HYDROGEOLOGIC CONTRIBUTIONS TO ECOSYSTEM ANALYSIS: A DIFFERENT USE FOR GROUND-WATER MODELS

By

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HYDROGEOLOGIC CONTRIBUTIONS TO ECOSYSTEM ANALYSIS: A DIFFERENT USE FOR GROUND-WATER MODELS

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PREFACE

One of the major constraints in the development of any ecosystem, and especially an aquatic ecosystem, is invoked by the physiography where water flows over and through the geologic units of an area. This preliminary investigation presents an attempt to model the ground-water/lake-water exchange in a small aquatic ecosystem. Designing a groundwater model specifically for an aquatic ecosystems model is new and combines two distinct disciplines in a truly interdisciplinary environmental study. Before participating in environmentally related projects, one should be familar with data acquisition techniques, the theoretical concepts for data interpretation, and the terminology employed by the other disciplines involved in such studies. The model in this thesis can be used to illustrate this point.

The theories and the tools most commonly used in geology were employed to establish the physical parameters of the ecosystem and the dynamic changes (flow of water) that occur within the ecosystem. The development and use of the model demonstrates that these measured parameters can be utilized readily in ecosystem analysis by limnologists, aquatic biologists, or aquatic chemists.

The author extends his sincerest thanks to Dr. Douglas Kent for his valuable advice throughout the study of this diversified and unusual topic. Special thanks is extended to Dr. Charles Bacon, Director of the Center for Systems Research for assisting the author with the theory of ecosystems analysis and the mathematics necessary for such an analysis; to Dr. Dale Toetz, Department of Zoology, for helping in the formulation of the topic for this thesis; to Dr. Gary Stewart and to Dr. John Stone of the Department of Geology for their suggestions during the writing of this thesis; and to Dr. Zuhair Al-Shaieb of the Department of Geology for his instruction and suggestions incorporated in the clay analysis section. Appreciation is also extended to Thomas D. Jordan who helped and advised the author with some of the theoretical mathematics and initial engineering of the model, and Robert Rutledge who helped the author to use the CSMP language. Finally, special gratitude is extended to James W. Naney, ground-water research investigator for the Agricultural Research Service (ARS), for his suggestions and for providing some of the hydrogeologic data necessary to construct the model. The hydrologic data and the core samples were provided by the Southern Plains Watershed Research Center, Agricultural Research Service, Chickasha, Oklahoma.

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CHAPTER I

ABSTRACT

A preliminary investigation of a small flood retention reservoir near Hinton, Oklahoma shows the interaction between ground water and lake water by using a mathematical model which can be incorporated into aquatic ecosystem models. Core samples of the alluvium and bedrock were analyzed in order to establish median grain size and permeabilities of the sediments, and the types of clay in the sediments. Physical parameters are described mathematically and incorporated into a systems model using the IBM System/360 Continuous System Modeling Program (CSMP) and the IBM-360/65 digital computer.

Results of this investigation indicate that a limited exchange of water occurs between the lake and the ground-water system during wetter periods of the year. It appears that the lake is not a major source of water supply for the entire ground-water system. However, ground-water seepage is one of the primary sources of water for the lake during the drier periods of the year. The model indicates that the ground-water/surface-water volumetric exchange occurs within a limited area of the impoundment during periods of low flow. The transfer of dissolved chemical constituents may

have a significant impact on some physical and biological parameters within the ecosystem. Isolating these effects remains for future investigations.

CHAPTER II

INTRODUCTION

The model presented in this thesis was created to simulate the hydrologic functions of a specific flood retention reservoir designated as Site 13. Site 13 is a flood control impoundment constructed near Hinton, Oklahoma on the Sugar Creek tributary of the Washita River, by the Soil Conservation Service (SCS).

The mathematical expressions employed in designing this model are similar to those used in formulating biological ecosystem models. This particular modeling format was selected to facilitate integrating this hydrologic model with any biotic or abiotic study conducted on this impoundment.

Generally hydrologic models are constructed for purposes other than defining the physical confines of an aquatic system specifically for ecosystem modeling. This model was created to describe the combined hydrologic effects of both surface water and ground water on an ecosystem. The model will serve as a base for a proposed nitrogen fixation study (Kent and Toetz, 1972) to be conducted on the impoundment. The model will be used to predict the spatial distribution and to trace the movement of nitrogen based compounds between the lake-water system and the bank storage portion of the ground-water system within the impoundment.

Water-budget models, ground-water flow and aquatic ecosystem models, if properly interpreted, may be useful in managing water systems while maintaining or improving the quality of the ecosystem (Van Dyne, 1969; Watt, 1968; Water Resources Engineers, Inc., 1972, 1968). However, ecosystems models are used also by those involved in resource management (Davidson and Clymer, 1966; Martin, 1972; Patten, 1971; King and Paulik, 1967; Garfinkel, 1962; Garfinkel and Sack, 1964; Garfinkel, MacAuthor and Sack, 1964).

Ecologists interested in aquatic ecosystems are describing mathematically the various parameters and their interconnections to further understand the total function of an ecosystem (Parker, 1968, Water Resources Engineers, Inc., 1972; Orlob and Subinski, 1969; Chen, 1970; Chen and Orlob, 1968; Deininger, 1973). Ecosystem models often exclude mathematical representation of the physical parameters within the ecosystem and the interactions between the biota and the abiotic environment in order to simplify the model design. However, community succession may be influenced by the physical parameters associated with the ecosystem. This is especially true in ecosystems where lithology of the area is responsible for compounds that inhibit community growth. In addition, the flow of groundwater may supply nutrients or toxins to the aquatic ecosystem in the form of dissolved salts. Some of these chemical constituents may be trapped temporarily or permanently within the geologic units due to the filtering action associated with percolation, which commonly occurs as ground water moves through the sediments within the system.

The various clay minerals within the sediments may be responsible for some of the natural variations in groundwater quality as reported by several investigators (Kemper, Massland, and Porter, 1964; Olsen, 1972; Quirk and Schofield, 1955; Back and Barnes, 1965; Blackmore, 1970; Day and Forsythe, 1957; Low, 1962). For example, the percentage and type of clay in the sediments of a system can affect the quality of the water as it passes from an impoundment into the ground, and vice versa, by the phenomenon of ion-exchange occurring within the clay minerals (Kemper, 1960, Back and Barnes, 1965, Marshall, 1958, Carroll, 1959).

The model presented in this thesis is designed to describe quantitatively the hydraulic flow of both surface water and ground water in a small watershed. This flow subsequently can be used in other studies to describe the fluctuation and distribution of nitrogen based compounds in an aquatic ecosystem. Predicting spatial distribution of these compounds would provide a base for studying the role of nitrogen fixation in lakes (Kent and Toetz, 1972). Theoretically, if the amount of water flowing through the system could be modeled, then the various ionic constituents (including nitrate) within the water could also be modeled as some function of the flow.

