develop and illustrate a design comparison model which will aid city planners and engineers in choosing among different surface runoff transport systems;
2. to develop trade-off relationships between economic costs and water quality for various storm water systems;
3. to examine the impact of alternative urban development at the test location on the cost and quality of stormwater removal systems;
4. to estimate the benefits that would result from installing adequate drainage facilities in flood-plagued residential areas and to compare the benefits of adequate storm drainage with the associated installation costs; and
5. to compare the benefit-cost analysis of installing the drainage system before urbanization with the benefit-cost-analysis of installing the system after urbanization is complete.

2.6 PHASE II

In Phase II methodologies will be presented for alternative solutions for collection, detention, transportation, recharge, disposal and reuse of storm water runoff and the means of evaluating the acceptability of alternatives for use by decision makers. Also to be included in Phase II will be the role of population distribution and community decisions as related to the stresses placed on the ecological and environmental system and the resultant impact on water quality.
CHAPTER 3

DEMOGRAPHIC ASPECTS

3.1 INTRODUCTION

Population growth or decline are significant indicators in the development of communities. Many aspects of the economic life of communities are tied to patterns of growth, as are aspects of quality of life such as the variety and quality of many services provided within the community. Trends in population growth and patterns of population distribution are of substantial interest within sociology because they are both indicators of social change and factors affecting the environment within which man lives.

Population growth in the United States has been accompanied by a shift in population distribution. There has been a consistent movement from a rural, agriculturally based society to an urban, industrially based society. These changes have been accompanied by dramatic changes in the patterns of social organization ranging from macro-level changes in the division of labor and community or regional inter-dependence to changes in family life cycle and individual life styles.

One perspective that can be used to describe these macro-level changes, which is the concern of the present study, has been given the acronym of POET. The components of this perspective are Population, Organization, Environment and Technology.

![Diagram of POET model]

Briefly, and therefore oversimplifying this perspective, population places a demand on the environment for natural resources. The types of resources and the quantities of them that are required or used are affected by the social organization and technology of the society as well as the size of its population. In American society technology is generally seen as a means of changing that demand rather than changing patterns of social organization.

In this portion of this project two aspects of the population component of this perspective have been under study. The first of these examined changes in expected length of life that have occurred in Indiana from 1950 to 1970. Expectation of life as portrayed in a demographic tool called the life table is an important component for making population projections. These projections of course play an important role in community planning in general as well as water resources planning more specifically. The second aspect of population studies was an examination of the use of census tract and block data for projecting residential water consumption. The advantage of being able to use tract and/or block data is that they are available for medium sized communities from the Bureau of the Census and would not require the collection of new data. The use of available data may be particularly important for medium sized communities which do not have the planning staff to undertake a massive data acquisition task.

For further details on the sociologic investigation the reader is referred to the following technical reports:


The sociologic investigation was divided in two parts: (1) the population projection and (2) the water consumption component.

3.2 POPULATION PROJECTION

A) METHODOLOGY

One of the principal tools used in developing population trends and projections is the life table. The life table is a demographic tool which relates
age specific deaths to an enumerated population in corresponding age categories. The life table is standardized to control for size, sex and age structure, thus permitting comparison of populations regardless of their size, sex, or age composition.

The chief statistics of a population’s exposure to the risk of death are (1) an age specific mortality rate (the probability of death within an age interval), and (2) the expectation of life (the average number of years of life remaining to persons at the start of each given age interval), which is calculated on the assumption that they will experience, during their future life time, the mortality rates shown in the life table.

The life table provides prerequisite data for population estimates and projections since the estimate of the probability of dying is necessary for the calculation of survival ratios.

Urban-Rural Mortality and Expectation of Life

The urban areas of the United States had higher mortality when compared with the rural areas in each region up to around 1940. However, in general, mortality has become less in urban areas than in rural areas of the United States since then.

Comparing the five most urban states with the five least urban states, a higher expectation of life at birth is shown for the five most urban states in 1950. In 1960 there is less difference among the states, although expectation of life at birth remains comparatively higher in the most urban states.

Several authors have suggested that these differences in urban-rural mortality would be explained in terms of the differences in the availability of medical care in urban as compared with rural areas.

These few studies do not give statistics comparing quantities of medical care in urban and rural areas. Each assumes that programs for increasing medical care are more oriented toward urban areas. Changes in urban medical care are reported to have produced lower infant mortality, higher expectation of life at birth, and higher expectation of life for the elderly. From 1900 to 1950 infant mortality for whites in the United States decreased by 63 percent (78 percent for urban areas and 47 percent for rural areas).

These urban-rural differences in expectation of life have implications for social organization. The decreases in mortality and increases in expectation of life have occurred more in urban compared to rural areas. Several authors have stated that the United States has placed more emphasis upon disease control and health programs in urban areas. Manifestations of these programs are sewage control and water purification, inoculations for contagious disease, establishing local health clinics, and more hospital beds. The concentration of hospital facilities in cities increases the proportion of doctors in urban areas and the availability of medical care for urban residents.

B) CASE STUDY-LIFE TABLES FOR THE 14 INDIANA ECONOMIC REGIONS

A life table for the State of Indiana for 1970 is given as Table 1, and the Life Table Functions are defined in Table 2.

In a study of urban-rural mortality and expectation of life differences it is useful to employ a number of populations which differ by proportion of population urban. The 14 state economic regions of Indiana provide such populations. Figure 1 shows the location of the Indiana Economic Regions.

There are significant differences among the economic regions in the urban-rural population distribution, in population size and in the medical care variables.

Abridged life tables were constructed for the white populations in each of the 14 state economic regions of Indiana for the census years 1950, 1960, and 1970. Differences in infant mortality, expectation of life at birth, and at age 65 were compared as the economic regions in each census year vary in proportion of population urban. Changes in the dependent variables were compared with change in proportion of population urban during decade intervals 1950-1960, 1960-1970, and 1950-1970.

In the data analysis a correlation which is not zero shows a relationship. However, in order to proceed with analysis of correlations that indicated substantial relationships, divisions were made in interpreting the correlations. Values which
Table 1

Life Table for State of Indiana, 1970

<table>
<thead>
<tr>
<th>Age</th>
<th>( n_x )</th>
<th>( n^0_x )</th>
<th>( n^p_x )</th>
<th>( n^d_x )</th>
<th>( l_x )</th>
<th>( n^l_x )</th>
<th>( T_x )</th>
<th>( e^0_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01908</td>
<td>0.97792</td>
<td>2208</td>
<td>100000</td>
<td>98454</td>
<td>7221671</td>
<td>72.2</td>
<td></td>
</tr>
<tr>
<td>1-4</td>
<td>0.0012</td>
<td>0.00488</td>
<td>0.99512</td>
<td>477</td>
<td>97792</td>
<td>390213</td>
<td>6923217</td>
<td>70.8</td>
</tr>
<tr>
<td>5-14</td>
<td>0.0005</td>
<td>0.00505</td>
<td>0.99495</td>
<td>492</td>
<td>97315</td>
<td>970685</td>
<td>6533004</td>
<td>67.1</td>
</tr>
<tr>
<td>15-24</td>
<td>0.0013</td>
<td>0.01255</td>
<td>0.98745</td>
<td>1215</td>
<td>96823</td>
<td>962152</td>
<td>5562318</td>
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</tr>
<tr>
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<td>0.0013</td>
<td>0.01275</td>
<td>0.98725</td>
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<td>95608</td>
<td>949983</td>
<td>4600166</td>
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<td>0.03293</td>
<td>0.97607</td>
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<td>932594</td>
<td>3650183</td>
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</tr>
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<td>0.93638</td>
<td>5861</td>
<td>92130</td>
<td>891994</td>
<td>2717588</td>
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</tr>
<tr>
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<td>0.12183</td>
<td>0.87817</td>
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<td>96269</td>
<td>810138</td>
<td>1825595</td>
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<td>0.00000</td>
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<td>75759</td>
<td>1015457</td>
<td>1015457</td>
<td>15.4</td>
</tr>
</tbody>
</table>


Table 2

Life Table Functions

The following life table functions were calculated for each population. In the subscripts, \( n \) is the number of years in an interval and \( x \) is exact age \( x \), the beginning year of an interval.

- \( n^M_x \): The death rate of the particular population under study between exact age \( x \) and age \( x + n \).
- \( n^q_x \): The probability of dying between exact age \( x \) and age \( x + n \).
- \( n^p_x \): The probability of surviving between exact age \( x \) and age \( x + n \).
- \( n^d_x \): The number of deaths occurring between exact age \( x \) and age \( x + n \).
- \( l_x \): The number of survivors in the cohort at exact age \( x \).
- \( n^l_x \): The number of years lived by the cohort between exact age \( x \) and age \( x + n \).
- \( T_x \): Total years lived by the cohort after exact age \( x \).
- \( e^0_x \): Expectation of life, the average number of years lived by cohort survivors after exact age \( x \).
<table>
<thead>
<tr>
<th>Table 3</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th></th>
<th>1950</th>
<th>1960</th>
<th>1970</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Highly Urban</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indianapolis</td>
<td>68.5</td>
<td>70.7</td>
<td>72.6</td>
</tr>
<tr>
<td>Gary-Hammond</td>
<td>67.1</td>
<td>72.5</td>
<td>70.9</td>
</tr>
<tr>
<td>South Bend</td>
<td>70.0</td>
<td>71.8</td>
<td>74.0</td>
</tr>
<tr>
<td><strong>Urban</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terre Haute</td>
<td>69.3</td>
<td>72.1</td>
<td>73.8</td>
</tr>
<tr>
<td>Muncie-Anderson</td>
<td>70.1</td>
<td>72.0</td>
<td>71.1</td>
</tr>
<tr>
<td>Evansville</td>
<td>69.3</td>
<td>71.0</td>
<td>74.2</td>
</tr>
<tr>
<td>Fort Wayne</td>
<td>70.3</td>
<td>69.7</td>
<td>70.9</td>
</tr>
<tr>
<td><strong>Mixed Urban-Rural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kokomo</td>
<td>69.7</td>
<td>70.8</td>
<td>70.5</td>
</tr>
<tr>
<td>Richmond</td>
<td>70.6</td>
<td>71.7</td>
<td>71.7</td>
</tr>
<tr>
<td>Bloomington</td>
<td>68.4</td>
<td>71.1</td>
<td>73.0</td>
</tr>
<tr>
<td>Lafayette</td>
<td>70.7</td>
<td>71.4</td>
<td>71.2</td>
</tr>
<tr>
<td><strong>Rural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Albany</td>
<td>69.8</td>
<td>72.3</td>
<td>72.7</td>
</tr>
<tr>
<td>Columbus</td>
<td>68.9</td>
<td>71.8</td>
<td>71.9</td>
</tr>
<tr>
<td>Lawrenceburg-Madison</td>
<td>70.2</td>
<td>72.4</td>
<td>72.7</td>
</tr>
</tbody>
</table>


were +.2 or larger and -2 or more negative were considered as showing enough of a relationship to note and consider further.

**Infant Mortality**

There is variation in infant mortality among the economic regions through the study period, although the differences are not on an urban-rural basis. While there are no significant urban-rural differences, the variation in infant mortality increased through the study period. Although infant mortality declines for each economic region during both 1950-1960 and 1960-1970 there is much variation in the decreases.

**Expectation of Life at Birth**

There are urban-rural differences in expectation of life at birth during the early part of the study period but those differences essentially disappear during the middle and later parts of the period. In 1950 an inverse relationship was indicated such that the more urban an economic region, the less was its expectation of life at birth. However, there is neither a trend to comparatively higher nor lower expectation of life at birth among the more urban economic regions during the 1960 and 1970 census years. This is shown by Table 3.

**Expectation of Life at Age 65**

There also are urban-rural differences in expectation of life at age 65. However the relationships show less strength than for expectation of life at birth. Although urban-rural differences decline after 1950 variation among the economic regions in expectation of life at age 65 increases throughout the study period as did infant mortality and expectation of life at birth as shown earlier. (See Table 4.)
Table 4
Indiana Economic Regions 1950-1970, Expectation of Life at Age 65 for
Regions Ranked by Proportion of Population Urban

<table>
<thead>
<tr>
<th></th>
<th>1950</th>
<th>1960</th>
<th>1970</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indiana</td>
<td>15.2</td>
<td>15.6</td>
<td>15.4</td>
</tr>
<tr>
<td>Highly Urban</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indianapolis</td>
<td>14.7</td>
<td>Gary-Hammond</td>
<td>15.7</td>
</tr>
<tr>
<td>Gary-Hammond</td>
<td>15.2</td>
<td>Indianapolis</td>
<td>15.9</td>
</tr>
<tr>
<td>South Bend</td>
<td>14.9</td>
<td>South Bend</td>
<td>15.2</td>
</tr>
<tr>
<td>Urban</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Terre Haute</td>
<td>15.2</td>
<td>Fort Wayne</td>
<td>15.8</td>
</tr>
<tr>
<td>Muncie-Anderson</td>
<td>15.5</td>
<td>Evansville</td>
<td>15.9</td>
</tr>
<tr>
<td>Evansville</td>
<td>15.1</td>
<td>Muncie-Anderson</td>
<td>15.0</td>
</tr>
<tr>
<td>Fort Wayne</td>
<td>15.2</td>
<td>Terre Haute</td>
<td>14.5</td>
</tr>
<tr>
<td>Mixed Urban-Rural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kokomo</td>
<td>15.9</td>
<td>Richmond</td>
<td>15.3</td>
</tr>
<tr>
<td>Richmond</td>
<td>15.9</td>
<td>Kokomo</td>
<td>16.3</td>
</tr>
<tr>
<td>Bloomington</td>
<td>14.6</td>
<td>Bloomington</td>
<td>14.7</td>
</tr>
<tr>
<td>Lafayette</td>
<td>15.7</td>
<td>Lafayette</td>
<td>15.6</td>
</tr>
<tr>
<td>Rural</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Albany</td>
<td>15.0</td>
<td>New Albany</td>
<td>16.0</td>
</tr>
<tr>
<td>Columbus</td>
<td>15.1</td>
<td>Columbus</td>
<td>16.0</td>
</tr>
<tr>
<td>Lawrenceburg-Madison</td>
<td>16.0</td>
<td>Lawrenceburg-Madison</td>
<td>16.6</td>
</tr>
</tbody>
</table>


**Medical Care and Infant Mortality**
Several demographic researchers have proposed a relationship between quantities of medical care available to a population and mortality and expectation of life. In this study there are no significant relationships demonstrated between infant mortality and those measures of medical care selected. All correlation values are within the range +.2 to -.2.

**Medical Care and Expectation of Life**
There are significant relationships between expectation of life at birth and four variables of medical care: number of physicians, hospital beds, patients admitted and patient days, but not for either occupancy rate or usage rate through the study period. The association between expectation of life at birth and the four medical care variables alters from inverse in 1950, to a direct relationship during 1950-1960. From 1960 through the succeeding decade there is no trend to either a higher or lower expectation of life among those economic regions with comparatively larger quantities of the medical care variables.

There are also significant relationships demonstrated between expectation of life at age 65 and these four medical care variables: number of physicians, hospital beds, patients admitted, and patient days. Again there are no significant correlations for occupancy rate or usage rate through the study period. That is, in 1950 expectation of life at age 65 is greater for those economic regions with comparatively less medical care. In contrast the greater the change in expectation of life at age 65, during 1950-1960, the greater are the increases in the four medical care variables. For 1960 and the succeeding decade to 1970, there are
no significant relationships indicated.

The strong negative relationship between expectation of life at birth and the five independent variables in 1950 was shown with multiple correlation, using step-wise regression. The order of the independent variables was (1) proportion of population urban, (2) patients admitted, (3) hospital beds, (4) patient days and (5) number of physicians. That is, the proportion of population urban had the greatest negative effect on expected length of life at birth, with each of the following variables having sequentially less negative effect. The multiple correlation in this inverse relationship is -.80, with 64 percent of the variance explained by the five variables.

The life tables from this study provide the basic tool for developing population projections by giving the prerequisite data for calculating age specific survival ratios. If mortality remains at the observed levels, the differing mortality rates among the economic regions will result in different proportions of the present populations alive in future years. Survival ratios provide the population base for calculating the volatile components of population change which are fertility and migration. The size, age structure and growth rates of the projected populations are important variables that affect water resource needs. The use of these data along with data pertaining to variables such as income distribution and industrial development in the economic regions, will enable us to make estimations of future water resource demands.