The simplest method for initiating this type of investigation is to measure all of the necessary physical parameters related to surface-water and ground-water flows associated with a small impoundment. Site 13 is an ideal example for modeling because the lake has a small surface area (approximately 56 acres at maximum elevation of 1428 feet) and volume (approximately 746 acre-feet at maximum elevation of 1428 feet). The lithology (sediment type and permeabilities) has been studied previously (Kent, et.al., 1973; Levings,1971). Additional permeability data were obtained by measuring the permeabilities of core samples taken at Site 13. The volume / elevation relationships which define the quantity of water needed in either the ground-water system or the lake to establish an elevation at any height were calculated by estimating the total volume of the entire system and subtracting the estimated volume of the lake at every 2-feet elevation increment. This information was stored as function curve data arrays in the model. Flows within the model are calculated in cubic-feet per day (ft^3/day). The data arrays enable the computer to convert the results of the model into information which can be compared to measured data. The only continuous information which can be used to verify model output is lake elevation. Since Site 13 is located in a semi-arid climate, lake elevation rarely fluctuates dramaticly throughout the year. For this reason, data collected during the storm period of September to October, 1965 were selected to compare the results of the model. The lake elevation varied over 10 feet in 2 days which was one of the largest inflows recorded at the site and provided an opportunity to examine the bank-storage component of the ground-water system.

The hydrologic model may also be used in the future to help answer the following questions: How does the varying salt concentration of the reservoir affect the biota during periods of little inflow? Do the sediments filter and concentrate salts and organic materials as the lake water interacts with the ground water? If such filtering of organic compounds and salts occurs, does the ground water flowing into the lake (bank storage) contain a high concentration of such constituents? Also, how do these conditions affect the aquatic biota? Once the relationships of the physical and biological parameters of a pond are measured, the mathematical relationships and interconnections of these processes and parameters can be incorporated into a water-flow model.

CHAPTER III

INTRODUCTION TO ECOSYSTEM MODELING

Definition of an Ecosystem Model

A systems approach for studying surface-water and ground-water flows associated with a lake ecosystem can be developed by describing the components of the system. The compartments with their interconnections (flows or fluxes) are illustrated both conceptually and mathematically as compartment models. Examples of a conceptual description are shown in Figures 1 and 2. The expressions of these relationships are manipulated functions in mathematical models.

Most ecosystem studies have omitted comprehensive evaluations of the environmental factors within the defined system by having reduced the abiotic components to average inputs per unit time, or by introducing such components into the state equations using varying or non-varying coefficients. Although the biota within an ecosystem may have some influence or control over various abiotic environmental constituents (Kormondy, 1969; Odum, 1959), the structure of an aquatic community will vary directly with the quantity and energy mode of the water within the ecosystem.

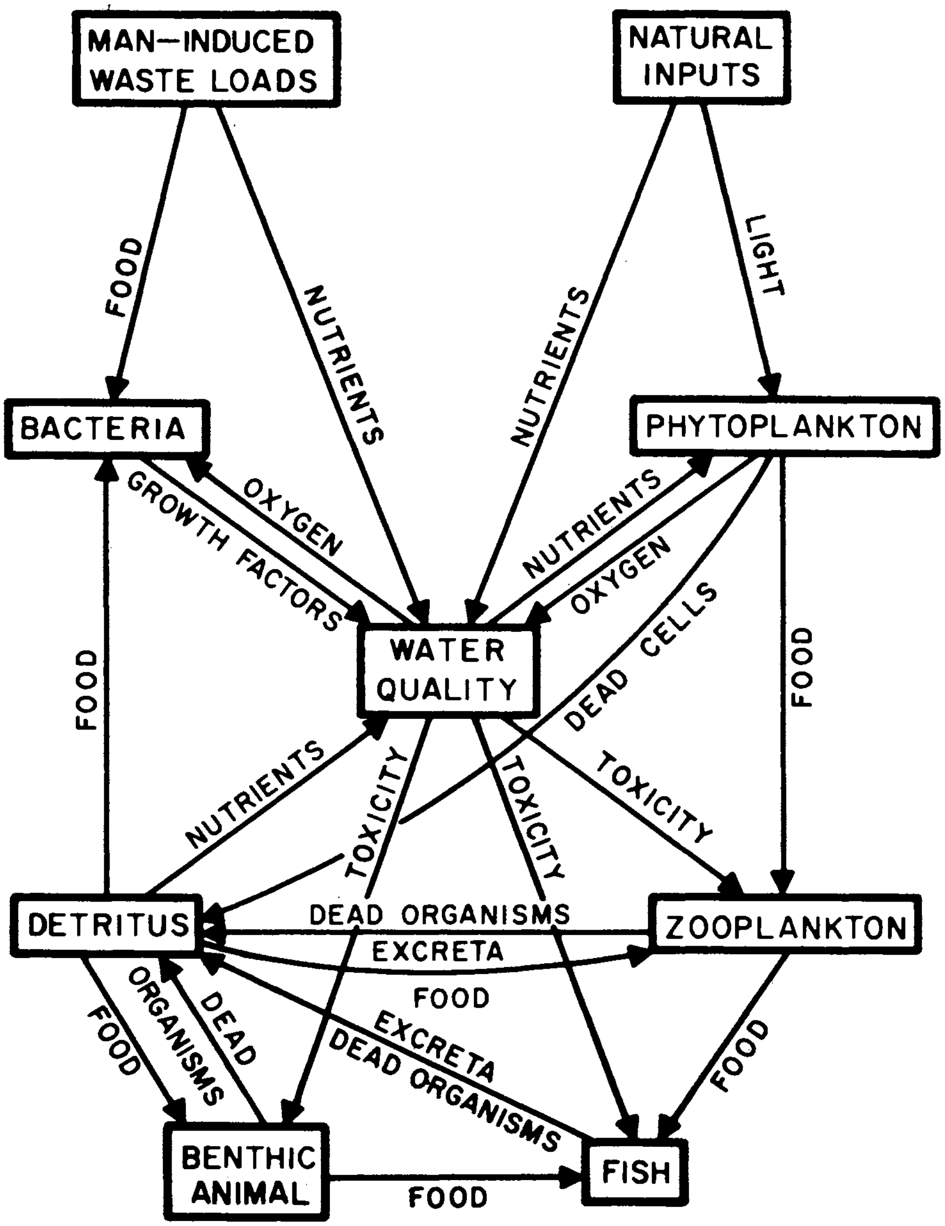


Figure 1. Generally Accepted Compartment Model of an Aquatic Ecosystem (Water Resources Engineers, Inc. 1972).