**Population Trends**

The purpose of developing the life table and studying urban-rural differences and medical care factors in relationship to it has been to better understand population trends and projections.

Population growth in the United States as a whole has been consistent and substantial as shown in Table 5. There was some decline in growth after the 1900-1910 decade with World War I and the establishment of immigration quotas; during the depression of the '30's the birth rate declined, reducing the percent of growth. Looking at areas within the nation shows more irregular rates of growth. This is shown in Table 5 for Indiana, the eight-county Lafayette-West Lafayette Region (BEA Region 59), Tippecanoe County and the two towns of more than 2,500 people within the county. The Region actually had a net loss during the early part of this century, with Tippecanoe being the only County to increase each decade since 1900.

A major point to be made about population growth is that patterns which exist at the national level may have little relationship to what occurs at the local level. The relative stability in growth rate for the nation is not shown at the region, county or city level. These differences in rates of growth become particularly important in interpreting population projections.

In addition to absolute numbers of people, the distribution of population is important in water

<table>
<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>21.0</td>
<td>15.0</td>
<td>16.2</td>
<td>7.3</td>
<td>14.5</td>
<td>18.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Indiana</td>
<td>7.3</td>
<td>8.5</td>
<td>10.5</td>
<td>5.8</td>
<td>14.8</td>
<td>18.5</td>
<td>11.4</td>
</tr>
<tr>
<td>Region 59</td>
<td>-3.1</td>
<td>-1.3</td>
<td>-1.0</td>
<td>3.4</td>
<td>15.6</td>
<td>11.0</td>
<td>10.1</td>
</tr>
<tr>
<td>Tippecanoe County</td>
<td>3.6</td>
<td>6.7</td>
<td>11.0</td>
<td>7.3</td>
<td>46.0</td>
<td>19.7</td>
<td>22.7</td>
</tr>
<tr>
<td>Lafayette</td>
<td>10.8</td>
<td>12.0</td>
<td>16.7</td>
<td>9.7</td>
<td>23.5</td>
<td>19.0</td>
<td>6.2</td>
</tr>
<tr>
<td>West Lafayette</td>
<td>68.0</td>
<td>-1.0</td>
<td>33.0</td>
<td>23.1</td>
<td>89.4</td>
<td>6.8</td>
<td>51.1</td>
</tr>
</tbody>
</table>
resources studies. The eight-county region has had a decline in the rural farm population over the last two decades, but has had an increase in people outside of towns not engaged in farming. In addition, annexation has accounted for the growth that has occurred in almost all of the towns in the Region, with 7 of the 9 towns of 2500 or more annexing land between 1960 and 1970. The increase of 36 percent in land area is substantial in terms of the provision of services such as water and sewers.

A better knowledge and understanding of the linkages between population growth and distribution, changing land use and water resources has become increasingly important. Increases in the world demand for food and high pollution levels in some areas have resulted in legislative and administrative actions affecting land and water resources. A knowledge of recent trends in population should be included in planning the future use of these resources, as should population projections.

**Population Projections**

Decisions which have a relatively long term effect or use, such as developing water supplies or building schools, should be made with some understanding of the amount of use they will receive over the next few decades. Population projections are a means of helping to estimate that use. They must be used with CAUTION; most importantly the assumptions used in making the projections need to be understood. The three factors that affect population are births, deaths and migration. The birth rate has been declining in the United States since 1957; it may be leveling off but that is uncertain. The death rate has been rather steady; it may decline some but probably not a great deal. Migration, however, for cities, counties or regions is very volatile. It is the factor that is most likely to render population projections inaccurate for such areas.

It is useful to briefly illustrate two points about projections with the data in Table 6 for the eight-county Lafayette-West Lafayette area (BEA Area 59). The first two rows of the table show the OBERS projections made for the Water Resources Council through 2020. The projected population shown in these two rows differ considerably, especially for 2000 and beyond, because of the differences in fertility and migration. In the first row the fertility assumed is an average of 2.8 births per woman during her lifetime compared to 2.1 in the second row. The specific migration assumptions are not given, but they are derived from estimates of employment in both sets of OBERS projections. The higher fertility rate, not obtained since the mid-1960's combined with the greater in-migration rate to the area, produced quite different results by 30 to 50 years into the future. Rows three and four show projections for the same area, made as part of this study. They use 2.5 (which would require a fairly substantial turn around from the present rate) and 2.1 fertility rates, and both use the migration rate for the eight-county area that occurred from 1960-1970, which showed a slight net out-migration of 0.7 percent. Row three assumes a decrease in the death rate of 4 percent by 2020, which is a little more of a decrease than used in either OBERS, and row four assumes a decrease of 8 percent by 2020 which is larger than is generally expected to occur by that time. The point of rows 2, 3 and 4 is that even though there are some variations in assumptions, the differences at 30 years and 50 years are not great. However, a major change in migration as in row 1, with or without higher fertility, could produce a substantial change.

To conclude this brief discussion of projections, we should note three points. First, the most current data available should be used to make projections; second, the assumptions on which the projections are based must be specified and considered; and third, it is desirable to have a series of projections based on somewhat different assumptions so that comparisons particularly for more distant points in the future can be made.

### 3.3 Residential Water Consumption

An examination of the factors that affect differential rates of residential water consumption can be important both in forecasting future water use and in setting policies that influence that use. Several studies have emphasized the importance of studying factors that affect each of the different types of water use, that is, residential, industrial
Table 6  Population Projections with Different Assumptions for BEA Region 59

<table>
<thead>
<tr>
<th></th>
<th>Fertility</th>
<th>1980</th>
<th>2000</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>OBERS(^a)</td>
<td>2.8</td>
<td>290,400</td>
<td>388,800</td>
<td>519,300</td>
</tr>
<tr>
<td>OBERS(^b)</td>
<td>2.1</td>
<td>260,800</td>
<td>286,400</td>
<td>309,200</td>
</tr>
<tr>
<td>Potter et al(^c)</td>
<td>2.5</td>
<td>250,000</td>
<td>267,000</td>
<td>265,000</td>
</tr>
<tr>
<td>Potter et al(^c)</td>
<td>2.1</td>
<td>249,000</td>
<td>262,000</td>
<td>278,000</td>
</tr>
</tbody>
</table>


and commercial uses. This study focuses on factors that affect residential water use.

There are two objectives to this portion of the study. First is to do a more detailed examination of the variables affecting residential water use than has been done previously and second to use data that are available to medium size communities for doing this.

A) METHODOLOGY

The tract and block method is used in this study, with tract and block referring to geographic areas for Standard Metropolitan Statistical Areas (SMSA's) as reported by the Bureau of the Census. The advantage of using these two units is that the data are available for S. M. S. A.'s, generally meaning those cities of 50,000 or more population. There are some disadvantages of this approach, particularly having to do with how homogeneous tracts or blocks are, and the fact that the data are for areas and not for individual residences.

Tract Characteristics

Census tracts are designed as relatively homogeneous areal units, that is a geographic territory whose population is similar in income, housing characteristics, education and occupational status. For example boundaries include main thoroughfares, open fields and railroad tracks. The entire area of every S. M. S. A. is divided into census tracts, with a population of 4000 to 6000 persons at the time the divisions are made.

The first step in the tract analysis is to graph the tracts that are used by medium family income and to compare this with the other variables. Mean family income and percent of families in single family dwelling units are two of the indicators of socio-economic status examined in the study; other indicators are median owned housing value, median rent, median number of rooms in occupied dwelling units, percent of population over 21 that are high school graduates, proportion of tract population employed in white collar occupations, and percent of families below poverty level. Three age composition measures were also used: percent of population under 5 years of age, percent under 18 and percent 65 years and older.

Block Characteristics

The use of block data for studying factors affecting residential water use has two specific advantages. First the blocks tend to be more homogeneous than the tracts since they are much smaller units. A block is indeed a city block, typically bounded by four streets. Another advantage is that there is a larger number of blocks. Statistically this larger number of study areas permit
detailed analysis. However, a major disadvantage is that less data are available for blocks.

Regression equations of the following type can be used to analyze the relationship between the socioeconomic variables and residential water use:

\[ Y = A + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 \]

where

\[ Y = \text{domestic water consumption in gallons per month per person for a block} \]
\[ x_1 = \text{mean owned housing value, $} \]
\[ x_2 = \text{mean number of rooms per person in owned housing (tenths of a room)} \]
\[ x_3 = \text{mean monthly rent, $} \]
\[ x_4 = \text{mean number of rooms per person in rented housing unit (tenths of a room)} \]
\[ x_5 = \text{proportion of population aged 18 and younger} \]
\[ x_6 = \text{proportion of population aged 62 and older} \]

The regression coefficients, the b's, show the amount of change in water used, in average gallons per person per month for a given change in the other variables.

**Interactions Among the Variables Affecting Water Use**

Thus far only the effect of one variable at a time on water use has been considered. In addition all possible combinations of these variables can be studied for interaction. The interaction terms that were found to be significant in the case study concern the age variables with owned housing value or home size.

The model is now of the type:

\[ Y = A + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_6 + b_7 x_1 x_5 + b_8 x_1 x_6 + b_9 x_4 x_5 + b_{10} x_4 x_6 + b_{11} x_3 x_5 x_6 \]

**B) CASE STUDY**

The Lafayette - West Lafayette, Indiana, area was the basis for this analysis. In 1970 the population of this S.M.S.A. was 109,378 people, with 79,117 living in the urbanized area. Of these 44,955 lived in the City of Lafayette, and 19,157 lived in West Lafayette.

There are 19 census tracts within the Lafayette-West Lafayette urbanized area. Three of those tracts comprise the campus of Purdue University, and had to be omitted because the university does not meter residential units water use separately from other use. Two additional tracts adjacent to the university are excluded because most of the residents are students, and as a result several categories of tract data are either not reported or would distort the analysis.

The findings of the tract analysis show that there are large differences in domestic water use among census tracts. Furthermore these differences are related consistently to levels of family income with the average per person use in the higher income tract being almost three times that of the low income tracts. The middle income and low middle income area fall consistently in between.

The relationships between domestic water use and income are also generally consistent for the other indicators of socio-economic status, that were mentioned above. Table 7 shows the socioeconomic variables and the water consumption for the 14 census tracts within the urbanized area.

There are 722 blocks within the 14 tracts analyzed. For the block analysis the unstandardized (b) and standardized (B) regression coefficients are shown in Table 8. The standardized B coefficients show that the greatest change in water use occurs with changes in mean owned housing value and mean monthly rent, and the least change is associated with changes in proportion of population under age 18 and proportion of population age 62 and older. It should be noted that block data do not contain family income information. As with the tract analysis, the block data show the strongest relationship between measures of socio-economic status and water use rather than with age composition variables.

Another way of interpreting the regression coefficients (using the unstandardized b weights) is, for example, that each $100 increase in home value is accompanied by a rise of 6.8 gallons per capita per month in water consumption. A house that costs $1000 more then would have approximately 70 gallons more consumption per person per month, or about 840 gallons per person per year. An increase of one full room per person in the size of a home is associated with an increase of approximately 240 gallons
TABLE 7

Lafayette-West Lafayette, Indiana, S.M.S.A.: Socio-Economic Characteristics and Mean Water Consumption for Census Tracts in the Urbanized Area

<table>
<thead>
<tr>
<th>S.M.S.A.</th>
<th>Median Owned Housing Value Dollars</th>
<th>Median Rent Dollars</th>
<th>Median Number of Rooms in Occupied Dwelling Units</th>
<th>Percent of Families Living in Single Dwelling Units</th>
<th>Percent of Population Over 21 That Are High School Graduates</th>
</tr>
</thead>
<tbody>
<tr>
<td>17,300</td>
<td>105</td>
<td>2.6</td>
<td>81.1</td>
<td>67.7</td>
<td></td>
</tr>
</tbody>
</table>

Census Tract Number (Tracts Ranked by Income)

(High Income)

| 52       | 34,200   | 147       | 2.9    | 95.1    | 93.1 |
| 53       | 23,100   | 147       | 2.3    | 91.2    | 91.8 |

(Middle Income)

| 11       | 17,900   | 103       | 2.3    | 87.3    | 73.1 |
| 10       | 21,300   | 85        | 2.4    | 84.2    | 63.1 |
| 13       | 17,000   | 139       | 3.4    | 77.1    | 80.5 |
| 12       | 14,200   | 95        | 2.3    | 79.2    | 59.7 |
| 03       | 15,600   | 104       | 2.9    | 76.7    | 74.0 |

(Low Middle Income)

| 08       | 14,300   | 96        | 2.3    | 78.6    | 58.8 |
| 02       | 12,800   | 88        | 2.6    | 78.4    | 48.7 |
| 09       | 9,800    | 65        | 2.7    | 79.7    | 42.7 |
| 07       | 11,700   | 88        | 2.1    | 53.1    | 48.0 |

(Low Income)

| 06       | 11,300   | 73        | 1.3    | 49.9    | 41.2 |
| 04       | 10,400   | 78        | 2.1    | 46.3    | 31.8 |
| 05       | 11,000   | 82        | 1.8    | 48.1    | 40.1 |
TABLE 8
MULTIPLE REGRESSION ANALYSIS, PER CAPITA WATER CONSUMPTION AND BLOCK DATA:

b REGRESSION WEIGHTS AND THE STANDARDIZED b* WEIGHTS, STANDARD DIVISION AND MEAN FOR EACH VEHICLE

Dependent Variable: Mean Monthly Water Consumption for Blocks
A Regression Constant: 1,549.08679

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>b Weights</th>
<th>B Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Owned Housing Value</td>
<td>.06743</td>
<td>.07711</td>
</tr>
<tr>
<td>Mean Monthly Rent</td>
<td>.81616</td>
<td>.06428</td>
</tr>
<tr>
<td>Mean Number of Rooms per Person in Owned Housing</td>
<td>23.77340</td>
<td>.02498</td>
</tr>
<tr>
<td>Mean Number of Rooms per Person in Rental Housing</td>
<td>20.13120</td>
<td>.2132</td>
</tr>
<tr>
<td>Proportion of Population Under Age 18</td>
<td>2.56937</td>
<td>.01441</td>
</tr>
<tr>
<td>Proportion of Population Age 62 and Older</td>
<td>-2.12910</td>
<td>-.01170</td>
</tr>
</tbody>
</table>

Multiple R = .81505
Multiple R Squared = .66431

* Beta weights are the standardized regression coefficients. Beta is interpreted as the amount of change in the dependent variable in standard deviation units occurring per standard deviation unit change in an independent variable from its mean, holding the remaining independent variable constant.

TABLE 9
PREDICTED VALUES OF DOMESTIC WATER USE, SHOWING INTERACTION OF AGE AND OWNED HOME VALUE

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>High Owned Home Value</td>
<td>4,874.31</td>
<td>4,129.27</td>
<td>3,989.51</td>
</tr>
<tr>
<td>Low Owned Home Value</td>
<td>2,910.91</td>
<td>2,487.41</td>
<td>2,591.97</td>
</tr>
</tbody>
</table>

Interaction of Population Aged 18 and Younger and Owned Home Value

Interaction of Population Aged 62 and Older and Owned Home Value
per person per month. A similar pattern is found for mean monthly rent and rooms per person in rental housing. The changes in water consumption with changes in age are small as already indicated and go in opposite directions. For example, a 1% increase in the proportion of population 18 years of age and younger is accompanied by an increase of only 2.6 gallons per person per month of water use. In contrast a 1% increase in the elderly population is associated with a decline of 2.1 gallons per person per month in water use.

After consideration of the interactions between the age variables and owned housing value or home size the correlation model becomes:

\[
Y = 1723.09 + 0.06597x_2 + 28.23x_2 + 0.8392x_3 + 9.813x_4 + 4.239x_5 - 3.930x_6 + 0.0047x_1x_5 - 0.0061x_1x_6 + 0.0027x_1x_6 + 0.0019x_4x_6 + 0.0034x_3x_6
\]

The interaction effects demonstrate that the relationship of age composition to domestic water use varies by housing value. Table 9 shows how owned home value interacts with age composition to affect monthly water use per person. In this table it is apparent that higher consumption is associated with high owned home value but that rate of consumption varies as the age composition of the block varies.