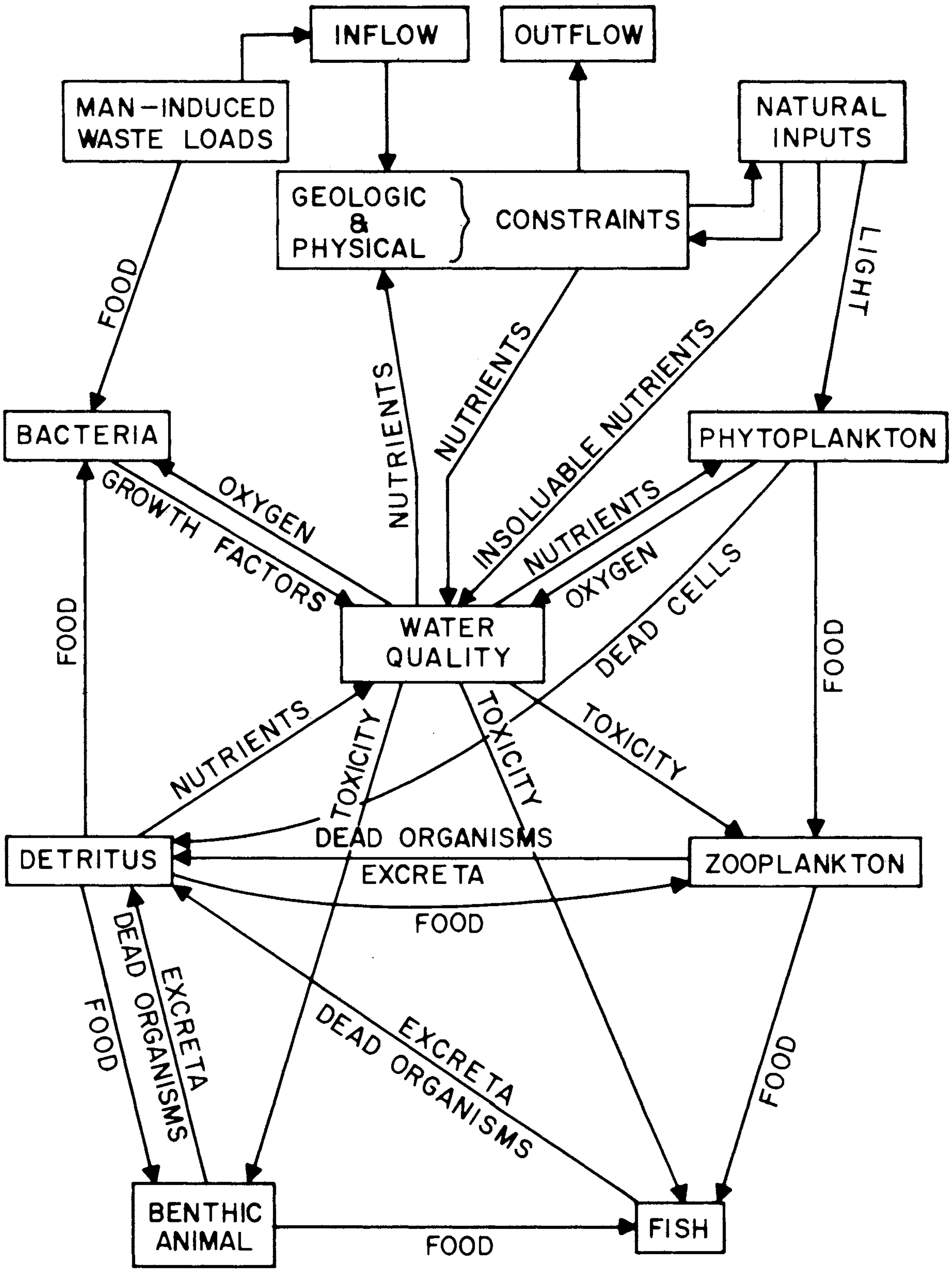


FIGURE 2. A MORE REALISTIC COMPARTMENT MODEL OF AN AQUATIC ECOSYSTEM (FROM WATER RESOURCES ENGINEERS, INC., 1972 MODIFIED BY THE AUTHOR).

The quantity of water within an ecosystem and the course of water movement within a small lake system (both surface water and ground water) will influence various abiotic factors within the impoundment such as dissolved solids, dissolved gases, and temperature and therefore will affect the biota.

Dynamic Model Construction

The theoretical systems model and some of the terminology and techniques employed in linear systems modeling are briefly described in this section. A comparison also is made between biotic and abiotic models.

Biological components in a dynamic linear system model are described, by definition, as states upon inflows and outflows, all "implicitly" linear. The differential equation is the basic mathematical expression for the dynamic systems model which may be used to model the abiotic components of an ecosystem, such as the water budget.

A systems model is used in this study to represent an idealized hydrologic system of a watershed impoundment. This model is similar in design to biological ecosystem models except the hydrologic systems model is not implicit or unidirectional. Most flows (fluxes) described in biological models are unidirectional between major trophic level compartments. This means that a flux of biomass travels only in one direction from trophic level to trophic level. Because the systems model used for this study is not biologically oriented, direct feedback or reverse flow conditions exist and are physically defined. The fluxes of this model are quantities of water expressed in volumetric units per unit time (ft^3/day). Therefore, unlike the biotic models, flow may occur from one compartment to another compartment in either direction depending upon the difference in the states of these compartments.

Mathematics of a General Reservoir Model

As an example of the mathematical form involved in ground-water modeling, consider the following equation which represents the state of X1, the volume of the lake, as described in this thesis:

$$\overset{o}{X1}(t) = Q01 + Q21 - Q12 - PEV - Q10, \quad X1(t) \text{ given at } t = 0,$$

where:

Q10 = seepage (ft^3/t)

Q12 = inflow to bank storage (ft^3/t)

Q21 = seepage from bank storage (ft^3/t)

PEV = evaporation (ft^3/t)

X1 = volume of the lake at any time (t) in ft^3

Q01 = runoff within the watershed .

The flows (Q12, Q21, and Q10) are determined by Darcy's equation which describes laminar flow of fluids through saturated permeable materials (Todd, 1959):

$$Q = - KAi$$

Q = volume/unit time (ft^3/.1t)

K = permeability constant (ft^3/ft^2/.1t)

A = frontal area (ft^2)

i = hydraulic gradient = $\frac{hi - hj}{L}$ $\frac{(ft)}{(ft)}$

L = length for water movement (ft)

hi = XiC = (state of Xi) (function C) head pressure

hj = XjC = (state of Xj) (function C) head pressure.

If flow occurs from Xi to Xj, then hi > hj. If hi = hj, the states Xi and Xj are in equilibrium.

Therefore:

$$Q12 = K\ (A)\ \frac{h2 - h1}{L}$$

or,

$$Q21 = K\ (A)\ \frac{h1 - h2}{L}.$$

Permeability (K) must be found experimentally. Although being depicted equal in this example, the interfacing areas (A) can vary under certain conditions which will be discussed later.

In the hydrologic reservoir model, the Qij's are flow rates by mathematical definition (Darcy's Equation). Therefore, when constructing the state equations in the model, the rate of change of any state (Xi) is the sum of the Qij's or Qji's representing the transfer of water to, or from the state Xi, and the other state(s) Xj where a transfer is possible, e.g., between the lake and the ground water near the shore of the lake.

Note that the Qij only appears once in the set of state equations and not twice as in a biological model. This is the second important difference between biotic and abiotic models. By its mathematical construction, the Darcy relationship,

$$Qij = \frac{K\ A\ (hi-hj)}{L}$$

states that Qij will be positive when hi > hj and negative if hi < hj. The position of hi and hj, or in this model H1 and H2, actually governs the direction of flow (i.e. whether the quantity Qij is positive or negative) and whether the flow Qij is added to or subtracted from compartment Xi.

Thus, Qji need only appear in the state equation of Xj since ground-water movement is not unidirectional. When hi > hj, the term Qji automatically becomes negative, the appropriate quantity is subtracted from the larger state. Such an interconnection cannot exist in a biological model with unidirectional fluxes. The reversal of a biomass flux would indicate that lower trophic levels would be feeding on higher trophic levels, e.g., the plants would be eating the herbivores which in turn would be eating carnivores, etc. Such a situation would be highly unlikely to occur in nature.

CHAPTER IV

S/360-CSMP MODEL FORMAT

The System Program

The mathematical model used in this study was executed on the S/360 Continuous System Modeling Program (S/360 CSMP) on the IBM 360/65 digital computer. The following description of S/360 CSMP is based upon information in the user's manual (IBM, 1972).

Briefly, S/360-CSMP is a problem-oriented program which employs digital simulation of continuous processes on a large storage capacity digital computer. The program is based on an application-oriented computer language which permits a graphical solution of a problem directly from conceptual block-diagrams or ordinary differential equations. Components of the system used in this study are represented by basic function blocks (mathematical expressions or functions) included within the program and/or by application-oriented statements which define the connections between these blocks. The S/360-CSMP accepts most FORTRAN statements. A fixed format is provided for printing (tabular format) and for plotting (graphic format) at selected increments of the independent variable. The simplicity of this system is a great advantage because it permits greater concentration on the system being modeled and not on specific programming steps. Note that the usual FORTRAN statements (READ,WRITE statements) are not necessary. Only basic parameter data are entered in the program. All other necessary format statements are stored in the program and are called when needed by the computer.

The S/360-CSMP program consists of three basic segments: INITIAL, DYNAMIC, TERMINAL. The INITIAL segment is an optional part of the system used for computing initial condition values and those parameters the user chooses to express in different dimensions. For example, when using the formula $Q = KAH/L$, where K (coefficient of permeability) is varied in a series of sequential computer runs, the computer will recompute Q automatically prior to each successive run. Data points representing arrays of information that define linear or non-linear functions are also placed in this section.

The DYNAMIC segment includes the complete description of the system dynamics. Computations needed during the computer run are generally placed in this segment.

The TERMINAL segment is used for those computations necessary for the presentation of results. Necessary information about integration step size, time information (TIMER used), and data printout information (PRTPLOT card) can be read into this section although the computer will also accept the information in the DYNAMIC segment (Rutledge, 1971).

S/360-CSMP assumes that the INITIAL AND DYNAMIC segments represent parallel structure (all of the statements are carried simultaneously) while the TERMINAL segment represents procedural structure (each step is done in order). For this reason, a NOSORT card is placed at the beginning of the DYNAMIC segment. This card changes the structure of the DYNAMIC segment from parallel to procedural, and permits the modeler to put the various "IF. . . " statements in the dynamic section. The computer rejects this type of programming without the NOSORT card.

S/360-CSMP provides two function blocks for handling functions of one variable: AFGEN (arbitrary function generator) and NLFGEN (non-linear function generator). In this model, lake elevation is a function of the quantity of water in the lake, and ground-water elevation is a function of the quantity of water in the lake ground-water system. These relationships are defined by various corresponding data points. The x, y coordinates of the function (volume, height) are entered sequentially in the data statement following the function label and symbolic name of the function.

Therefore, when constructing the data array (CURVE 1) the independent variable (volume of the lake, X1) is listed first followed by the dependent variable (height of the lake surface, H1) . The function is described by the following statement as an example:

H1 = AFGEN (CURVE 1, X1).

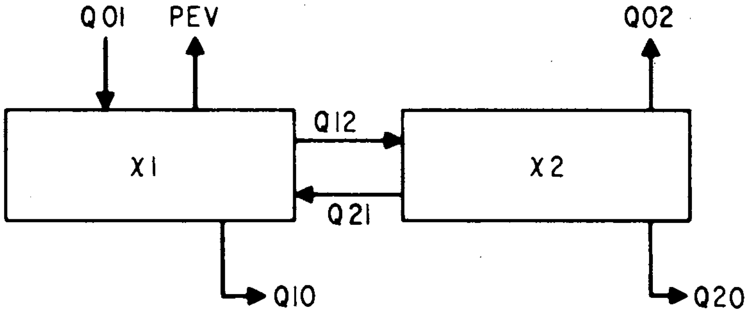
The arbitrary function generator, AFGEN, provides linear interpolation between consecutive points and defines the volume/elevation relationship for each volume (either ground water or lake water) used in the model.

CHAPTER V

MODEL CONSTRUCTION

Designing the Theoretical Model

The mathematical model in this study was constructed to demonstrate the relationship between a ground-water system and the lake surface-water system of the small watershed impoundment (Site 13). Most ecosystem models are constructed in a series of steps. The first step includes measuring the quantity of material in a state, or compartment at various time increments. The second step in model construction involves establishing the various compartments and the interconnections of those compartments as illustrated in Figure 3. State equations are written next. The transfer coefficients governing the fluxes are estimated by interpreting the real data. Model responses are verified by operating the model and comparing simulations with measured data. Some of the various parameters included in the compartment model are: lake volume (X1); ground-water volume (X2); ground-water input from outside the system (Q02); evaporation (PEV); seepage from bank storage into the lake (Q21); flow into bank storage (Q12); seepage under the dam (GUD); seepage through the dam (GTD).



STATES
X1 = Volume Of Impoundment (Lake Water)
X2 = Volume Of Ground-Water Compartment

FLOWS
Q12 = Flow From The Lake Into Ground-Water Compartment (Contribution Of Bank Storage)
Q21 = Seepage From Ground-Water Compartment Into The Lake
Q10 = Total Loss From The Lake By Seepage Through The Dam (GTD) And Seepage Under The Dam (GUD)
PEV = Loss By Evaporation
Q01 = Runoff Within The Watershed
Q02 = Ground Water Base Flow (Input)
Q20 = Ground Water Base Flow (Output)

Figure 3. Compartment Model Showing Structure Of The Reservoir

Defining the Hydrogeologic System

The impoundment selected for this study is a small, flood retention structure (Site 13) constructed by the Soils Conservation Service and located approximately 4 miles south and 1 mile west of Hinton, Oklahoma. The location is shown in Figure 4. A topographic map of Site 13 is shown in Figure 5.

The reservoir is situated on alluvial sediments within a channel cutting into the Rush Springs Sandstone (Permian). This sandstone is a fine-grained, silty, highly crossbedded sandstone consisting of sub-angular to sub-round grains loosely cemented with iron oxide and calcite (Levings, 1971). The unconsolidated alluvial sediments consist of silts and clays in a highly organic matrix which affects the permeability of the sediments and contributes a dark brown or black color to some of the samples. After treating the sample with hydrogen peroxide (Kittrick and Hope, 1963) most of the samples changed to a rust-red color.

The measured permeabilities of core samples from previously cored wells and from wash samples of Well #774 were used in constructing the cross-sections A-A' and B-B' (Figure 6). The locations of the cross-sections are shown in Figure 5 (topographic map).