**Summary of Tract and Block Findings**

The findings of both the tract and block analyses were similar. There were substantial variations in monthly consumption of water per person. The indicators of socioeconomic status showed a consistently stronger relationship to water use than did the age composition variables. The relationship of socioeconomic status to water use are strong enough to suggest that these factors might appropriately be taken into account in water resources planning and policy decisions, and that available census data can be used.

**C) RELATIONSHIP TO PHASE II**

Water resources planning needs to include patterns of population growth and distribution among the many factors to be considered in decision making. Size of population is related to water con-
CHAPTER 4

GEOLOGIC INVESTIGATION

4.1 INTRODUCTION

The objectives of this investigation are to devise methodologies to (1) locate the principal sources of groundwater in the vicinity of an urban area and (2) to locate the areas of ground water recharge and inflow. The first objective is an essential prerequisite for the development of a mathematical model of the aquifers. Such a model will suggest the probable response of an aquifer under different stresses corresponding to possible future land use patterns and future water demands. The second objective is essential in order to prevent possible damage through urbanization to the areas of groundwater recharge. These recharge areas must be identified and preserved, perhaps in green belts, parks or other land use that would not interfere with the inflow to the groundwater or contaminate it at the points of entry to the aquifers.

An understanding of the location of the aquifers and of their recharge areas will contribute to the orderly development of groundwater resources. This will help to meet the growth demands of a medium-size community without damaging or depleting the aquifers, and will help to guide proper development of the community so as to preserve this vital resource.

For detailed information and analysis of the test area in Tippecanoe County, the reader is referred to Purdue Water Resources Research Center Technical Report No. 61 entitled "Hydrogeology of Glacial Deposits in Tippecanoe County, Indiana" by A. Maarouf and W. N. Melhorn, June 1975, 107 pp. and 4 pocket plates.

4.2 METHODOLOGY

A systems approach to the geologic analysis is given in Figure 2. Acquisition of the geologic data starts with the compilation of the well records. These records include the driller's well logs and static water level information for the observation wells. Other data inputs include seismic data, topographic and soil maps and outcrop information.

From these data several types of information are developed and presented in sets of maps. These are:

1) lithofacies ratio maps
2) map of the configuration and geology of the bedrock surface
3) unconsolidated material thickness map
4) orographic features map
5) infiltration properties and surface geology map.

The lithofacies ratio maps are based on the lithologic information between the ground surface and the bedrock surface as obtained from well records. The subsurface materials are divided into a number of slices of equal thickness extending from ground surface to bedrock. A thickness interval of 50 feet per slice was used in this application. A map is prepared for each slice and the ratios of the probable thickness of water-bearing sand and/or gravel to the total thickness of the slice are shown on the maps. These maps may be overlaid progressively from the bottom upward, and an estimate of the cumulative percentage of sand and/or gravel thickness may be obtained, which is related to the probability of finding a water producing aquifer at a given location. Although the technique of lithofacies ratio maps is not new it has not generally been used elsewhere in groundwater studies. The use of lithofacies maps optimizes the location of exploratory or developmental wells.

The map of the configuration and geology of the bedrock and the map of the unconsolidated material thickness are derived from well records and seismic data. The control points are the same for both maps.

The map of the orographic features and surface drainage can be obtained from U. S. Geological Survey 7½ minute series topographic maps. The in-
FIGURE 2  SYSTEMS APPROACH TO GEOLOGIC ANALYSIS
filtration properties and surface geology map is accomplished by combining soil maps with surface material maps. The infiltration map is a new product which represents a major contribution to hydrogeology as it combines all physical properties of soils, the engineering geology, and the topography in an overall index of surficial material infiltration capacity. For the purpose of the present study the soils were grouped into four categories:

a) high permeability: infiltration rate exceeds 2 inches/hour
b) moderate permeability: infiltration rate is 2 to 0.6 inches/hour
c) low permeability: infiltration rate is 0.6 to 0.06 inches/hour
d) very low permeability: infiltration rate is less than 0.06 inches/hour.

Interglacial paleo-surface maps were also prepared. These are based on the top of oxidized till sections, the top of thick outwash sections and/or the occurrence of buried muck, peat or wood chunks. These maps represent the approximate topography during each of the glacial stages that affected the area.

Cross-sections and fence diagrams are based on well records and the bedrock map. Lines of cross-section and their geographic spacing are determined relative to distribution of available data, thickness variation of units, and the need to get an areal coverage across the country and more detailed local coverage in the metropolitan area.

The end result is the aquifer maps which are prepared using data from well records, topographic maps, interglacial paleo-surface maps, and the cross-section and fence diagrams. This procedure makes it possible to discriminate aquifers in terms of their geological age.

4.3 CASE STUDY

As the communities of Lafayette and West Lafayette are located approximately at the center of Tippecanoe County, the entire county was used for the case study. Tippecanoe County, located in west-central Indiana, is a rectangle 24 miles long and 21 miles wide. Tippecanoe County was invaded during 3 major episodes of Pleistocene continental glaciation. The 3 major drift sheets are pre-Illinoian, Illinoian, and Wisconsinan in age. These drifts are separated by 2 major buried paleosols. The Yarmouthian soil developed on the uppermost pre-illinoian deposit, whereas Sangamonian soils developed on the surface of the Illinoian drift.

The principal bedrock formations underlying the drift mantle in the county are shale, siltstone and limestone. Figure 3 shows the classification of the bedrock and overlying deposits. In this figure the first set of columns gives the geologic age of the deposits, the fourth column compares their general physical characteristics, the sixth gives the deposit thickness, the sixth gives a history of the area indicating what the terrain was like and what conditions may have induced the preservation of aquifer material. The last column shows what are at present the properties and possibilities of each deposit as potential aquifers.

The drift mantle overlies marine sediments deposited during the Silurian, Devonian, Mississippian, and Pennsylvanian periods of the Paleozoic Era. Paleozoic rocks were subjected subsequently to almost continuous erosion to produce a well-dissected mature topographic surface before the first ice advance. The boundaries and distribution of the different rock formations are not definitely known because of the thick overlying cover. The bedrock surface configurations, as well as structure and lithology of the formations affect to some extent the ground water conditions.

The pre-Pleistocene drainage pattern does not coincide with the present drainage pattern, as is shown in Figure 4. The most significant changes were caused by the Illinoian ice which dammed the pre-glacial Teays River channel and formed Glacial Lake Lafayette. An outlet channel, developed to drain this lake, was perpetuated as the present Wabash River drainage southwest of Lafayette.

Unconsolidated glacial deposits of the county range in thickness from zero to 450 feet but average about 200 feet. The glacial drift contains significant aquifers. The aquifer distribution has been mapped, and the lithologic, stratigraphic and
<table>
<thead>
<tr>
<th>TIME UNIT</th>
<th>ROCK UNIT</th>
<th>PHYSIOGRAPHIC ASPECTS</th>
<th>HYDROGEOLOGIC ASPECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene</td>
<td>mostly alluvium, some colluvium and lacustrine deposits of Martinsville Fm</td>
<td>development of present drainage</td>
<td>possible aquifer, if materials are pe and below the water table</td>
</tr>
<tr>
<td></td>
<td>Loessal sand and silt, and lacustrine deposits of Atherton Fm</td>
<td>lakes and swamps, dunes on lower terrace and flood plains</td>
<td>permeable material below water table may yield adequate domestic supplies clay may confine the underlying aquifer</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>mostly sand and gravel outwash of Atherton Fm</td>
<td>formation of lower Wabash terrace initiation of present drainage formation of Wabash upper terrace and outwash plains</td>
<td>large supplies along the Wabash Valley subject to pollution if not protected</td>
</tr>
<tr>
<td></td>
<td>mostly till, some gravel and sand of ice contact stratified drift (Leifalar Fm)</td>
<td>ground moraines, and moraines, kames, and eskers; burial of some older drainage lines</td>
<td>till may act as a confining bed to the underlying aquifer</td>
</tr>
<tr>
<td>Sangamonian</td>
<td>mostly sand and lacustrine deposits</td>
<td>development of local erosion surfaces lakes and swamps</td>
<td>possible water-bearing zones in coarse-grained alluvium</td>
</tr>
<tr>
<td>Cenozoic</td>
<td>mostly sand and gravel outwash of Atherton Fm</td>
<td>re-excavation of Wabash channel as an outwash slough; drainage west of Lafayette, elimination of the Leipsic-Mahomet drainage line</td>
<td>contains large supplies of water especially if connected with a surface water resource</td>
</tr>
<tr>
<td>Illinoian</td>
<td>mostly till of Buttsville Member (Issemm Fm)</td>
<td>Glacial Lake Lafayette ground moraines, and moraines?, and local outwash plains</td>
<td>till confines the underlying aquifer; possible adequate domestic supplies if a sand lens is present</td>
</tr>
<tr>
<td></td>
<td>Kankakee sand and lacustrine deposits</td>
<td>development of local erosion surfaces lakes and swamps</td>
<td>possible water-bearing zones in coarse-grained alluvium</td>
</tr>
<tr>
<td></td>
<td>mostly sand and gravel outwash of Atherton Fm</td>
<td>re-excavation of Wabash channel as an outwash slough; filling of Ottowa Valley, ground moraines, and moraines?, and local outwash plains</td>
<td>large under developed water supplies</td>
</tr>
<tr>
<td></td>
<td>mostly till of Cleveland Member (Cassopolis Fm)</td>
<td></td>
<td>may confine the underlying aquifer</td>
</tr>
<tr>
<td>Silurian</td>
<td>mostly sandstone of Mansfield and Brazil Fms</td>
<td></td>
<td>water may be adequate for domestic or municipal supplies, possibility of contamination</td>
</tr>
<tr>
<td></td>
<td>mostly shale and siltstone of Rixford Group, some limestone of Rockford and lower part of Herrickburg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Devonian</td>
<td>New Albany Shale</td>
<td></td>
<td>water in joints may be adequate for domestic or municipal uses, possibility of contamination</td>
</tr>
<tr>
<td></td>
<td>limestone and dolomite of Geneva, Jeffersonville, and N. Vernon Fms</td>
<td></td>
<td>water in joints at top may or may not yield adequate domestic supplies; sulfur contamination high acts as confining layer to the underlying aquifer water in joints enlarged by solutions supplies adequate for domestic, municipal and industrial purposes, contaminated by sulfur from overlying New Albany Shale</td>
</tr>
<tr>
<td></td>
<td>limestone of Linton Creek Member (Wabash Fm)</td>
<td></td>
<td>probably aquifer; water in joints enlarged by solutions</td>
</tr>
</tbody>
</table>
A. Present Drainage

B. Sangamonian Drainage

C. Yarmouthian Drainage

D. Pre-Pleistocene Drainage

FIGURE 4  CHANGES IN DRAINAGE, PRE-PLEISTOCENE TO PRESENT
hydrogeologic aspects have been analyzed.

Aquifers in the county are delineated, mapped and classified according to their stratigraphic position. They are ranked in decreasing order of productivity as follows: (1) pre-Illinoian outwash aquifer, (2) Illinoian outwash aquifer, (3) Wisconsinan outwash aquifer, (4) Holocene alluvium aquifer, (5) bedrock aquifer and (6) disconnected sand and gravel lenses within the till.

Figures 5 through 8 are maps showing the distribution of the four principal aquifers in Tippecanoe county. These maps are the end product of the methodology described in Figure 2. It is the first attempt in this area to discriminate the aquifers in terms of the geological age of the formation.

Figure 5 shows the Pre-Illinoian outwash aquifer. It is areaally extensive but has not been greatly developed. Thickness ranges from zero where there is no pre-Illinoian sand or gravel, to approximately 200 feet in the buried Teays channel. The aquifer is covered by Illinoian till, which acts as a confining bed, and is bounded below by bedrock. However, it may be covered locally by Illinoian or Wisconsinan outwash.

Figure 6 shows the Illinoian aquifer. It is the most extensive aquifer in the county. The thickness ranges from zero to more than 100 feet in the buried Clarks Hill Valley. Most of the aquifer is covered by Wisconsinan till as a confining bed, and is underlain by Illinoian till. At West Lafayette the aquifer is unconfined, and thus is bounded upward by the water table. The aquifer is connected hydraulically with the Illinoian aquifer in the surrounding counties.

Figure 7 shows the map of the Wisconsinan aquifer. It extends over a large area but most of it is unsaturated. Most of the saturated Wisconsinan outwash is in the Wabash Valley. The total thickness varies from zero to about 50 feet. The aquifer is not widely utilized. The Wisconsinan outwash aquifer in the Wabash Valley is connected downward with the Illinoian aquifer. It is bounded upward by the water table or by a confining fine-grained alluvium. Away from the Wabash Valley it is underlain by Wisconsinan till.

Figure 8 shows the map of the Holocene alluvium aquifer. It is less important and less developed than the underlying aquifers because of its limited distribution and hydrologic potential.

Recharge to ground water in Tippecanoe County is from direct precipitation, intermittent influent streams on the upland, influent seepage of perennial streams at high stage, vertical leakage from overlying deposits, or subsurface underflow from the east or northeast. Concurrent studies of the digital ground water model suggest that the probable recharge rate for glacial sand and gravel in the Wabash River valley is about 0.9 mgd (million gallons/day)/mi² and in the terraces ranges from 0.25 mgd/mi² to 0.4 mgd/mi².

The Wabash River receives considerable base flow from the aquifers, which is computed to be about 6.5 mgd/mi².

The outwash aquifers are an excellent source for industrial and municipal water supplies. Medium-diameter wells generally yield more than 100 gallons per minute. The Holocene alluvium aquifers and disconnected sand and gravel lenses within the till are potential sources for individual domestic supplies. However, wells generally yield less than 12 gallons per minute. The areas of largest yield and best potential for intensive future development are those where outwash aquifers are hydraulically connected to the Wabash River. Pumpage, if limited to the amount of recharge, should not produce a decline in water levels in the future.

Figure 9 is the drainage map of Tippecanoe County. The county lies in the Middle Wabash River drainage basin. The river courses southwestward from the northeastern corner of the county and receives most of the natural surface and subsurface drainage. The northern, northeastern and northwestern parts of the county are mainly drained by the Tippecanoe River, and Burnetts, Sugar, Buck, Indian and Little Pine Creeks. The southern and southwestern parts are essentially drained by Wea, Dismal, Flint and Shawnee creeks. The Tippecanoe River and the Wildcat, Wea and Indian creeks have diverted the Wabash River away from their outlet and against the opposite bluffs. The widest part of the Wabash Valley is north of Lafayette where
FIGURE 5  GENERALIZED MAP SHOWING DISTRIBUTION OF THE PRE-ILLINOIAN OUTWASH AQUIFER, TIPPECANOE COUNTY
FIGURE 6 GENERALIZED MAP SHOWING DISTRIBUTION OF THE ILLINOIAN OUTWASH AQUIFER, TIPPECANOE COUNTY
FIGURE 7 GENERALIZED MAP SHOWING DISTRIBUTION OF THE WISCONSINIAN OUTWASH DEPOSITS, TIPPECANOE COUNTY
FIGURE 9 DRAINAGE MAP, TIPPECANOE COUNTY, INDIANA SHOWING THIRD ORDER DRAINAGE
joined by Wildcat Creek. The valley is also wide southwest of Lafayette, where joined by Wab Creek.

The Wabash River upstream of Lafayette is partially controlled by the Huntington, Salamone and Mississinewa Reservoirs. In addition, the Lafayette Reservoir on Wildcat Creek has been proposed but at the time of the writing of this report its construction had not been authorized.

Parts of the City of Lafayette are subject to flooding. The Corps of Engineers in conjunction with the Indiana Department of Natural Resources have prepared a map which shows the areas flooded by the 100-year flood.

4.4 THE GROUND-WATER RESOURCE

The recent U.S. Geological Survey Professional Paper 813A entitled, "Summary Appraisals of the Nation's Ground-Water Resources - The Ohio Region" by Richard M. Bloyd Jr. states that an estimated 108 trillion gallons of water - about one fourth the volume of Lake Ontario - is available from groundwater supplies in the 160,000 square-mile Ohio River Region, which includes parts of Pennsylvania, Ohio, West Virginia, Kentucky, Tennessee, Virginia, Indiana and Illinois.