The mathematics of the model are based on the assumption that the layers of sediments lie horizontally. This is a common modeling assumption because it simplifies the flow equations within the model. Based upon well core

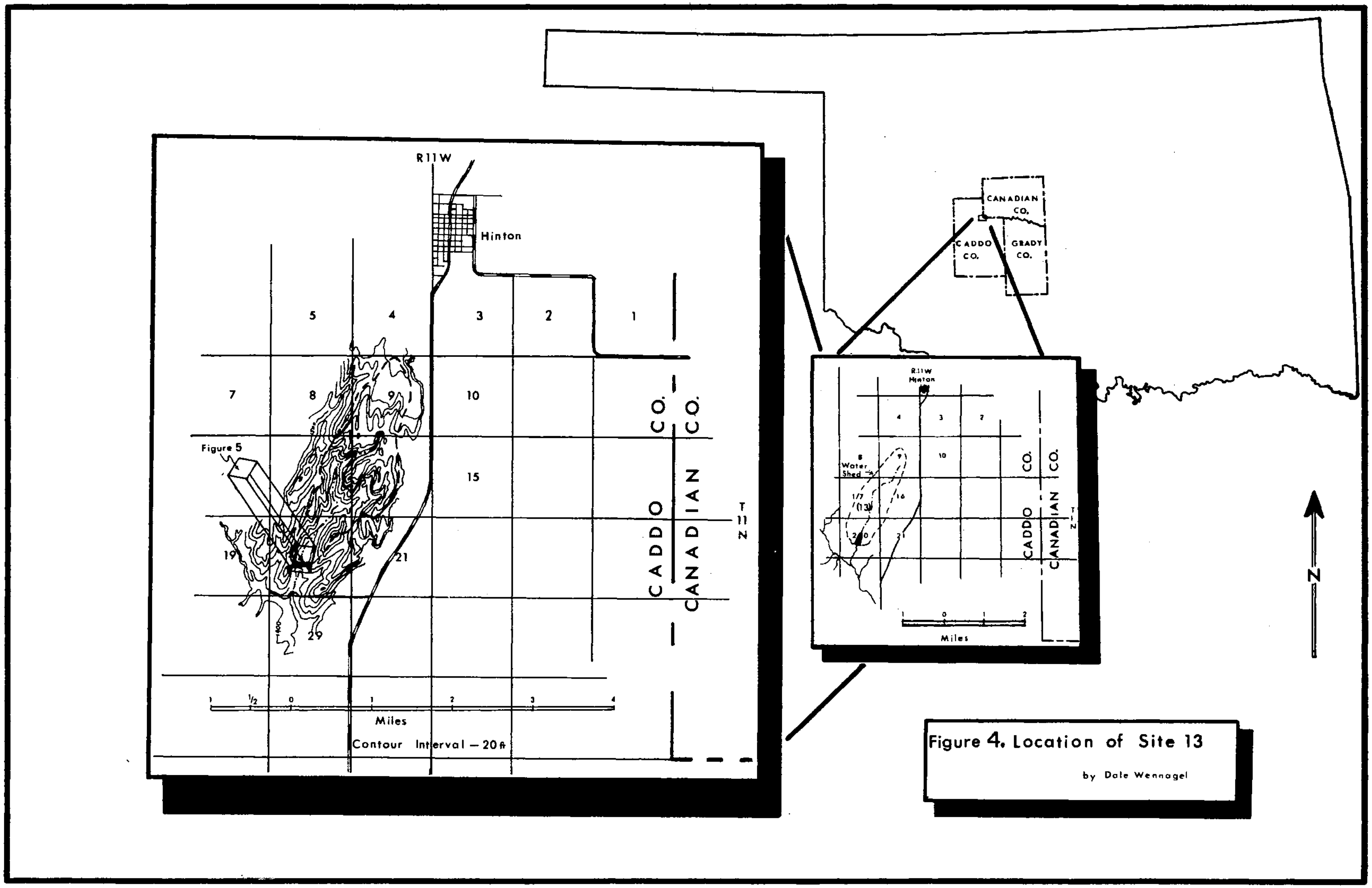


Figure 4. Location of Site 13

by Dale Wennagel

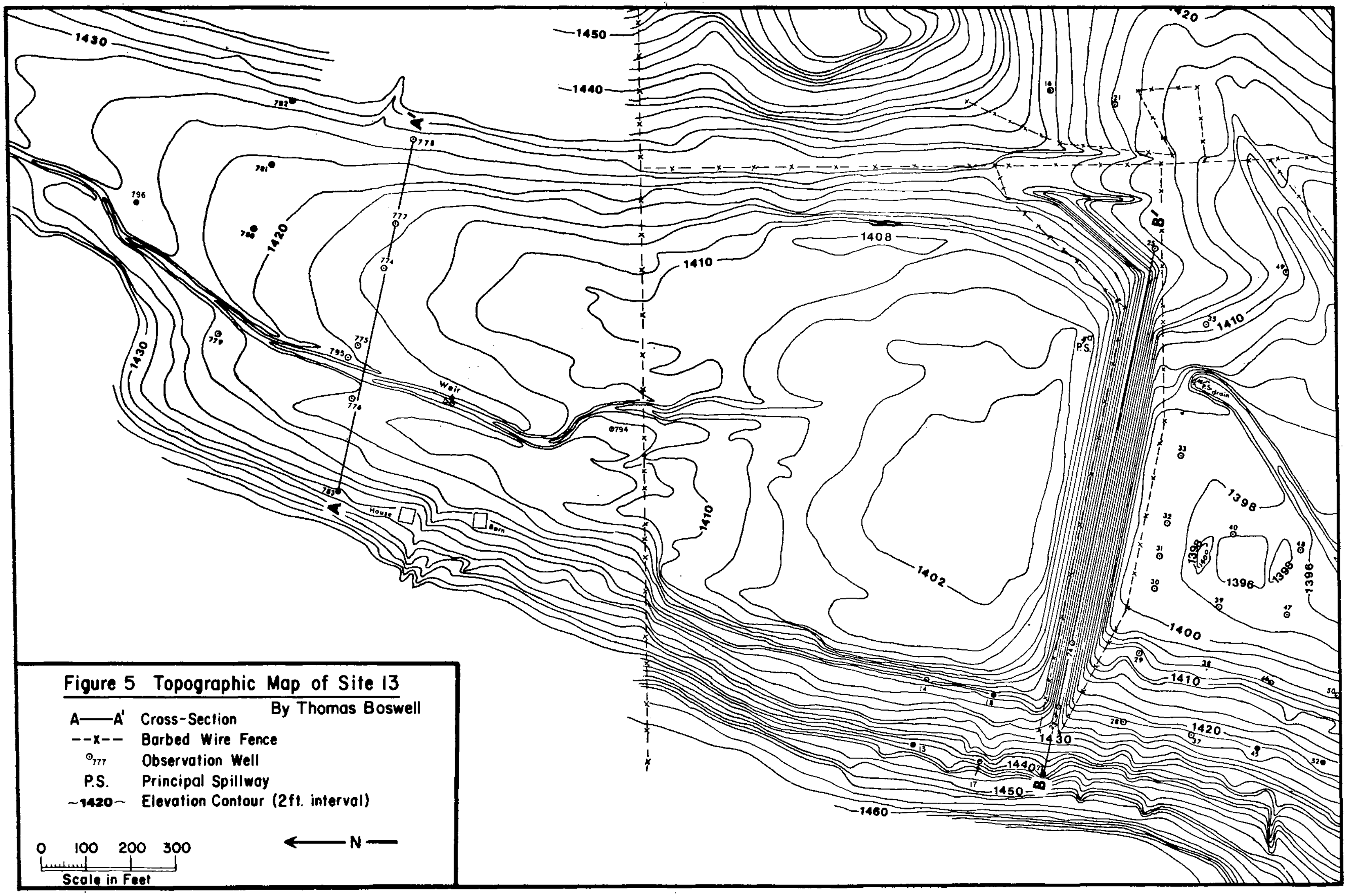


Figure 5 Topographic Map of Site 13

By Thomas Boswell

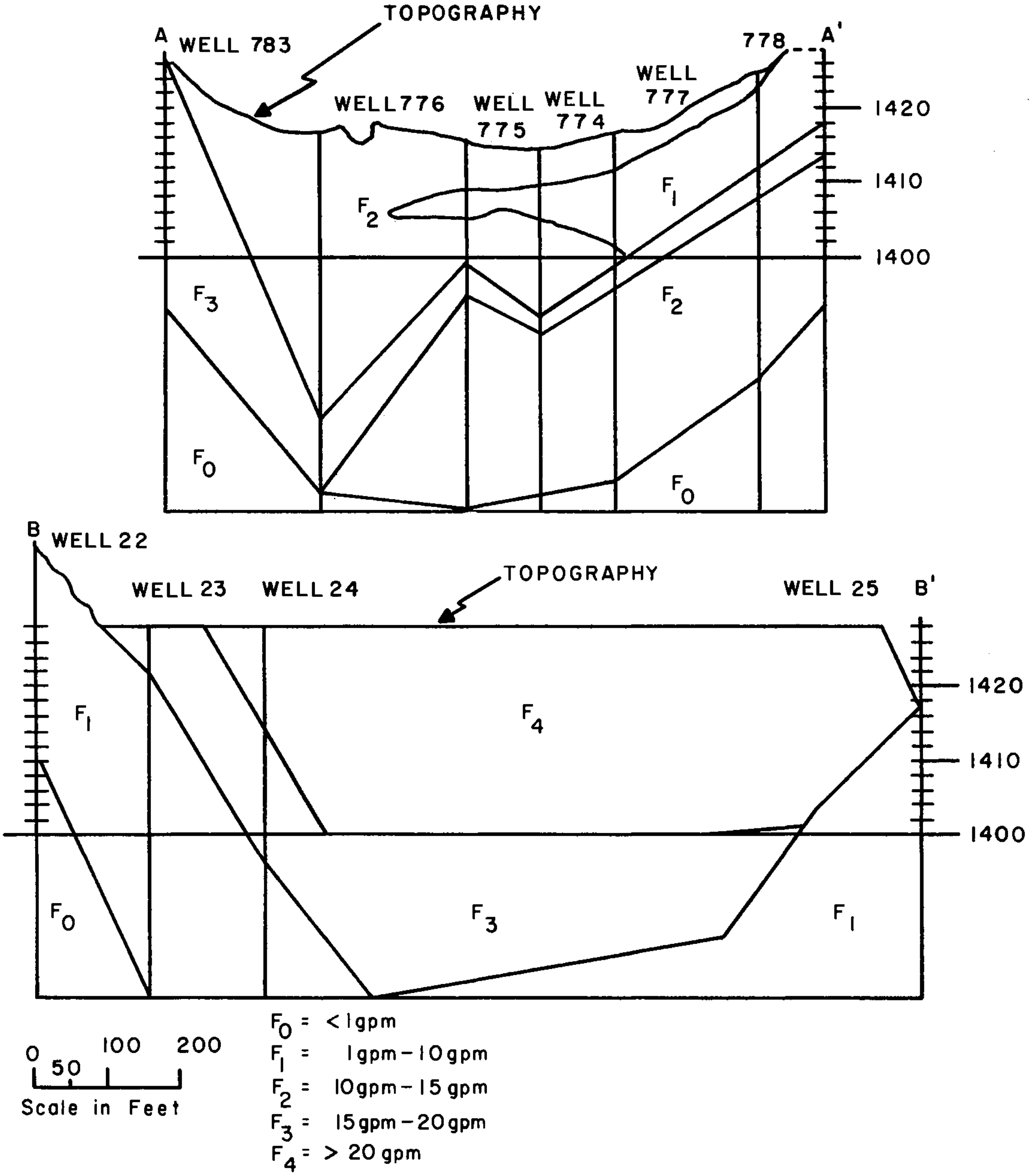


Figure 6. Cross-Sections A-A' and B-B' Depicting Distribution of Permeable Materials at Site 13.

data, an isometric diagram of the sediments around the site was constructed (Figure 7). The sediment layers were projected onto the topographic map creating hypothetical outcrops of each layer within the impoundment basin. Figure 8 is a map of the impoundment area showing the permeabilities using a range of measured permeability coefficients which have been assigned to the sediment types (F1,F2,F3,and F4).

Permeability of Unconsolidated Material

Two observation wells at Site 13 were cored (#774 and #784). Descriptions of the cores from these two wells appear in Table 1. The permeabilities of the unconsolidated sediments within the core samples were determined in the laboratory using standard gas-permeameter techniques. The results appear in Table 2. Grain size distribution was determined by using the visual accumulation tube. The median grain size and the percent of fines by weight are shown in Table 2. Table 3 lists similar data for the wash samples collected from the observation wells at Site 13.

The measured permeability data (gpd/ft^2) were plotted against median grain size (Figure 9). The resulting permeability envelope is based on earlier studies by Levings (1971) and Kent, et. al., (1973). Modification of the envelope was made for the clay and silt sizes based on new data presented in this thesis. Plotting permeability (gpd/ft^2) vs. percent by weight of the fine fractions