The report also notes that:

"Under certain conditions, this excess of ground water recharge over the present use could supply the water needs of an additional 22 million people in the Wabash River basin (which includes Lafayette, Ind.)...."

"The Wabash and White River basins probably have the highest potential for additional ground water development in the Ohio Region. About 30 trillion gallons, or 28 percent of the total potable ground water stored in the region, is contained in these basins. Current development plans, however, do not approach the full ground water potential."

The report also notes limitations and problems associated with increased development of the resource, such as a drop in the water table and quality and pollution of the ground water.

Ground water is the most important natural resource in Tippecanoe County. Ample supplies are available in most of the county, where ground water development potential is much more than the present consumption. Ground water currently provides for all domestic, farm, municipal and industrial needs.

Wells average 200 feet deep and yield between 5 and 2,000 gallons per minute. The present pumpage for the county is approximately 35 million gallons per day. Assuming an exponential annual increase slightly in excess of 1 million gallons per day, the pumpage is expected to be 100 million gallons per day by the year 2020. There is a good possibility of obtaining this future consumption from the ground water resources without recourse to surface supplies.

Future development of ground water resources in Tippecanoe county is most favorable in unexploited areas of thick sand and gravel which occupy the Teays, Anderson, Clarks Hill and other preglacial bedrock valleys. These aquifers extend beyond the county boundaries as do the preglacial channels. The ground water occurs under both leaky artesian and water table conditions. No apparent long-term, continuous decline in water level exists. Quality is good, but subject to pollution by dispersed wastes. The Lafayette community has relied on groundwater historically (since 1911 as a municipal system) and will do so for the time horizon programmed.

4.5 GROUND WATER QUALITY

All ground water contains dissolved minerals, and the mineral content is related to the materials through which the water flows or percolates, the length of time it is contact with the materials (flow rate), and internal pressure-temperature relations of the aquifer. Ground water in the Lafayette area moves through glacial drift materials derived in large part from the erosion and redeposition of sedimentary and granitic rocks, and is especially high in calcium and magnesium carbonates. Water having a hardness of more than 200 parts per million is considered "hard", and thus ground water of the Lafayette area is considered "very hard." Iron content of more than .3 parts per million is also considered objectionable, and some waters in Tippecanoe County exceed these limits. However, the iron concentrations seem to be localized, and in general is less than that encountered in similar
areas elsewhere in the glacial drift region. It
does not present much of a treatment problem in
municipal, industrial, or individual water supply.

Although a good deal of data are available on
bacteriological quality of waters in this area, com-
plete chemical analyses are scanty. Table 10 pre-
sents data obtained from Lafayette and West Lafay-
ette municipal wells for the period from 1958 to
1975. Because different wells were tested at dif-
ferent times, and because analyses for certain ele-
ments was not performed at the earlier dates, it
is impossible to determine whether any trends exist
over time. There is a slight suggestion that ni-
trate is increasing but this trend may be more ap-
parent than real. Changes and improvements in
analytical procedures, sampling methods, or other
control factors could account for this apparent
change.

The abundance of good quality ground water un-
doubtedly has been an attraction to industry and a
major factor in the increase in the number of food
processing and other water consumptive industrial
developments in the community in recent years.
This trend is likely to increase as water shortages
or limits to supply become apparent elsewhere. De-
crease in use of boilers or other hot water pro-
cessing procedures by industry has resulted in a
great diminution of problems concerning scaling and
iron precipitates which result in inefficiency or
periodic shutdowns in manufacturing. Other dis-
solved solids do not appear to present any problems.

It seems to the writers, however, that the
monitoring of chemical quality of ground waters of
the Lafayette area is far from satisfactory. It is
sensible to recommend that an expanded observation
network of wells should be established and regularly
timed chemical analyses performed. This should be
done on at least an annual basis, and preferably
seasonally, in order to determine what influence
seasonal decline of water tables and increased pum-
page has on water quality.

Ground water pollution is possible. Many minor
cases have been recorded in the county. The most
potential sources of pollution are disposed wastes.
Common pollutants are micro-organisms, dissolved
solids, detergents, phenols, pesticides and toxic
materials.

4.6 RELATIONSHIP TO PHASE II

Phase I of the hydrogeological study of the
Lafayette urban area has concentrated on analyses
of 1) the geological setting, physical origins,
and geographical distribution of the local sub-
surface aquifers, 2) estimates of present consump-
tion and potential limits of future yield, and
3) water quality and dangers of deterioration by
pollution. These are fairly standard determinations
that are inherent in most regional or areal hydro-
egologic studies. However, because Lafayette has
in the past and will in the foreseeable future con-
tinue to rely upon local ground water resources,
it is imperative to have available the best pos-
sible current base line study if any meaningful
contribution is to be made to the ongoing parallel
studies in demography and socioeconomics. Updated
information and status reports in these other areas
can be combined in Phase II of the study to pre-
dict future demands on the ground water reserves,
in both time and space. The resultant multidis-
ciplinary analyses then can be used as an aid in
planning further development and allocation of the
ground water resources in terms of various human
needs and demands, as well as suggesting options
for other uses of water resources that will tend
to enhance the quality of life in the Lafayette
urban area.
### Table 10. Quality of Ground Water in Tippecanoe County.

<table>
<thead>
<tr>
<th>Year</th>
<th>1958</th>
<th>1965</th>
<th>1969</th>
<th>1971</th>
<th>1971&lt;sup&gt;l&lt;/sup&gt;</th>
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<tbody>
<tr>
<td>Well</td>
<td>WL2</td>
<td>WL3</td>
<td>WL4</td>
<td>WL5</td>
<td>L2</td>
</tr>
<tr>
<td>pH</td>
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<td>8.0</td>
<td>8.1</td>
<td>8.1</td>
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<td>VS*</td>
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<td>354</td>
<td>360</td>
<td>348</td>
<td>360</td>
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<td>Ca</td>
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<td>90</td>
<td>93</td>
<td>88</td>
<td>94</td>
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<td>Mg</td>
<td>32</td>
<td>31</td>
<td>31</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Na</td>
<td>11</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>14</td>
</tr>
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<td>3</td>
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<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Fe</td>
<td>0.08</td>
<td>0.8</td>
<td>0.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Mn</td>
<td>&lt;0.05</td>
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<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
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<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Pb</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Cl</td>
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<td>22</td>
<td>15</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>SO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>70</td>
<td>61</td>
<td>68</td>
<td>56</td>
<td>74</td>
</tr>
<tr>
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<td>0.4</td>
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<td>F</td>
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<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.5</td>
</tr>
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<td>N</td>
<td>0.8</td>
<td>0.8</td>
<td>0.4</td>
<td>0</td>
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</tr>
<tr>
<td>Mo</td>
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<td>278</td>
<td>278</td>
<td>284</td>
<td>288</td>
</tr>
<tr>
<td>CaCO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>286</td>
<td>278</td>
<td>278</td>
<td>284</td>
<td>288</td>
</tr>
</tbody>
</table>

* very slight
1 West Lafayette
2 Lafayette
Table 10. Quality of Ground Water in Tippecanoe County, continued.

<table>
<thead>
<tr>
<th>Year</th>
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</tr>
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<tr>
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<td>WL 2</td>
<td>WL 3</td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
<td>7.5</td>
</tr>
<tr>
<td>Sediment Turbidity</td>
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<td>20.0</td>
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<td>Hardness CaCO$_3$</td>
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<td>318</td>
</tr>
<tr>
<td>Ca</td>
<td>83</td>
<td>85</td>
</tr>
<tr>
<td>Mg</td>
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<td>8</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Fe</td>
<td>&lt;0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Mn</td>
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<td>0.12</td>
</tr>
<tr>
<td>As</td>
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<td>&lt;0.01</td>
</tr>
<tr>
<td>CCl</td>
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</tr>
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<tr>
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<td>0.2</td>
</tr>
<tr>
<td>N</td>
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<td>&lt;0.1</td>
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<tr>
<td>Mo</td>
<td>230</td>
<td>239</td>
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<tr>
<td>CaCO$_3$</td>
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</table>
5.1 INTRODUCTION

The hydrologic investigation includes two parts pertaining to surface runoff and ground water hydrology. The principal objective of the research in surface water hydrology is to develop a deterministic nonlinear runoff model which will accept stochastic inputs to determine the surface runoff from heavily urbanized areas as well as the surrounding sparsely urbanized areas. This portion of the study includes the acquisition of rainfall and runoff data at four locations in the West Lafayette area. The establishment of the rain gages and runoff gaging station and the analysis of these data were parts of previous and parallel researches in urban hydrology.

The objectives of the investigation in ground water hydrology are: to extend the geologic investigation in order to estimate the characteristics (transmissivity and storage coefficient) of the aquifers which are potential sources of water supply to the test community; and to develop a deterministic model which will accept stochastic inputs, for the long range determination of the ground water supply under increasing demand due to population growth.

For a detailed discussion of the hydrologic investigation the reader is referred to the following reports:


5.2 SURFACE RUNOFF

The purpose of this portion of the study was to develop a deterministic model that would accept stochastic rainfall inputs which would be applicable to the determination of surface runoff from heavily urbanized areas and from surrounding sparsely urbanized areas.

A) NONLINEAR RAINFALL - RUNOFF MODELS

The rainfall-runoff process and the effects of urbanization on runoff can be modeled by using conceptual or physical models, linear or nonlinear models. The internal storages, the loss rate mechanisms and the motion of the runoff are governed by nonlinear differential equations. As a result the rainfall-runoff process is generally assumed to be nonlinear. A lumped nonlinear model of the rainfall-runoff process may thus include first, second and possibly higher order terms involving the rainfall input. The linear formulation involves only the convolution of the rainfall input and the
instantaneous unit hydrograph (also called kernel function). Higher order formulations, such as the Volterra representation, include, in addition, double, triple, . . . convolutions of higher order kernels and products of the input. In this formulation the kernel coefficients are linear but the model is nonlinear because it includes successively higher products of the input. Hydrologic models of this type are usually limited to the second order formulations which include the sum of a convolution of the first order kernel and the input plus a double convolution of the second order kernel and the products of the input. Such a representation is assumed to be time invariant. The superiority of a nonlinear model over a linear model must be established in each application. In some cases a linear model may perform as well as a nonlinear one and the adoption of the linear model simplifies the problem.

The Volterra representation and the corresponding polynomial approximation is receiving increasing attention in representing the rainfall-runoff process. Different methods of estimation of kernel coefficients in these models are available and the performances of these different schemes have been evaluated by their regeneration and prediction properties. These methods vary in their relative computational ease and computer storage requirements. Some of the methods give good regeneration properties, but have inferior prediction abilities. Some of these methods cannot be generalized for orders higher than two. Also, these methods are not recursive in the method of estimation of kernel coefficients, and hence are not suitable for "on-line" operation. This aspect is necessary if these models are to be used in real time control of urban runoff. However, the nonlinear functional models generally perform better than the linear functional model or the convolution integral in representing the rainfall-runoff process.

Therefore, in the present study a second order nonlinear functional model of the rainfall-runoff process was used. A new, recursive identification procedure has been proposed to estimate the kernel functions in this model. A nonlinear stochastic model has been developed to characterize the urban rainfall-runoff process. Both of these models were used to investigate the effects of urbanization on runoff.

4) SUMMARY OF THEORETICAL DEVELOPMENTS

The methods of kernel function estimation for the nonlinear functional models proposed in the past demand considerable computer storage or time. Consequently, a recursive kernel function estimation scheme has been proposed. The kernel functions estimated by using these methods were used to investigate the effects of urbanization on runoff.

A nonlinear stochastic model of the rainfall-runoff process was also used to estimate the effects of urbanization on runoff. This model includes the observed rainfall and the time derivatives of rainfall as inputs. The rationale for developing the models of the rainfall-runoff process with the time derivatives of rainfall is simply that the runoff is affected not only by the magnitude of rainfall but also by the time rate of occurrence of rainfall.

4.1) The Functional Series Model
Let \( I(k) \) and \( Z(k) \), \( k = 1, 2, \ldots, N \) be the observed daily rainfall and runoff values. The second order nonlinear functional model of the rainfall-runoff process is given in eq. 1 for single input and output series,

\[
Q(k) = H_0 + \sum_{\tau=0}^{M} H_1(\tau) I(k-\tau) + \sum_{\tau_1=0}^{M} \sum_{\tau_2=0}^{M} H_2(\tau_1, \tau_2) I(k-\tau_1) I(k-\tau_2)
\]  

(1)

where

\( Q(k) = \) model output; \( H_0, H_1(\tau), H_2(\tau_1, \tau_2) \) are the kernels.

\( M = \) length of memory.

Equation (1) can be rewritten as in equation (2),

\[
Q(k) = a^T x(k),
\]  

(2)
\[ J_k(a) = \sum_{j=1}^{k} [Z(j) - a^T x(j-1)]^2 \]  

where \( a \) = estimate of \( a(k) \)

The parameter vector \( a \) can be estimated by using the recursive algorithm AL.

**The Algorithm AL**

At any iteration \( k \), \( a(k) \) can be estimated by using the algorithm AL.

\[
S(k+1) = S(k) - \frac{S(k) x(k) a^T(k) S(k)}{1 + x^T(k) S(k) x(k)}
\]

\[ a(k+1) = a(k) + S(k+1) x(k) [Z(k+1) - a^T(k) x(k)] \]

where \( S(k) \) = (nxn) positive definite weighting function matrix

The initial estimates of \( S(k) \) and \( a(k) \) can be obtained by using the first \( k \) values of \( Z(k) \) and \( I(k) \). The algorithm can be used for prediction in two ways. The parameter vector \( a(N) \) can be estimated by using \( N \) observations. The estimates \( a(N) \) can then be used for prediction by using the rainfall values at \( N+1, N+2, \) etc. On the other hand, the parameter vector \( a(N) \) can be updated by using the additional data and these updated parameter estimates can then be used for prediction. Thus the algorithm AL is convenient for real time operation.


ii) The Nonlinear Stochastic Model

The basic principle of the nonlinear stochastic model is as follows. The model is composed of several subsystems in parallel. The total runoff is a sum of the outputs from these subsystems. Each of these subsystems is nonlinear. The first subsystem utilizes the observed rainfall and runoff values as input and output respectively. This subsystem is called the zero order subsystem. Several higher order subsystems act in parallel with the zero order subsystem. The input to the second subsystem is the sequence of first derivatives of rainfall and the error in forecasting the output from the first subsystem is considered as the output of this subsystem. Similarly the input to the third subsystem is the sequence of second derivatives of rainfall and the error in forecasting the output from the second subsystem is considered as the output of this subsystem. In this way several subsystems are added in parallel. The number of subsystems required to model rainfall-runoff process depends upon the accuracy desired. The error in forecasting the runoff is progressively reduced by each of these subsystems.

The method of analysis of each of these subsystems is the same except that different inputs and outputs are used in characterization of the subsystems. The optimal output of each of the subsystems is estimated by minimizing the corresponding mean square error and the estimation procedure is based on the theoretical concept of filters. The estimation procedure involves the joint probability density functions of rainfall and runoff and their derivatives and these are approximated by orthogonal polynomials. The coefficients in the system equations are computed by using the statistical moments of rainfall and runoff and their derivatives. The details of this model are found in Rao and Rao "Analysis of the Effects of Urbanization on Runoff Characteristics by Nonlinear Rainfall-Runoff Models", Purdue University Water Resources Research Center, Tech. Rept. No. 58, December 1975, 76 pp.

C) CASE STUDY

Daily rainfall-runoff records in Salt Creek basin at Arlington, Eastern Illinois were used in the present study. Salt Creek basin, located in Cook and DuPage Counties of the Chicago metropolitan area has a drainage area of 150 sq. miles and is 35 miles in length. In 1964, the population in the Salt Creek basin was about 400,000 and 40% of the land was urban while the population and urbanized land prior to 1956 were about 150,000 and 22% respectively. The population in Salt Creek basin is expected to number 550,000 to 650,000 by 1990 with about 70% of the land urbanized. Low flows in Salt Creek are generally due to sewage effluent and high flows are due to combined storm flows and treated sewage. The frequent (every 2 - 3 years) overbank flooding in Salt Creek basin present problems because of urbanization and developments on the flood plain.

The data from the Salt Creek basin were selected for analysis for the following reasons.

1) The basin is small in size but large enough to present a variety of urbanization related water-management problems.

2) The water and land use problems of this basin is typical of those of the metropolitan area as a whole.

3) The basin is relatively close to Chicago and is squarely in the path of urban expansion.

The mean annual precipitation over the basin is about 30" and varied from 22" to 46" during 1871 - 1966. Although the precipitation is roughly evenly distributed over the year, much of the precipitation results from thunder storms of relatively short duration and high intensity. The low flows in the stream are affected by sewage disposal and seepage into the stream from the aquifers. Flood flows are influenced by precipitation and groundwater pumping. Nearly all the public water supplies in the basin depend on groundwater. Pumping of groundwaters deplete stream flow or the rate of groundwater flow into the stream. The double mass curve of rainfall and runoff indicates an increase in runoff as the basin became more and more urbanized, according to A. M. Spieler ("Water in Urban Planning", Salt Creek Basin, Illinois, U. S. Geol. Survey Water Supply Paper No. 2002, 1970).

Urbanization in the Salt Creek basin has been shown by Spieler to have changed the low and flood flow characteristics. Intense urbanization of the
basin started in 1956. Consequently, two sets of two years of daily rainfall-runoff recorded during 1952-1954 (first period) and 1963-1965 (second period) were selected for analyzing the effect of urbanization. The period between 1952-54 would represent a less urbanized period and the period between 1963-65 represents a period of intense urbanization. The mean annual rainfall in these years 1952-54 and 1963-65 are approximately the same.

c) Data Analysis and Results

The following procedure was used to evaluate the effect of urbanization on daily runoff characteristics.

(a) As urbanization changes the runoff characteristics, the model fitted to the data during the first period cannot be expected to perform well as a runoff predictor for the second period and vice versa. This hypothesis was tested by separately fitting valid models by using the data from the two periods and evaluating the prediction performances of these models in the other period.

(b) The effect of urbanization on runoff characteristics was investigated by simulation studies. For example, the valid models of the rainfall-runoff process developed by using the data from a period such as the first period were used to generate synthetic runoff in the second period by using the rainfall in the second period and the parameters estimated by first period data. The simulated runoff sequence was used to evaluate the difference in runoff characteristics in the two periods brought about by urbanization. The valid models, however, were tested for good simulation performance. The effect of urbanization was quantified by comparing several properties of the simulated runoff series in the two periods, such as mass curves, flow duration curves, frequency analysis of exceedence values, and flood peaks etc.

The prediction performance during the second period of the models calibrated by using the first period data were poor. A similar result was obtained for the opposite case. In fact even the structure of the kernel functions and the parameters of the nonlinear stochastic models were very different for the two periods.

A comparison of the characteristics of the generated and observed data of the two periods brought out the effects of urbanization on runoff.

1. Basic Statistics of Runoff

The basic statistics of the generated and observed data in the two periods are given in Table 11. All the statistics are different in the two periods. The characteristics of the data generated by different models are in close agreement with the observed values.

2. The Histograms

The histograms of the runoff data indicated that the low flows had increased considerably during the second period. For instance, about 63% of the runoff was less than 10.5 cfs during 1952-53 and about 50% of runoff was less than the same quantity during 1963-64.

3. Cross Correlation Coefficients

The cross correlation between runoff and rainfall was high for smaller lags and became smaller for increasing lags. Significant cross correlations between rainfall and runoff were found at smaller lags in both the periods. The cross-correlation coefficients varied from 0.341 at lag zero to 0.095 at lag 8 for the 1952-53 data and from 0.330 at lag zero to 0.114 at lag 2 for the 1963-64 data. The significant cross correlations approximately indicate the memory of the rainfall-runoff system. Therefore, the rainfall-runoff process of the Salt Creek basin can be assumed to have a memory of 8 days during 1952-53 and 2 days during 1963-64. Thus the memory of the rainfall-runoff process has decreased with increased urbanization.

4. Flow Mass Curves

The mass curves of the observed and generated runoff of the 1963-64 period were consistently to the left of the mass curve of the 1952-53 data indicating an increase in runoff volume. Similar results were obtained by the double mass curve analysis.

5. Flow Duration Curves

The flow duration curves of the 1952-53 and 1963-64 data indicated a pronounced deviation in the low flow characteristics (up to about 100 cfs) in the two periods. The flow duration curves indicated
Table 11

<table>
<thead>
<tr>
<th>DURATION (WATER YEARS)</th>
<th>MODEL*</th>
<th>MEAN</th>
<th>VARIANCE</th>
<th>SKEWNESS COEFF.</th>
<th>MAX. VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1952-53</td>
<td>obs</td>
<td>13.641</td>
<td>1109.2</td>
<td>6.634</td>
<td>448.00</td>
</tr>
<tr>
<td></td>
<td>MS2</td>
<td>13.810</td>
<td>1212.1</td>
<td>5.582</td>
<td>416.80</td>
</tr>
<tr>
<td></td>
<td>ML2</td>
<td>12.320</td>
<td>1212.1</td>
<td>5.592</td>
<td>431.00</td>
</tr>
<tr>
<td></td>
<td>MN2</td>
<td>14.581</td>
<td>1319.0</td>
<td>4.176</td>
<td>428.90</td>
</tr>
<tr>
<td>1963-64</td>
<td>obs</td>
<td>17.701</td>
<td>1112.0</td>
<td>3.392</td>
<td>262.00</td>
</tr>
<tr>
<td></td>
<td>MS1</td>
<td>17.480</td>
<td>1221.5</td>
<td>2.892</td>
<td>247.80</td>
</tr>
<tr>
<td></td>
<td>ML1</td>
<td>18.230</td>
<td>1300.0</td>
<td>3.027</td>
<td>253.70</td>
</tr>
<tr>
<td></td>
<td>MN1</td>
<td>17.694</td>
<td>1173.2</td>
<td>2.921</td>
<td>290.80</td>
</tr>
</tbody>
</table>


perceptible difference in the 90% flows: the 90% flow during 1963-64 was greater than that during 1952-53. Similarly the flow equaled or exceeded 20% of the time was higher during 1963-64 than during 1952-53.

6. High Flow Frequency Analysis

A frequency analysis of the exceedence series indicated that for a given probability of occurrence, the magnitude of the floods were larger in the second period than in the first period.

The results obtained from the simulated and observed data were in general agreement in all the above cases.

ii) Conclusions

The methods developed in the present study can be used to successfully model the urban rainfall-runoff process and to study and quantify the effects of urbanization on runoff.

5.3 GROUNDWATER STUDY

"With new tools and techniques, such as mathematical and statistical models of groundwater systems, and with increased information and understanding of groundwater, planners can more readily consider and include groundwater supplies in plans for future development. This is especially significant for the Ohio Region because a comparison of projected groundwater withdrawals for the year 2020 with estimated groundwater recharge indicates that the ground water resources of the Ohio Region will not be used at repenishment rates under existing existing development plans." This statement is from "Summary Appraisals of the Nation's Ground Water Resources - Ohio Region" by R. H. Bloyd, published as USGS Professional Paper 813 A, 1975.

The use of both digital and stochastic models of groundwater systems are illustrated in the present study. The limitations of the digital models applied to the glacial formations of the Midwestern United States with the available data are indicated.

The present study deals with the development of a groundwater model using stochastic inputs. The glacial aquifer underlying Lafayette and West Lafayette, in Tippecanoe County, Indiana is selected for investigation. Previous investigations on the development of groundwater models have essentially dealt with characterization of the aquifers, estimation of recharge and evapotranspiration, calibration of the model, estimation of aquifer capacity, etc. In the present study we have considered the following aspects: (1) The study of the location and characteristics of the aquifers which are potential sources of water supply to the community, (2) The development of a deterministic, digital computer model with stochastic inputs for the long range determination of the groundwater supply capability under an increasing demand due to population growth, (3) The calibration of the groundwater model using historical input variables and pumping records, (4) The development of stochastic models for ground water levels and river stages and (5) The determination of the feasibility.
and cost of constructing digital models for medium size communities and the explanation of their limitations.

A) METHODOLOGY

The digital computer technique developed by Prickett and Lonquist (Selected Digital Computer Techniques for Groundwater Resource Evaluation, Bulletin 55, Illinois State Water Survey, Urbana, 1971) was used in the present study. The computer program was modified so as to suit the local conditions of the study area. Only a two-dimensional analysis was considered. The basic concepts of developing the finite-difference equations and the method of solution may be found in Prickett and Lonquist (1971).

The digital model for Lafayette, West Lafayette and the vicinity was formulated by expressing the governing differential equation in the finite difference form as explained in Prickett and Lonquist (1971). A square node system with 1000 foot spacing was found to be most advantageous from the standpoints of programming ease, computational time and storage requirements. The resulting finite-difference network consisted of twenty-four columns and thirty-three rows with 792 nodes.

The average January piezometric levels obtained during the period, 1953-72 were taken as the initial water levels for the digital model. Inflow and outflows through the boundary nodes were estimated from a flow net analysis of the study area. The base flow contributions of the aquifer to the rivers were introduced as constant net-withdrawals from each node representing the rivers. The recharge due to ponds in the area which are hydraulically connected to the aquifer were introduced as lumped quantities at their respective nodes. A study of the cross-correlation between rainfall and groundwater levels in the study area indicated that the groundwater levels lag rainfall by about eight months. This lag period was considered while introducing recharge due to rainfall. The infiltration characteristics of surface and near surface conditions were also taken into account.

The digital model was calibrated as follows. A parameter adjustment procedure was adopted. The storage coefficient, the hydraulic conductivity and the net recharge rates were treated as variables for purposes of simulating the observed water levels. Historical pumping values were introduced into the model at the nodes corresponding to the pumping centers. Reasonable estimates were made for the missing pumpage data. The computed water levels at the nodes corresponding to the observation wells and the river nodes were compared with their respective historical values. The calibration of the model was considered adequate if the computed water levels compared within reasonable limits with the observed water levels. However, the limitations on the accuracy and the length of the available data were major factors in the calibration of the model. Many trials were required to adequately refine the model.

The input variables, rainfall and river stages which contribute to the net recharge into the aquifer are stochastic in nature. Consequently, these stochastic variables need to be simulated in order to use them as inputs into the digital model for the long range determination of aquifer capacity.

The autocovariance and the power spectral estimates of the rainfall and river stage data exhibited a twelve month periodicity. Based upon these results, stochastic models were fitted to the above data. The general form of the models developed is shown in the following equation.

\[
y(k) = a_0 + \sum_{j=1}^{n_j} a_j y(k-j) + \sum_{j=1}^{n_j} b_j \sin\left(\frac{2\pi j k}{12}\right) \\
+ \gamma_j \cos\left(\frac{2\pi j k}{12}\right) + W(k)
\]

where,

\[
y(k) = \text{value of input variable at the } k^{th} \text{ time step (month)}
\]
\[
y(k-j) = \text{value of input variable at the } (k-j)^{th} \text{ time step (month)}
\]
\[
W(k) = \text{residuals}
\]

The coefficients \( a_0, a_j, b_j, \text{ and } \gamma_j, j = 1, 2, 3, \ldots \) were estimated by using the observed data series.
The characteristics of the residuals were analyzed by the correlogram, cumulative periodogram and the Portmanteau tests. The residuals were found to be uncorrelated and without periodicities.

After the model was calibrated the capacity of the aquifer under an increasing water demand due to population growth was estimated by introducing these stochastic inputs of rainfall and river stages. The resulting water levels show the capacity of the aquifer to meet future water demands.

B) CASE STUDY

The study area envelopes the cities of Lafayette and West Lafayette, in Tippecanoe County, Indiana. The area is 4.36 miles wide to east and 6.06 miles long north to south. It is bounded on the north by latitude 40° 20' 35" N., on the east by longitude 86° 50' 52" W., on the south by latitude 40° 23' 17" N., and on the west by longitude 86° 55' 52" W. The location of the study area and other pertinent details are shown in Fig 10.

The geological, hydrological and pumping data used in the present study were collected from federal agencies, state agencies, and Purdue University.

i) Geological Data

The geological information on the location and the logs of various wells drilled in Lafayette, West Lafayette and the vicinity were collected from the Division of Water, Department of Natural Resources of the State of Indiana as part of the geological portion of this project. The information on wells drilled before 1956 were obtained from the basic data compiled by Rosenshein and Cosner, (Groundwater Resources of Tippecanoe County, Appendix: Basic Data, Bulletin No. 8, Indiana Dept. of Conservation and Water Resources, State of Indiana (1956)).

ii) Hydrological Data

The monthly average static water levels measured in the observation wells located in the study area were collected from the Water-Supply papers published by the United States Geological Survey. These records were available for varying periods of time since 1944.

In addition, the monthly values of rainfall measured at the Purdue Agronomy Farm, West Lafayette; the mean monthly stages of Wabash River at Lafayette and the mean monthly stages of Wildcat Creek near Lafayette were also used in the present study. The rainfall data are available since 1953. The stream stages of the Wabash River and of Wildcat Creek date back respectively to 1914 and 1955.

iii) Pumping Data

Three major pumping centers in the study area were considered. These are, (i) the Lafayette City Water Works, (ii) the West Lafayette Water Company and (iii) Purdue University. The monthly pumpage data for the Lafayette City Water Works and the West Lafayette Water Company are available since 1961. The data from Purdue University date back to 1954. A few of the industries in the locality use their own well fields. These are, (i) the Aluminum Company of America, (ii) the Eli-Lilly & Co., and (iii) the Duncan Electric Co. At the present time, pumpage data from the above industries are not available.

iv) Location and Characteristics of the Aquifers

The geology and hydrogeology of Tippecanoe County and the study area were investigated by Gordon (1986), Rosenshein (1958) and as part of this project by Maarouf (1974) (See Geologic Investigation). The salient feature of the geology of Tippecanoe County, and of the study area in particular, is that it is entirely covered by glacial drift except for a few small bedrock outcrops. The glacial outwash is the principal source of groundwater. The alluvial deposits lying along the buried preglacial Teays valley have the highest groundwater potential. The previous investigations (Rosenshein, 1958; and Maarouf, 1974) have revealed that the aquifer to the east of the Wabash River and underlying most of Lafayette is in general under leaky artesian conditions. The aquifer on the west side of the river underlying West Lafayette and the Purdue University Campus is mostly under watertable conditions.

v) Hydrologic Properties

The parameters that primarily control the development of wells in an aquifer are the hydraulic conductivity and storage coefficient. The hydraulic conductivity and the storage coefficient for
FIGURE 10  MAP OF INDIANA AND THE GROUND WATER STUDY AREA
the study area were estimated by analyzing pumping test data and also from specific capacity information derived from water well records. However, pumping test data were available only for a few wells in the study area. The available specific capacity information is not reliable because pumping was not continued for longer periods of time and most of the wells do not tap the complete thickness of the aquifer. The average aquifer parameters were estimated with this limited information by making reasonable assumptions and approximations wherever necessary.

The hydraulic conductivity near the Wabash River and the Wildcat Creek is about 240 ft/day. The value reduces to about 160 ft/day away from the Wabash River on either side. The storage coefficient was found to vary from 0.1 to 0.05 on either side of the river for a few hundred feet and decreased to about 0.0005 away from the river towards the east. No appreciable change was observed in the storage coefficient for the aquifer underlying West Lafayette and the value remained at about 0.1.

vi) Piezometric Surface

Piezometric contour maps were prepared for different time periods by using the water levels recorded in the observation wells and the static water levels measured from the wells at the time of drilling. The stage in the Wabash River and the Wildcat Creek were also considered in the preparation of the maps. Once again, the data available is not sufficient for preparation of piezometric contour maps at regular intervals of time. Consequently, maps were prepared for May 1954, November 1959 and November 1962. The maps drawn for the above time periods are similar to one another. Consequently, it was concluded that the water levels in the study area do not fluctuate very much with time. In addition, average piezometric contour maps were prepared for the months of January and July using the water level information available during the period 1953-72. The above maps did not show any significant seasonal fluctuations in the study area except for some local fluctuations near the Wabash River. Therefore, the average piezometric contour map of January as shown in Fig. 11 was considered as the reference map for the digital model study.

vii) Recharge to the Aquifer

The stream valleys and the terraces are the most favorable areas for recharge in the study area. Locally, deposits of clay may decrease the recharge. Rosenshein (1956) and Maxia (1974) have mapped the surface and near-surface conditions related to recharge in Tippecanoe County. The above maps provide qualitative information on the infiltration characteristics of different regions in the study area.