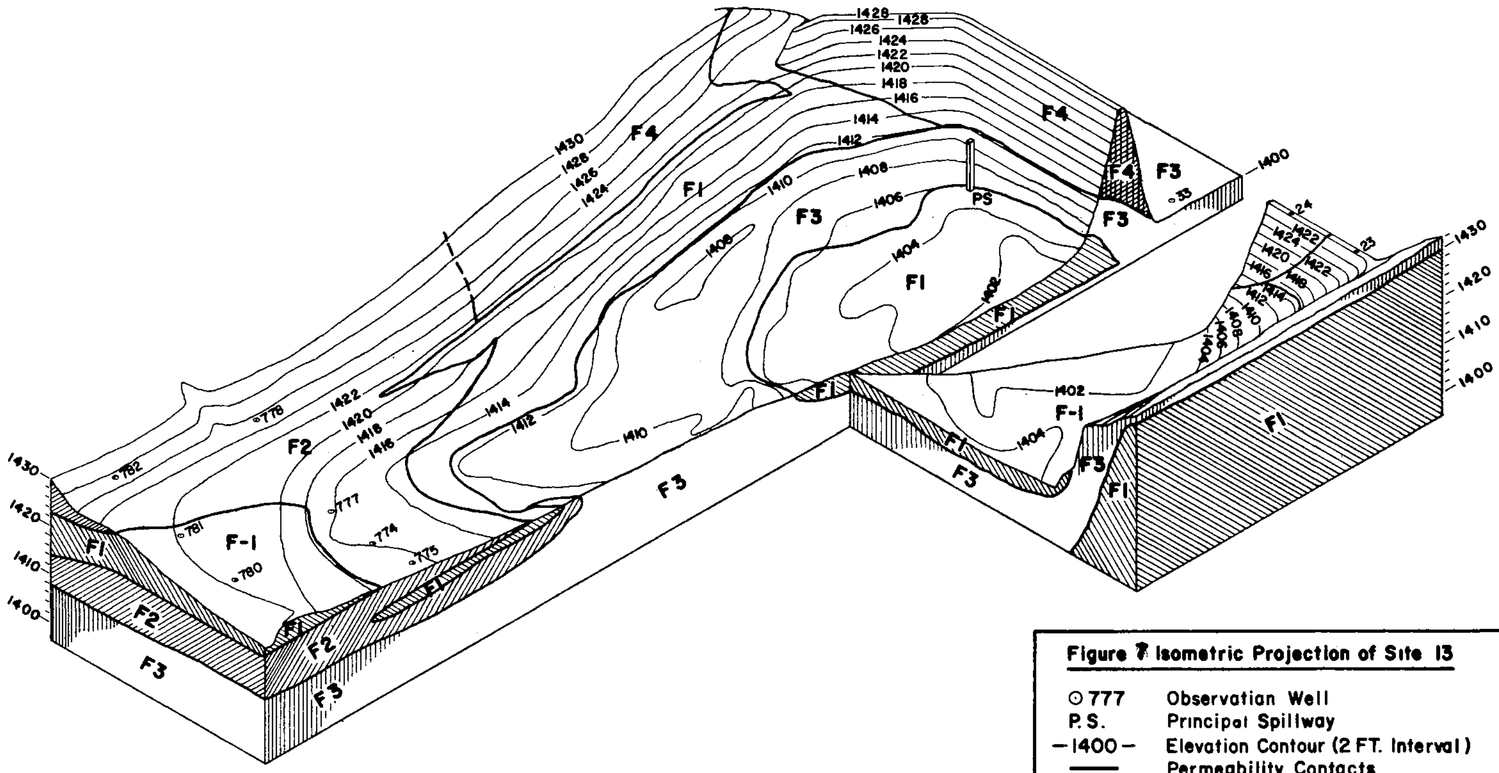


Figure 7 Isometric Projection of Site 13

⊙777 Observation Well

P.S. Principal Spillway

—1400— Elevation Contour (2 FT. Interval)

—— Permeability Contacts

▧ = F1
▨ = F2
▥ = F3
▦ = F4
PROGRAM SYMBOLS FOR VARIOUS PERMEABILITIES (SEE TEXT)

0 100 200 300 400
SCALE IN FEET

N

DALE WENNAGEL

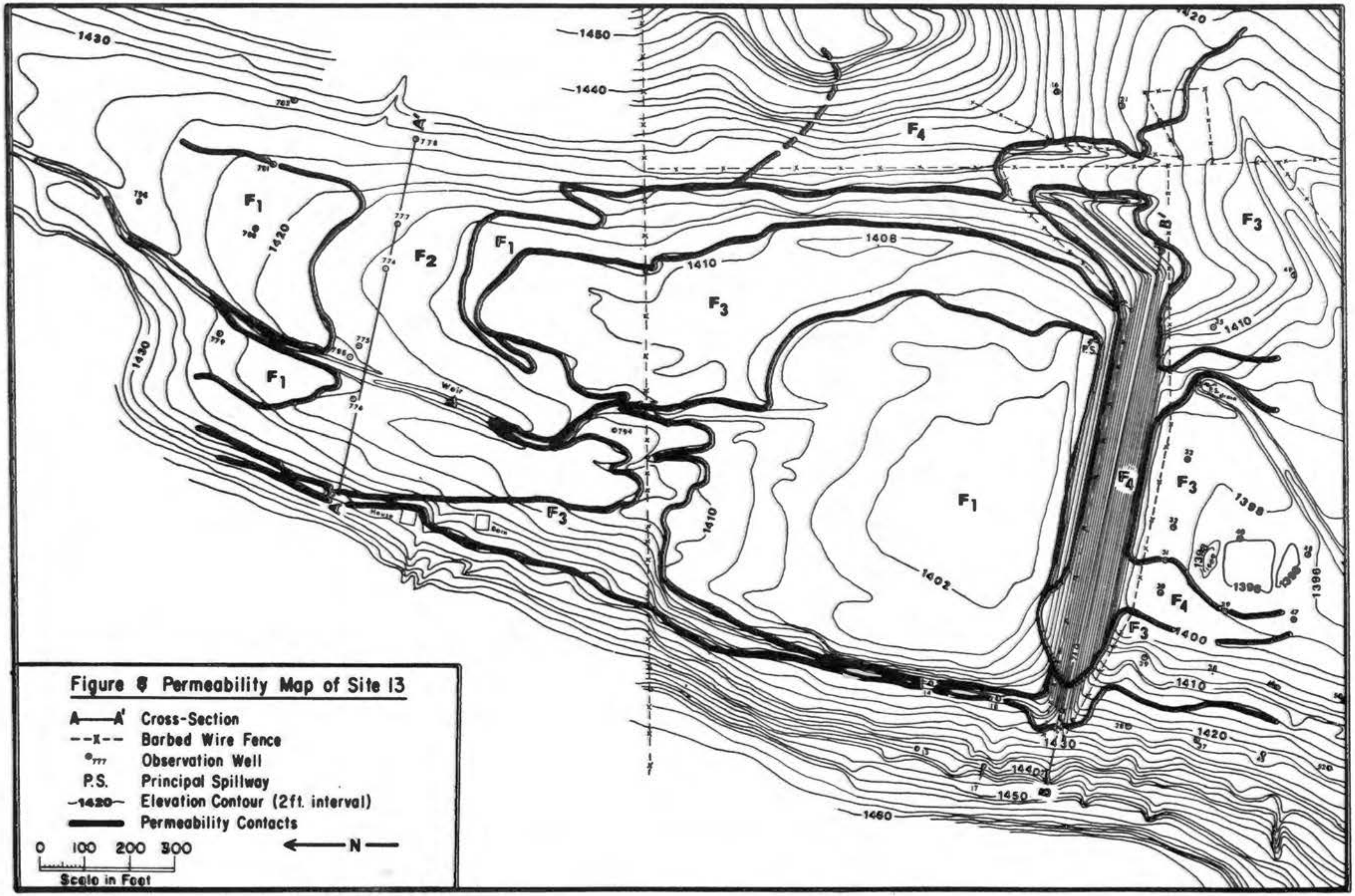


Figure 8 Permeability Map of Site 13

Table 1. Laboratory Description of the Core Samples taken at Site 13.