Apart from the recharge due to rainfall over the ground surface, the gravel pit in the Purdue University campus and the Wabash River also form constant sources of recharge to the aquifer. From the digital groundwater model analysis, the average recharge through the gravel pit was estimated to be 16 mgd. Although there may be local recharge into the aquifer from the Wabash River, the piezometric maps show that there is a considerable amount of base flow contribution to the river from the groundwater reservoir. From the digital model analysis, the base flow contribution to the Wabash River was estimated to be about 54 mgd. in the river reach located in the study area.

C) THE DETERMINISTIC GROUNDWATER MODEL

The digital model for the study area was formulated and calibrated as explained in Sec. 5.3.1 A pumping period of 5 years was considered for calibrating the digital model. Several simulation runs were needed to calibrate the digital model while adjusting the input variables suitably. The computed head distribution that compared most satisfactorily with the reference piezometric map (Fig. 11) is shown in Fig. 12. The maximum absolute difference between the computed and the observed heads at any single node is less than 10 ft. However, comparison of contours indicates good agreement. The results of the water budget from the calibrated digital model is shown in Table 12. The total recharge into the study area approximately balances the total discharge which indicates that the model is capable of duplicating the steady state conditions prevailing in the aquifer system.

One of the primary objectives of the present study is to demonstrate the use of stochastic in-
FIGURE 11 AVERAGE PIEZOMETRIC CONTOUR MAP OF JANUARY (1953-1972)
FIGURE 12  COMPUTED HEAD DISTRIBUTION FROM THE CALIBRATED DIGITAL MODEL
puts in groundwater models for the long range determination of aquifer capacity. This analysis was conducted by using two experiments designated experiment A and experiment B. The historical rainfall and river stage values were used as inputs in experiment A. Experiment B was executed by using stochastic inputs. In both the experiments, critical conditions were simulated by considering a sequence of low rainfall and the corresponding river stage values and a sequence of high pumpage values. In addition, a hypothetical well field was introduced in the vicinity of the Columbian Park in Lafayette in order to examine its effect on the aquifer system. The computed head distribution that resulted after 5 years of pumping from both the experiments looked similar. The head distribution resulting from experiment B is shown in Fig. 13. The piezometric contours of Fig. 13 show the combined effect of additional pumping at Columbian Park, increased pumping at the other well fields and decrease in rainfall. The water budgets resulting from the above experiments are presented in Table 13. The results indicate that the base flow into the Wabash River has decreased to 45.9 mgd in experiment A and to 43.9 mgd in experiment B in comparison to 54.2 mgd obtained from the calibrated model (Table 12). The above discrepancies are essentially due to additional pumpage at Columbian Park, increased pumpage at the other well fields and decrease in rainfall over the study area.

### Table 12

**AVERAGE GROUNDWATER BUDGET FROM CALIBRATED DIGITAL MODEL**

<table>
<thead>
<tr>
<th>S. No</th>
<th>Item</th>
<th>Recharge (mgd)</th>
<th>Discharge (mgd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rainfall</td>
<td>17.4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Purdue Gravel Pit</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Other Ponds</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Wabash River (Base Flow)</td>
<td></td>
<td>54.2</td>
</tr>
<tr>
<td>5</td>
<td>Wildcat Creek (Base Flow)</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>Flow Across Boundaries</td>
<td>31.5</td>
<td>0.1</td>
</tr>
<tr>
<td>7</td>
<td>Municipal and Industrial Pumpage</td>
<td></td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td><strong>Total Balance</strong></td>
<td><strong>67.0</strong></td>
<td><strong>70.7</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Error</strong></td>
<td><strong>3.7</strong></td>
<td><strong>5.5%</strong></td>
</tr>
</tbody>
</table>

### VIII. Conclusions

1. The limitations on the availability of sufficient funds and adequate data are the major factors in developing a digital model for the evaluation of groundwater resources of Lafayette and West Lafayette area.

2. Steady or near steady conditions prevail in the aquifer system underlying the study area.

3. The average hydraulic conductivity of the aquifer underlying the Wabash River valley is about 240 ft/day and that of the aquifer underlying the

### Table 13

**AVERAGE GROUNDWATER BUDGET WITH HISTORICAL AND STOCHASTIC INPUTS (EXPERIMENTS A AND B)**

<table>
<thead>
<tr>
<th>S. No</th>
<th>ITEM</th>
<th>EXPERIMENT - A</th>
<th>EXPERIMENT - B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RECHARGE (mgd)</td>
<td>DISCHARGE (mgd)</td>
</tr>
<tr>
<td>1</td>
<td>Rainfall</td>
<td>16.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Purdue Gravel Pit</td>
<td>16.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Other Ponds</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Wabash River (Base Flow)</td>
<td></td>
<td>45.9</td>
</tr>
<tr>
<td>5</td>
<td>Wildcat Creek (Base Flow)</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>Flow Across Boundaries</td>
<td>31.1</td>
<td>0.04</td>
</tr>
<tr>
<td>7</td>
<td>Municipal &amp; Indus. Pumpage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(a) Existing</td>
<td></td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>(b) Proposed at Columbian PK</td>
<td></td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td><strong>Total Balance</strong></td>
<td><strong>65.9</strong></td>
<td><strong>70.94</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Balance</strong></td>
<td><strong>5.04</strong></td>
<td><strong>5.61</strong></td>
</tr>
</tbody>
</table>
FIGURE 13 COMPUTED HEAD DISTRIBUTION USING STOCHASTIC INPUTS (EXPERIMENT B)
terrace is about 160 ft/day. The storage coefficient is estimated to be about 0.05 on the east side of the Wabash River for a few hundred feet and it is about 0.0005 away from the river. The coefficient is about 0.1 for most of the aquifer towards the west of the Wabash River.

4) Rainfall is the major source of recharge to the aquifer in the study area and this was estimated to be 17.4 mgd. The average rate of recharge due to rainfall in the Wabash River valley is about 0.9 mgd/sq. mile and that in the terraces varies from about 0.25 to 0.4 mgd/sq. mile.

5) The Wabash River is hydraulically connected to the aquifer and the total base flow contribution into this river in its 8.2 mile reach in the study area is 54.2 mgd. The average rate is about 6.5 mgd mile of the river. About 60% of the total base flow is received from the aquifer on both sides of the river downstream of the stream gage in Lafayette.

6) The gravel pit in the Purdue University campus is hydraulically connected and forms a steady source of recharge to the aquifer. The average recharge from the gravel pit is about 15.9 mgd. A considerable amount of this recharge goes as base flow into the Wabash River.

7) An additional quantity of 6 mgd can be pumped at the hypothetical well field at Columbian Park without serious depletion of water levels. However, this is not the ultimate capacity of the aquifer.

c) STOCHASTIC MODELS FOR GROUND WATER LEVELS

In the development of deterministic ground water models based on the continuity equation, the estimation of parameters such as the transmissivity and storage coefficient becomes very difficult when the necessary data, such as the results of pumping tests, are not available. In fact, in such cases, these coefficients are assigned by trial and error based on the knowledge of soil types and the performance of the model. Consequently, the results from the model may not be very reliable.

Second, the processes which affect ground water storage such as aquifer recharge by precipitation and discharge from the aquifer into streams, are random processes. The water stored in an aquifer is affected by these natural as well as man-made causes such as pumping. Pumping also is a stochastic process, which is demand dependent and is usually nonstationary, especially in developing urban areas. In view of these considerations, stochastic models were developed to represent the fluctuations in ground water levels.

1) Methodology and Case Studies

Both univariate and multivariate models were developed to simulate water levels. The univariate model was an autoregressive (AR) model with external inputs. In this formulation, the water levels of a well are treated as the autoregressive variables, and the other variables such as the water levels in other wells, the stages in a stream and precipitation are treated as external inputs. The univariate models are useful in the investigation of the effects of the external inputs on the water levels in a given well. Simulation of groundwater levels by using this type of model is cumbersome because the external inputs will also have to be modeled and simulated.

The multivariate model, on the other hand, can be easily used for simulation, although the parameter estimation in the multivariate model is computationally difficult. A multilag-multivariate AR model was found adequate to model the processes.

After the parameters of the models were estimated their significance was tested, and the insignificant terms were eliminated from the model. The residuals from the models were tested for whiteness and for presence of periodicities. The residuals from the multivariate models were further tested for absence of cross correlation. All these tests affirmed the validity of the models. Further, the multivariate models were simulated and the statistical properties of the simulated data were found to agree with the corresponding properties of the observed data.

Data from two locations were used in the study. The monthly data from two wells, one near the Wabash River (L1) and the other (L2) at a distance of about 1.5 miles from the river (on the Purdue Campus), the Wabash River stages and precipitation at Lafayette, Indiana constituted the first set. The water levels at a well (W1, in Wood County,
Wisconsin, USGS No. Wd. 29), and the precipitation data from Marshfield, Wisconsin Rapids, Stevens Point and Nellsville in Wisconsin constituted the second data set.

Apart from the observed data, three types of transformed data were also used in the study. In the first of these, the deterministic trends were removed from the data by Fourier analysis and the residuals from the Fourier analysis were used. If \( x(t) \) represents the observed data sequence, then the transformed data sequence \( x_1(t) \) is defined below.

\[
x_1(t) = x(t) - e_1 \sin \left( \frac{2\pi t}{12} \right) - e_2 \cos \left( \frac{2\pi t}{12} \right) - e_3 \sin \left( \frac{2\pi t}{6} \right) - e_4 \cos \left( \frac{2\pi t}{6} \right)
\]

In both the Indiana and Wisconsin data, the annual cycle is much stronger than the semi-annual cycle. The \( x_1(t) \) series is designated S1.

In the second type of transformation, \( x_2(t) \), the monthly mean of the \( x(t) \) series is subtracted from \( x(t) \) and the resulting values are divided by \( \sigma_j \), the standard deviation of the \( x(t) \) series, \( j = 1, 2, \ldots, 12 \).

\[
x_2(t) = \frac{x(t) - \bar{x}_j}{\sigma_j}
\]

The data series \( x_2(t) \) is designated S2.

In the third type of transformation, \( x_3(t) \), the mean of the square root transformed \( x(t) \) series is subtracted from \( \sqrt{x(t)} \) and the resulting values are divided by \( \sigma_j \), the standard deviation of the square root transformed data.

\[
x_3(t) = \frac{\sqrt{x(t)} - \bar{x}_3}{\sigma_j}
\]

The \( x_3(t) \) is designated S3.

Sometimes, the S1 sequence is referred to as the detrended data and the S2 and S3 sequences as the normalized or standardized data in the following discussion. We will now consider some results obtained in the study.

(a) Univariate Models For Fluctuations In Water Levels In Well L2

The models for water level fluctuations in L2, constructed by using the observed data, show a weak annual periodicity and a weaker 6-month periodicity. In one of the models for the observed data from L1 both the autoregressive and moving average parameters were predominant. In another model, in which the fluctuation in the well L2 is also included, the moving average terms were not significantly different from zero. The parameters related to precipitation in Lafayette were not very significant, which indicate a rather weak dependence of the fluctuation in L1 on precipitation.

The models for transformed data were all similar to each other. In these models, terms related to the effects of changes in the Wabash River stages and precipitation at Lafayette were significantly different from zero and so were the autoregressive and moving average terms. The terms representing the effects of changes in stage had a negative sign indicating an inverse relationship between the levels in L1 and the Wabash River stages in these models of transformed data.

(b) Univariate Models For Water Level Fluctuations In Well L2

The parameter estimates in the models of observed data fitted for water level fluctuations in well L2 indicated very weak effects of annual and six-month periodic fluctuations. The highly correlated structure of fluctuations in L2 was obvious by the closeness of the autoregressive coefficients in the model fitted to observed data to unity (0.979, 0.969, etc.). The water level fluctuations in L2 were not very much affected by the fluctuations in the Wabash River stages, but were affected more by the precipitation in Lafayette. The moving average terms in the models fitted to the original data were not as large as they were for the corresponding models for L1. The terms representing the water levels in L1 were not significantly different from zero, which indicated that the fluctuations in L1 did not affect those in L2. On the other hand, the models fitted to the water level fluctuations in L1 indicated a dependence of fluctuations in L1 on those in L2.

The models for the transformed data indicated very weak effects of precipitation and Wabash River stages on the water level fluctuations in L2, but very strong dependence of fluctuations in L2 on its own lagged values. The moving average terms in the
models for the detrended data (S1) were highly significant but they were not as highly significant in the models of S2 and S3.

(c) Univariate Models For Water Level Fluctuations In Well W1

The models fitted to the observed data from W1 confirmed the presence of weak periodicities in W1, and in the rainfall. The parameter estimates of the AR terms and the moving average terms were also predominant. The rainfall at Wisconsin Rapids and Marshfield had greater effect on the water levels in W1 than that at Stevens Point and Neillsville. Stevens Point and Neillsville are farther away from W1 than Wisconsin Rapids and Marshfield and hence this effect is easily explained. The rainfall at Marshfield has a higher and inverse effect on the fluctuations in W1 whereas the precipitation at Wisconsin Rapids has a weaker and direct effect. The inverse effect of the rainfall at Marshfield on the water levels in W1 may be explained by the lag which exists between the occurrence of rainfall and the time taken for it to manifest itself as water level changes in W1.

The parameters fitted to the detrended (S1) and normalized (S2, S3) data also indicated the high correlation in the water levels, the small dependence of fluctuations of water levels in W1 on rainfall and the presence of strong moving average terms.

(d) Multivariate Models For Indiana and Wisconsin Data

The multivariate model was fitted to the detrended (S1) and the normalized (S2, S3) data sequences. As precipitation at Neillsville has negligibly small influence on the water levels in W1, as indicated by the analysis of scalar models, it was not included in the multivariate model of the Wisconsin data. The precipitation sequences at Stevens Point, Marshfield and Wisconsin Rapids were, however, included. The precipitation at Lafayette, Wabash River stages, and the levels in L1 and L2 were used in the model for Indiana data.

Based upon the results of goodness of fit tests a second order AR model was selected for the Lafayette data. For the Wisconsin data, second order AR models were found to be adequate for the S1 and S2 series and a third order AR model was satisfactory for the S3 series. These conclusions were arrived at after exhaustive tests were carried out on the residuals and also after the characteristics of simulated data were compared with those of observed data.

The statistics of the data generated from the model of the transformed series S1 and S2 were closer to the corresponding statistics of the observed data than those obtained from the models fitted to the S3 sequence. Also, the lag-one multivariate model was found to be inadequate to characterize the transformed data sequences.

(ii) Conclusions

The results from the study are useful in modeling the ground water resources in a small area. The interaction between the causal variables such as rainfall and stream flows on the water levels in an aquifer and the significance of these causal variables themselves may be investigated by using the methodology developed in the study.

5.4 RELATIONSHIP TO PHASE II

The rainfall-runoff models developed in Phase I of the project and the demonstration of their use in investigating the effects of urbanization on runoff are useful for modelling these processes not only in the second phase of this project but also in other cases where such models are needed. However, the data requirements for using these rainfall-runoff models may not always be met. In such a circumstance, other simpler models which have been developed in previous studies in urban hydrology at Purdue and elsewhere may have to be used.

Two basic conclusions have emerged from the ground water model of the test area. The first of these, and perhaps the most significant one as far as the present study is considered, is that the ground water resources of the Tippecanoe County are adequate for moderate expansion in the next 20 to 30 years. The second conclusion is that the data and financial resources which are usually available in medium sized communities are not adequate to develop a digital ground water model such as that developed in the present study. Alternative models and methods of analysis which are better suited for use by medium sized communities are presently under development.
CHAPTER 6

WATER QUALITY ASPECTS

6.1 INTRODUCTION

Stormwater runoff is a diffuse source rather than a point source of pollution of receiving waters. For years stormwater runoff has been ignored as a source of pollutants because it is not readily identified, characterized, and quantified. Urbanization affects both the hydraulic and pollution characteristics of a watershed. Changes in land use may, therefore, affect not only the quantitative yield characteristics of a drainage basin but the quality of its stormwater.

Better knowledge of the amount of diffuse pollution is a current need as a logical prerequisite to an understanding of its future role in stream pollution abatement. The amount and nature of stormwater runoff is desirable information prior to commitment of extensive financial resources for construction and operation of separation and/or treatment facilities.

With the increasing quality standards for wastewater effluents and the increasing efficiency of waste treatment plant operation, it is easy to conclude that this form of pollution may soon become the major degrading factor of the Nation's streams.

The main objectives of this portion of the study were: 1) to develop sampling procedures to best characterize the pollutants in surface runoff from small urban and semi-urban/rural watersheds; 2) to characterize and quantify the pollutants in stormwater runoff from small watersheds with varying degrees of urbanization; and 3) to examine the effects of first flushing, length of antecedent dry period, and rainfall intensity and duration on the "peak" and "total" mass emission rates of the various water quality parameters studied.

For detailed information and specific results of stormwater quality measurements in the test watersheds in West Lafayette, Indiana, the reader is referred to the following technical reports:


6.2 METHODOLOGY

The first objective of this study was to develop a satisfactory procedure for obtaining the water quality of stormwater runoff from watersheds of varying degrees of urbanization. This procedure involved such factors as: 1) the limitations of the sampling equipment; 2) sampling interval or sampling frequency; 3) sample volume; 4) sampling duration; and 5) the appropriate water quality analyses to be performed.

Due to the inadequacies of manual sampling and the inability to accurately describe the variations of stormwater quality with time, using either grab or long-term composite samples, automatic sequential composite samplers were used. A sequential composite sampler gave a series of frequently collected samples which were composited and retained in individual containers, each of which represented a sub-period within the over-all sampling period of a storm event. The sampler tested in this study was found to be entirely adequate for obtaining samples of stormwater runoff from the test watersheds.

The minimum sampling interval, or sampling frequency, is limited by the equipment and the maximum interval is determined by the desired "detail" of the water quality plot as a function of time. In the test watersheds, a sampling interval of 0.5 hours was used. This corresponded to approximately one or two times the "time of concentration" of the watersheds. This thus gave somewhat less "definition" than the runoff hydrograph which commonly is discretized at ¼ to ½ the "time of concentration".

The sampling interval is also related to the required sample volume. The capacity of the sam-
ler's pump will affect this relationship. In order to test a sample for total and fecal coliforms, BOD, and suspended solids, a sample volume of at least one liter (1,000 ml) is necessary. The time required to obtain this volume may exceed the minimum sampling interval, particularly if there is a long distance between the sampling point and the container.

The sampling duration is dependent upon the duration of the runoff which, in turn, is dependent upon the intensity and duration of the rainfall. It is important to take as many samples as possible so as to best describe the quality of the runoff as a function of time. However, the number of samples in any given storm event may exceed the analysis capacity of the laboratory. In this case, the investigators should attempt to visually isolate important transients as well as long-lasting, quasi-steady conditions. A visual observation of the turbidity of the sample quite often will suffice to select which samples, if not all, are to be analyzed.

As a minimum, it is recommended that suspended solids and BOD be analyzed. If possible, it is desirable to perform total and fecal coliform counts, but this requires a considerable amount of time. Other possible analyses, time permitting, include: total solids, COD, nitrogen, and phosphorus. All analyses should be performed in accordance with the appropriate methods and procedures given in "Standard Methods for the Examination of Water and Wastewater" or an accepted method such as those given by the Environmental Protection Agency.

6.3 CASE STUDY

Two of the four West Lafayette watersheds described in the Hydrology section of this report were used for the water quality case study. These are: 1) the Ross-Ade upper watershed which is an urban catchment with an area of 29 acres, consisting of 72 single-family dwellings; and 2) the lower Purdue Swine Farm Watershed which is a semi-urban/rural catchment with an area of 292 acres of which 178 acres is partially developed as a residential area and 114 acres is farmland.

The sampling equipment consisted of a Sentry Sequential Composite Sampler with a floatless liquid level control. The sampler collects 24 composite samples of 250 ml each over a period of 3, 6, 8, 12, or 24 hours with each sample being made up of 2 to 8 individual samples. The pump has a lift of up to 15 feet. The sampler is capable of purging itself after each aliquot. Each time an aliquot sample is to be collected, the pump operates in reverse for a preset period to clear the inlet line.

In order to accommodate larger sample containers, the number of samples per run were reduced from 24 to 12. It was also necessary to run through five pumping cycles of four minutes each, purging only between samples rather than between aliquots in order to provide continuous sampling and approximately one liter per sample.

The liquid level controller allowed for activation of the sampler as soon as the flow in the storm sewer (urban watershed) or drainage ditch (semi-urban/rural watershed) rose above "background (dry weather) flow.

As expected, the sampling interval (frequency) had a definite effect on the magnitude of the peak emission rates throughout any storm event. Decreasing the sampling frequency (increasing the sampling interval) decreased the peak value by as much as forty percent. The sampling frequency had little effect on the shape of the pollutographs (mass emission rates versus time) except at the peaks.

Water quality samples of stormwater runoff were obtained during the summer and fall of 1972, 1973, and 1974. A total of 21 and 17 individual storms were monitored at the urban and the semi-urban/rural watersheds, respectively. A listing of the dates of these storms is presented in Table 14.

Because the mass emission rate (lbs/day) of a pollutant from a watershed is of prime importance when considering the effect of such drainage on a receiving body of water, the water quality data were converted from concentrations (mg/l) to mass emission rates (lbs/day). A plot of such rates versus the duration of the storm is considered a "pollutograph". Figures 14 and 15 are two examples of the variation in rainfall, flow, BOD, and suspended solids during a storm event at each of the two watersheds. These pollutographs clearly indicate
FIGURE 14  TYPICAL BOD AND SUSPENDED SOLIDS POLLUTOGRAPHS FOR STORMWATER RUNOFF AT THE URBAN WATERSHED
FIGURE 15 TYPICAL BOD AND SUSPENDED SOLIDS POLLUTOGRAHS FOR STORMWATER RUNOFF AT THE SEMI-URBAN/RURAL WATERSHED
Table 14
Number of Stormwater Runoff Events Sampled at West Lafayette, Indiana

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Urban Watershed</th>
<th>Semi-Urban/Rural Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1972</td>
<td>2</td>
<td>---</td>
</tr>
<tr>
<td>November 1972</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>July 1973</td>
<td>3</td>
<td>---</td>
</tr>
<tr>
<td>August 1973</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>September 1973</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>June 1974</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>July 1974</td>
<td>1</td>
<td>---</td>
</tr>
<tr>
<td>August 1974</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>September 1974</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>October 1974</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>November 1974</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

the similarities, as well as the differences, between the two watersheds. A further comparison is obtained from the range of "peak" values for all the storms monitored during the three year sampling period. These data are presented in Table 15. The data clearly show a significant difference in the pollution concentration of BOD and suspended solids between the urban watershed and the semi-urban/rural watershed. In all cases, the "peak" concentration of pollutants was higher in the urban watershed; being, in most cases, one or more orders-of-magnitude higher than in the semi-urban/rural watershed.

The mass emission pollutants were affected by both concentration and flow. However, the flow hydrograph has a more significant effect on the shape and magnitude of the pollutants than did concentration.

A "first flush" of suspended solids and BOD was exhibited at the urban sampling station for most of the storm events. However, no "first flush" of BOD and only a very small "first flush" of suspended solids was evident at the semi-urban/rural sampling station. During many of the storm events, peaks in suspended solids concentration occurred later in the storm, particularly in conjunction with sudden increases in flow. However, upon reaching the maximum flow for that storm, the concentration would then decrease and not rise again regardless of the flow pattern. This indicates that some "minimum" flow is required to completely flush the solids from the watershed and that, until such "minimum" flow occurs, various "peaks" in concentration can continue throughout the storm event due to sudden increases in flow.

Although the data would indicate that the antecedent dry period prior to a storm event has a definite effect on the magnitude of the mass emission pollutograph, not enough data were available to develop a reliable relationship between these two parameters. With additional data being obtained under Phase II of the project, efforts will be continued to investigate this seemingly significant factor. At the same time an investigation will be made concerning the frequency of street sweeping during such antecedent dry periods, particularly in the urban watershed.

6.4 RELATIONSHIP TO PHASE II:

The stormwater runoff quality data obtained in Phase I of the project was necessary as a basis for one or more appropriate water quality models to be investigated during Phase II. Such a data base, to be expanded somewhat during Phase II, will allow a comparison of various models as to their reliability in predicting stormwater quality from various lands-use watersheds. The development of a suitable model(s) would then be integrated with the hydrologic (surface and groundwater); economic, and socio-
Table 15

Summary of Stormwater Runoff Quality Data

<table>
<thead>
<tr>
<th>Quality Parameter</th>
<th>Units</th>
<th>Range of Values for Urban Watershed</th>
<th>Range of Values for Semi-Urban/Rural Watershed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Peak BOD Concentrations:</td>
<td>mg/l</td>
<td>11 - 45</td>
<td>3 - 7</td>
</tr>
<tr>
<td>a. Oct., Nov. 1972</td>
<td></td>
<td>5 - 81</td>
<td>3 - 10</td>
</tr>
<tr>
<td>2. Peak SS Concentrations:</td>
<td>mg/l</td>
<td>62 - 250</td>
<td>6 - 160</td>
</tr>
<tr>
<td>3. Peak Total Coliforms:</td>
<td>Organisms/ml</td>
<td>930 - 240,000</td>
<td>930 - 46,000</td>
</tr>
<tr>
<td>a. Oct., Nov. 1972</td>
<td></td>
<td>930 - 240,000</td>
<td>2 - 110</td>
</tr>
<tr>
<td>4. Peak Fecal Coliforms:</td>
<td>Organisms/ml</td>
<td>430 - 93,000</td>
<td>930 - 9,300</td>
</tr>
<tr>
<td>a. Oct., Nov. 1972</td>
<td></td>
<td>430 - 93,000</td>
<td></td>
</tr>
</tbody>
</table>

logic models to be developed in Phase II. The various components of the over-all model will involve numerous linkages with water quality. Directly or indirectly, water quality is linked to: 1) precipitation (hydrology); 2) watershed surface (land-use); 3) water demand (social and land-use); 4) surface water supply (hydrology, hydraulics, social, environmental); 5) groundwater supply (hydrology, hydraulics, geology, environmental, social); 6) treatment facilities and/or detention facilities (social, economic, environmental); 7) receiving stream (hydrology, hydraulics, social, environmental); and 8) water re-use (social, environmental, economic). It is therefore evident that the formation of a good water-quality data bank, previously non-existent for the test watersheds being used as a case study in this project, was a necessity for the development in Phase II of a comprehensive urban water resources management plan.
CHAPTER 7
ECONOMIC INVESTIGATION

7.1 INTRODUCTION
Public planners and officials are continually confronted with the problem of evaluating the feasibility and effectiveness of a wide range of public policies and programs. The benefits afforded by a given proposal, the cost necessary to implement that proposal and the environmental impacts are necessary information to consider in the decision making process. This study attempts to provide some guidance to the decision makers in the selection of drainage systems, and in the improvement of drainage systems in flood prone areas. To this effect the study is divided in two parts. The first part compares the relationship between the economic system costs and the level of water quality for alternative surface runoff systems. The second part was designed to estimate and compare the benefits and the costs of providing adequate storm drainage facilities to flood prone urban residential areas.

For a detailed discussion of the economic investigation the reader is referred to the following two partial reports:

7.2 ECONOMIC AND ENVIRONMENTAL IMPACTS OF SURFACE RUNOFF DISPOSAL SYSTEMS
This portion of the study focused on the following objectives:
(1) To illustrate a design comparison model which will aid city planners and engineers in choosing among differing surface runoff systems.
(2) To develop trade-off relationships between economic costs and water quality for alternative storm-water systems.
(3) To examine the impact of alternative urban development in Tippecanoe County on the cost and water quality of stormwater removal systems.

A) METHODOLOGY
The surface runoff systems are compared in an integer programming model designed to consider both system cost and water quality. Prices in both the factor and product market were assumed constant for the period of analysis - Linear production functions were postulated for each system analyzed. The scale of analysis of all systems was standardized to handle the intensity and duration of rainfall which has historically occurred in the case study watershed.

The determination of the cost of alternative system designs, and the sensitivity of the optimal solution to varying levels of interest rates and water pollution were accomplished through the use of a pure linear integer programming model. This program was used to examine the effect of varying levels of acceptable environmental pollution parameters on the total system costs of rainfall runoff removal in the case study watershed. This type of program allows only discrete activity levels in the objective function and further stipulates that only one activity is considered per solution.

The model minimizes the present value of systems costs which are taken as the sum of the costs of all the activities included in the objective function. As an example, the activities considered for an urban residential area are listed in Table 16. The costs are discounted over a 50-year period. The minimization is subject to a set of water quality constraints. The water quality constraints were: total solids, suspended solids, chemical oxygen demand, chlorides, and an index which combines these four quality parameters. Several rates of interest may be used in the calculations.

The responsiveness of water quality to different system costs is analyzed and tradeoff relationships between system costs and the level of water quality can be generated and studied.

Figure 16 presents an outline of the alternative systems examined to develop the trade-off
Table 16
Drainage Systems Examined for the Case Study Watershed

<table>
<thead>
<tr>
<th>Acronym</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCNT</td>
<td>Open channel no treatment</td>
</tr>
<tr>
<td>OCHP</td>
<td>Open channel holding pond</td>
</tr>
<tr>
<td>PLNT</td>
<td>Pipeline no treatment</td>
</tr>
<tr>
<td>PLHP</td>
<td>Pipeline holding pond</td>
</tr>
<tr>
<td>OCPT</td>
<td>Open channel primary treatment</td>
</tr>
<tr>
<td>OCHPPT</td>
<td>Open channel holding pond primary treatment</td>
</tr>
<tr>
<td>PLPT</td>
<td>Pipeline primary treatment</td>
</tr>
<tr>
<td>PLHPPT</td>
<td>Pipeline holding pond primary treatment</td>
</tr>
<tr>
<td>OCST</td>
<td>Open channel activated sludge secondary treatment</td>
</tr>
<tr>
<td>OCHPST</td>
<td>Open channel holding pond activated sludge secondary treatment</td>
</tr>
<tr>
<td>PLST</td>
<td>Pipeline activated sludge secondary treatment</td>
</tr>
<tr>
<td>PLHPST</td>
<td>Pipeline holding pond activated sludge secondary treatment</td>
</tr>
</tbody>
</table>

functions. The first section of the analysis yielded trade-offs between system costs and the level of water quality in an urban residential area. Initially only one pollution parameter, i.e. total solids, was considered. In section II the water quality was measured by an index which includes several quality parameters. Several indexes have been proposed in the literature. The one used here is estimated as the average of the total solids, suspended solids, the chemical oxygen demand and the chlorides, all expressed in grams/second. The third section examines the costs of urban developments. A number of alternative development plans may be considered. Three alternative plans for future urban development are suggested: (1) 100% apartment type dwellings, (2) 50% apartment and 50% single family dwellings and (3) 100% single family dwelling development.

For an urban residential area a total of twelve alternative drainage systems are proposed for examination. Each of these systems corresponds to discrete activity of the linear programming model.

d) Case Study

The methodology described above was applied to the Ross-Ade upper watershed located in West Lafayette, Indiana. The watershed encompasses an area of 29.12 acres and contains only residential housing. Using the present drainage system as a base for comparison, alternative systems were developed to handle the flow expected in this watershed, and the economic and environmental impact of these alternatives were determined for several rates of interest. The water quality data to directly compare open channel and pipeline systems were not available for West Lafayette, therefore those for an urban residential area in Tulsa, Oklahoma, were used instead.

The analysis indicates several interesting relationships among the key parameters of system cost, water quality, system design and the rate of interest. The cost, quality level and design are presented in Table 17 for the ten percent rate of interest. When the water quality requirements are not constraining, i.e. the pollution index level permitted is greater than or equal to 719 grams per second the optimum system design is the open channel system with no treatment. The present value of the cost of this system is $102,000 when costs are discounted at ten percent per annum. When the water quality requirements are progressively increased, the complexity of system design and the
Figure 16. Diagram of Alternative Systems Examined to Develop Tradeoff Functions.
<table>
<thead>
<tr>
<th>Pollution Index(^a) (Grams per second)</th>
<th>System Acronym(^b)</th>
<th>System Cost(^c) (Thousand Dollars)</th>
<th>Rank Order of System in Optimum Design(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>719</td>
<td>OCNT</td>
<td>102</td>
<td>1</td>
</tr>
<tr>
<td>607</td>
<td>OCHP</td>
<td>109</td>
<td>2</td>
</tr>
<tr>
<td>413</td>
<td>PLNT</td>
<td>110</td>
<td>3</td>
</tr>
<tr>
<td>349</td>
<td>PLHP</td>
<td>117</td>
<td>4</td>
</tr>
<tr>
<td>288</td>
<td>OCPT1</td>
<td>123</td>
<td>5</td>
</tr>
<tr>
<td>243</td>
<td>OCHPPT</td>
<td>129</td>
<td>6</td>
</tr>
<tr>
<td>165</td>
<td>PLPT</td>
<td>131</td>
<td>7</td>
</tr>
<tr>
<td>138</td>
<td>PLHPPT</td>
<td>137</td>
<td>8</td>
</tr>
<tr>
<td>36</td>
<td>OCST</td>
<td>150</td>
<td>9</td>
</tr>
<tr>
<td>30</td>
<td>OCHPST</td>
<td>153</td>
<td>10</td>
</tr>
<tr>
<td>21</td>
<td>PLST</td>
<td>159</td>
<td>11</td>
</tr>
<tr>
<td>17</td>
<td>PLHPST</td>
<td>161</td>
<td>12</td>
</tr>
</tbody>
</table>

\(^a\) This is a weighted index which includes the parameters of total solids, suspended solids, chemical oxygen demand, and chlorides.

\(^b\) These are described more fully in Table 16.

\(^c\) The system cost is based on the present value of the total costs of system design as reflected by 1973 price levels discounted at ten percent for a 50 year project life. It includes both capital and operating and maintenance costs for each system.

\(^d\) When the pollution index was constrained from 800 grams per second to 10 grams per second, this column indicates the order in which each system was selected as the optimum design based on an objective function which minimized cost.
Table 18
Ordering of System Designs in Least Cost Solution

at
Selected Levels of Water Quality and Rates of Interest

at
Expected Operating and Maintenance Costs

<table>
<thead>
<tr>
<th>Pollution Indexa (Grams/Sec.)</th>
<th>Total Solids</th>
<th>Discount Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>719</td>
<td>PLNT</td>
<td>OCNT</td>
</tr>
<tr>
<td>607</td>
<td>PLNT</td>
<td>OCNT</td>
</tr>
<tr>
<td>413</td>
<td>PLNT</td>
<td>OCHP</td>
</tr>
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<td>PLNT</td>
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<td>243</td>
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<td>138</td>
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<tr>
<td>36</td>
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<td>21</td>
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</tr>
<tr>
<td>17</td>
<td>PLHPST</td>
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</tbody>
</table>

a This is a weighted index including total solids, suspended solids, chemical oxygen demand, and chlorides. Data for this index was derived from McElroy and Bell ("Storm-water Runoff Quality for Urban and Semi-Urban/Rural Watersheds", Purdue University Water Resources Research Center, Tech. Rept. No. 43, February 1974, 156 pp.) and Economic System Corporation ("Storm Water Pollution from Urban Land Activity", Federal Water Quality Administration, Department of the Interior, 1970).

Associated cost both increase. If the level of the pollution index must be reduced to 607 grams per second, holding ponds are added to the open channel system at an additional cost of $7,000. The holding ponds are introduced first because they are the least costly method to achieve some improvement in water quality at this rate of discount. To further lower the levels of pollution, pipelines, primary treatment facilities and finally secondary treatment facilities are added to the system design at increasingly higher costs. Although holding ponds and open channel systems have not been extensively used in urban areas, this analysis indicates they are minimum cost for some levels of pollution in this case study.

The sensitivity of the solution to the index of pollution utilized was examined in some detail. In general the conclusions indicated above are not sensitive to the index of pollution used. This occurs because the systems in general have similar impacts upon the parameters examined. For example, shifting from a pipeline system with no treatment to one with holding ponds and primary treatment reduced the concentration measured in grams per second of all four of the water quality parameters, i.e. total solids, suspended solids, chemical oxygen demand, and chlorides. The solution was examined for alternative weights for each component and there was little change in the order in which systems entered the solution at least cost when the water quality requirement was progressively increased. Then each of the four parameters were used separately as pollution indicators and the relative rank of the systems was essentially the same for each of
these parameters at the ten percent rate of discount.

Exploration of the sensitivity of the least cost designs to changes in the rate of interest results in different conclusions than the stability which occurred when the water pollution parameters were changed. When the rate of discount is altered significant changes occur in the types of systems which are least cost and the order in which they enter the optimum design. Contrast the zero percent with the twenty percent rates of discount presented in Table 18. At a zero percent rate of discount only pipeline systems enter the least cost design as the water quality is progressively increased. As lower levels of pollution are required holding ponds, primary treatment and secondary treatment facilities are combined as needed with the pipeline transmission component to develop a least cost system. When the rate of interest is increased to ten percent, open channel systems replace pipeline systems as the least cost solution at some levels of water quality. Note particularly that when water quality is unconstrained the open channel no treatment system is the least cost design. As the rate of interest is increased further to twenty percent the open channel systems replace more of the pipeline systems in the least cost system design.

The changes in least cost system design as the rate of interest is increased are illustrated in more detail in Figure 17. The isosystem design (or isopollution level) lines presented in Figure 17 show the least cost system designs as the rate of discount is increased from zero to twenty percent. Points where two isosystem lines cross indicate the rate of discount at which one system changes from being more costly than another system to being less costly or vice versa. For example, consider the changes that occur in the relative cost of the pipeline no treatment system as the rate of interest is increased. At zero rate of discount the pipeline no treatment is the least cost system. Between six percent and eight percent the open channel no treatment system becomes lower cost than the pipeline no treatment system. Therefore, as the interest rate is increased from six percent to ten percent the pipeline-no-treatment system drops from the lowest cost system rank to the third rank behind two open channel systems. Changes such as these are illustrated in Figure 17 for several other systems also.

These changes occur because the systems have different scales of total cost and different ratios of capital cost to operating cost. The total cost of the open channel system is greater than the pipeline system at zero rate of discount due to the high operating and maintenance costs of the open channel system. As the rate of discount is increased the dollar reduction in operation and maintenance costs is greater for the open channel system than for the pipeline system. Therefore at progressively higher rates of discount several open channel systems become less costly as measured by the present value of the total system cost.

It is interesting to note that holding ponds do not exhibit the sensitivity to interest rate that was reflected by the open channel transmission system. Holding ponds are included as part of the least cost system at several levels of water quality and at all rates of interest. Even though the holding ponds have a low capital to operating cost rates, the low total cost of the holding ponds brings them in the optimum design at all interest rates. The holding ponds also reduce the pollution index when added to the other components of the system. Holding ponds and treatment plants are partially redundant when included in the same system. The pond acts as a pre-treatment settling basin prior to the water entering the primary or secondary treatment facilities. However, the ponds do even out the flow of water in the system which results in a scaling down of the size of the treatment facility.

C) POLICY IMPLICATIONS

The analysis suggests certain policy implications for designing urban drainage systems. High rates of interest make it economical to shift from pipeline transmission systems to open channel transmission systems. Although open channel systems have been used for decades in low density rural areas, the economic situation has not been favor-
FIGURE 17 ISOSYSTEM LINES FOR NORMAL OPERATING COSTS
able to their adoption in subdivision development in expanding urban areas. They should be carefully explored as system components with the current high rates of interest.

Since holding ponds are cost effective at several levels of water quality and at all interest rates, they should be seriously considered as part of the urban drainage system design. Careful consideration needs to be given to analysis of the size, number, and location for holding ponds in an urban drainage system. Minimizing the cost of these aspects of the design will include changes in the capital and operating costs of treatment facilities, as well as transmission components of the system. Although holding ponds are cost effective methods to reduce pollution levels and they have low capital costs, when a very high level of water quality is required it will be necessary to supplement them with primary and secondary treatment facilities.

Open channel systems and holding ponds have another advantage to complement their low total cost as high rates of interest. Both of them have relatively low capital costs which is of a great deal of interest to local governments today.

7.3 **THE ECONOMICS OF INSTALLING ADEQUATE STORM DRAINAGE IN FLOOD-PRONE RESIDENTIAL AREAS**

This portion of the study focused on the following objectives:

1. to establish the benefits that would result from providing adequate storm drainage to flood-prone residential areas.
2. to compare the benefits of adequate storm drainage with the costs of providing the drainage system, thus providing a framework in which to measure the economic efficiency.
3. to illustrate and compare the benefit-cost analysis of providing an adequate storm drainage system to an area before urbanization has begun with the benefit-cost analysis of providing the same system after urbanization has been completed.

**A) METODOLOGY**

The first objective was to estimate the benefits that would result from installing adequate storm drainage facilities. This objective was accomplished through the use of a linear regression model of the type

\[ Y = b_0 + b_1 x_1 + b_2 x_2 + \ldots + b_k x_k + e \]

where \( Y \) is the dependent variable, the \( b_i \) are the regression coefficients, the \( x_i \) are the independent or explanatory variables and \( e \) is the error.

In applying this regression equation to a residential area a set of possible variables is:

\[ Y = \text{sale price of property} \]
\[ x_1 = \text{date of sale in months prior to the median data from which sales data are obtained from multiple listing service} \]
\[ x_2 = \text{number of bathrooms} \]
\[ x_3 = \text{existence of a drainage problem} \]
\[ x_4 = \text{existence of central air-conditioning} \]
\[ x_5 = \text{existence of a fireplace} \]
\[ x_6 = \text{age of house in years} \]
\[ x_7 = \text{siding, or construction, of house (brick or frame)} \]
\[ x_8 = \text{extras included in the sale (rating of 1 to 3: avg. = 2)} \]
\[ x_9 = \text{number of garage spaces} \]
\[ x_{10} = \text{quality of home (rating 1 to 3)} \]
\[ x_{11} = \text{size of house in square feet of living area} \]

The variables \( x_3, x_4, x_5, x_7 \) are dummy variables which take the value of zero or one. The remaining variables are discrete variables.

The coefficient \( b_3 \) estimates the amount that home-buyers discount the sale value of a residence located in an inadequately drained residential area. This value is equal to the discounted value of the home-buyers expected streams of future damages which are attributable to the flooding hazard. The expected damages are interpreted as the benefits of eliminating the hazard.

**B) CASE STUDY**

Although there are some areas with inadequate drainage and flooding in the main test community of Lafayette - West Lafayette, the city of Anderson, Indiana, was chosen for the case study because of the availability of the damage cost information. The city of Anderson is located in the east-central part of Indiana. It is the largest city in and the seat of Madison County. Anderson is located 35
miles northeast of Indianapolis. Its population is in excess of 70,000 inhabitants.

Nearly all of the urbanized areas of the city existing before the 1962 annexation are served by combined sewers intended to convey domestic and industrial wastes as well as storm runoff from streets, roofs, yards, etc. In many cases the combined sewers are badly overburdened and in need of relief.

The failure to provide adequate storm drainage facilities to flood-prone areas has resulted in various types of flood related damage. Perhaps the most dramatic form of damages are those manifested in the form of real property damages, including those to houses and yards.

The regression model applied to Anderson, Indiana was as follows:

\[ Y = -579.99 + 199.95X_1 + 1457.76X_2 - 1763.41X_3 
+ 1194.03X_4 + 709.19X_5 - 297.07X_6 
+ 1682.68X_7 + 752.84X_8 + 3213.08X_9 
+ 1522.76X_{10} + 7.92X_{11} \]

The coefficient of determination is \( R^2 = 0.811 \). All the variables except \( X_5 \) and \( X_7 \) are significant to the 0.05 level - the estimated coefficient for \( X_3, $1763.41, \) may be interpreted as the value of the average benefit that would accrue to each residence located in flood-prone residential areas of Anderson if the flooding problems were eliminated.

For the second objective (comparison of the benefits of adequate storm drainage with the cost of providing the drainage system) the area of 38th Street and Columbus Avenue was used. It is representative of most residential areas of the city. The costs to install the drainage system in this area were calculated on a per residence basis assuming urbanization was already completed. This allowed the costs to be strictly comparable with the benefits since both were estimated on the same basis. The cost per residence served was found to be $2,350. This includes the costs of sewer pipes, manholes, pavement repair, drainage structures and non-construction costs, but does not include any provision for the treatment of the sewage. The net-reduction in economic rent associated with providing adequate storm drainage to urbanized flood-prone residential areas of Anderson was thus estimated to be approximately $1753 - 2350 = $597 per residence.

The third section of the analysis estimated the cost of providing the storm drainage system before urbanization. The costs of tearing up and repairing streets and the costs of granular backfill would not be incurred before urbanization. These costs accounted for $427,332, or 23.9% of the total cost estimate made for the urbanized area. Thus, the per residence cost of installing the drainage system prior to urbanization was $1789 per residence. Hence, the benefits of installing the drainage system prior to urbanization were found to be nearly equal to the costs.

C) POLICY IMPLICATIONS

The results of this analysis suggest some interesting public policy implications. A comparison of the benefits and the costs revealed that the benefits of providing adequate storm drainage facilities to residences situated in existing inadequately drained residential areas of Anderson is more than offset by the installation costs. Therefore, the results suggest that extending storm drainage facilities to these areas is not economically justified. The question remains, however, as to the value of damages not accruing to the homeowners, but which are incurred by other members of society. These damages, which are mainly in the form of inconvenience to detoured motorists and damages to city streets, were not specifically evaluated in this analysis, but possibly could change the results and implications of the study.

A comparison of the benefits and costs of providing storm drainage prior to urbanization resulted in a more favorable ratio of benefits to costs. The homeowner benefits were found to be nearly equal to installation costs in this case. Assuming that some benefits will accrue to members of society other than those accruing directly to homeowners, the results suggest that installing drainage facilities in flood-prone areas prior to urbanization is economically justified. It is important, then, for city planners to closely monitor the residential development patterns within the city in order to identify potential problem areas before the areas are developed for residential use. This will allow the city to provide drainage systems, where required,
prior to development, thereby minimizing future residential flooding damages.

Certain aspects of this study relating to the theory, the procedures, and the data base, serve as limitations to the results and conclusions. The use of the case study approach severely limits the general applicability of the results. Because of the many variables involved in estimating the benefits and the costs, the results tend to be valid and usable only for the study area itself. It is possible, however, to use a similar approach to evaluate the benefits and costs of a storm drainage system in a different area.

D) RELATIONSHIP TO PHASE II

There are two key links between phase I and II of this research project. The minimum cost analysis of alternate system designs completed as part one of phase I provided information about the economically optimal system designs to explore in more depth in phase II. In this case the first phase served a screening role in directing special attention to systems designs for phase II which include sediment in basins of alternate sizes, numbers, and locations.

The second link involves the analysis of the damage reduction functions for urban areas when drainage systems are installed prior to development versus their installation after development of the residential area. This was the second part of phase I and it directed attention in the phase II study toward emphasis on the undeveloped areas north of the city of Lafayette. Drainage systems will be developed for these new areas where growth is expected in the future because it was shown that the potential economic benefits of rebuilding drainage systems in the city where drainage problems occur would probably be exceeded by the cost of this reconstruction.

In addition to these two direct links the engineering and cost data developed in phase I are directly useful as input into the extension of the analysis in phase II to study indirect economic impacts in addition to the direct economic impacts explored in phase I. The input-output model that will be developed for Tippecanoe County will permit analysis of the direct costs of alternative drainage systems in the broader framework of total community impact. The results of this indirect analysis should be quite interesting when comparing drainage systems with sediment basins to those systems without because one would expect a priori that the indirect economic impact of these two alternatives would differ greatly.