	DATA NUMBER	DETAILED LABORATORY DESCRIPTION
	Core and/Data/Depth Sample No. No. (feet)	type, size; color; other
NORTH WELL	5A/774/0-.1	Silt and clay; black
	5B/774/.1-1.0	Sand, very fine; red brown with vertical black silt streaks and vertical rootlets; no visible crossbedding
	4A/774/5.1-5.4	Sand, very fine; red brown with laminated silt streak; no visible cross bedding
	4B/774/5.4-5.9	Silt and clay; Gray
	4C/774/5.9-6.6	Silt and clay; Gray and buff
	7A/774/7.4-7.7	Sand, very fine; brown and silt; black
	7B/774/7.7-8.7	Sand, very fine and fine; brown
	3A/774/11.0-12.5	Silt and clay; black
	10A/774/18.7-18.9	Sand, very fine and fine; red brown with silt
	10B/774/18.9-19.8	Sand, very fine and fine; red brown
	1A/774/23.7-24.9	Sand, very fine; red brown, Massive, no visible crossbedding
	1B/774/23.2-23.7	Sand, very fine and silt; dk gray brown; Massive, no visible crossbedding
	8A/774/49.3-50.7	Sand, very fine and fine; red brown
SOUTH WELL	2B/784/1.5-2.2	Sand, very fine; buff
	2A/784/1.2-1.5 2.2-2.7	Sand, very fine and silt; dark brown; massive, no visible crossbedding
	9A/784/3.0-3.3	Sand, very fine and silt; brown
	9B/784/3.3-3.6	Silt; brown
	6A/784/3.6-4.5	Sand, very fine; red brown; with short vertical streaks of black silt and with vertical streaks of light gray very fine and fine sand; massive, no visible crossbedding
	11A/784/60.0-60.4	Clay; dark gray
	11B/784/60.4-60.5	Sand, fine; tan
	11C/784/60.5-61.3	Clay; dark gray
BEDROCK	12A/Bedrock/38.5-38.7	Sandstone; massive, well cemented
	12B/Bedrock/38.7-39.0	Sandstone; with horizontal fractures filled with soft sandy clay
	12C/Bedrock/39.0-40.0	Siltstone, with sandstone; medium hard
	12D/Bedrock/40.0-40.4	Sandstone and sandy clay; alternating lenses
	12E/Bedrock/40.4-40.5	Sandstone, friable

Table 2. Grain Size Distribution and Permeablilties of Core Samples from Site 13.

DATA NUMBER	GRAIN SIZE DISTRIBUTION			PERMEABILITY		
Sample/Data/Depth No. No. (feet)	% by weight of fine fraction(.062mm)	Grain size D50(mm)	Uniformity coeff. 60mm/10mm	Falling head 24°C/16°C (gpd/ft^2)	Constant head 24°C/16°C (gpd/ft^2)	Direction
5-A/774/0-.1	Not sampled	(Too thin)				
* 5-B/774/0.1-1.1	29.5	.07	1.29	2.09/1.71	1.64/1.35	Horizontal
5-B/774/0.1-1.1	10.7	.105	1.88	2.82/2.31	2.56/2.10	Vertical
*+ 4-A/774/5.1-5.4	35.6	.069	1.5	14.35/11.77	9.12/7.48	Horizontal
*+ 4-A/774/5.1-5.4	17.1	.081	1.53	4.94/4.05	4.06/3.33	Vertical
*+ 4-B/774/5.4-5.9	65.8	.05	1.54	Impermeable	Impermeable	Vertical
4-C/774/5.9-6.6	Not sampled	(Impermeable)				
7-A/774/7.4-7.7	Not sampled	(Too thin)				
7-B/774/7.7-8.7	15.4	.08	1.5	2.1/1.73	2.80/2.30	Horizontal
7-B/774/7.7-8.7	11.3	.071	1.5	3.33/2.73	3.57/2.93	Vertical
3-A/774/11.0-12.5	66.1	.04	2.09	Impermeable	Impermeable	Vertical
*+ 3-A/774/11.0-12.5	59.8	.059	1.61	Impermeable	Impermeable	Horizontal
*+ 10-A/774/18.7-18.9	24.4	.072	1.32	3.91/3.2	5.05/4.14	Horizontal
*+ 10-B/774/18.9-19.8	19.7	.08	1.47	Lost	Lost	Vertical
+ 1-B/774/23.2-23.7	41.9	.067	1.29	Impermeable	Impermeable	Vertical
*+ 1-B/774/23.2-23.7	39.6	.068	13.33	Impermeable	Impermeable	Horizontal
* 1-A/774/23.7-24.9	18.6	.078	1.4	21.06/17.27	15.87/13.02	Horizontal
*+ 1-A/774/23.7-24.9	20.2	.079	1.44	4.67/3.83	5.79/4.74	Vertical
*+ 8-A/774/49.3-50.7	12.2	.085	1.48	8.83/7.24	10.66/8.74	Horizontal
8-A/774/49.3-50.7	10.9	.085	1.51	38.87/31.87	41.86/34.32	Vertical
12-A/Bedrock/38.5-38.7	Not sampled	(Too thin)				
12-B/Bedrock/38.7-39.0	Not sampled	(Too thin)				
12-E/Bedrock/40.4-40.5	Not sampled	(Too thin)				
* 12-C/Bedrock/39.0-40.0	71.8	.04	2.04	Impermeable	Impermeable	Horizontal
*+ 12-D/Bedrock/40.0-40.4	45.5	.066	1.64	Impermeable	Impermeable	Horizontal
2-A/784/2.2-2.7	30.3	Wax contaminated		43.39/35.58	33.49/27.46	Vertical
* 2-B/784/1.5-2.2	8.3	.078	1.27	3.03/2.48	2.62/2.15	Horizontal
* 2-B/784/1.5-2.2	15.7	.077	1.81	54.91/45.03	41.49/34.02	Vertical
2-A/784/2.2-2.7	32.8	.07	1.36	18.47/15.15	61.59/50.51	Horizontal
* 9-A/784/2.5-3.3	40.8	.06	1.4	1.87/1.53	1.31/1.07	Horizontal
* 9-B/784/3.3-3.6	34	.07	1.36	.74/.61 –	1.28/1.05	Horizontal
* 6-A/784/3.6-5.0	17	.085	1.5	1.12/.92	.575/.472	Horizontal
* 6-A/784/3.6-5.0	35.8	.073	1.39	.956/.984	.991/.813	Vertical
11A/784/60.0-60.4		Clay		Impermeable	Impermeable	
11C/784/60.5-61.4		Clay		Impermeable	Impermeable	
11B/784/60.4-60.5	Not sampled	(Too thin)				

+ Glycolated
* one test run for identification X-rayed samples

Table 3. Grain Size Distribution of the Wash Samples Collected at Site 13.

DATA NUMBER	GRAIN SIZE DISTRIBUTION		
Sample/Data Process/Depth No. No. (feet)	% by weight of fine fraction	Grain size D50 (mm)	Uniformity Coeff. $\frac{60mm}{10mm}$
N-1/774/0.15	35.3	.07	1.50
N-1/774/5.6-7.4	31.4	.068	1.88
N-1/774/7.1	19.4	.082	1.84
N-1/774/10	37.5	.07	1.55
N-1/774/12.7	72	.05	1.57
N-1/774/20.4	29.9	.077	1.62
N-1/774/24.9	17.3	.08	1.50
N-1/774/53-77	29	.078	1.60
N-1/774/53	54.4	.06	1.75
N-2/775/5-50	47.2	.069	2.26
N-3/776/0-40*	18.7	.077	1.33
N-3/776/40-50	15.5	.09	1.58
N-3/776/47	54.3	.063	1.68
N-4/777/17-47	18.7	.08	1.64
N-5/778/6-16	40.1	.072	1.60
N-5/778/16.5-20	25.9	.11	6.50
N-6/779/20	14	.085	1.48
N-6/779/26-34	79	.028	4.38
N-6/779/40	60.6	.055	2.03
N-7/780/5-7	52.9	.062	1.75
N-7/780/5-10	47	.061	1.15
N-7/780/40	18.9	.099	2.00
N-8/781/40	27.3	.084	1.95
N-9/782/43	42.0	.08	1.60
N-9/782/47	87.1	.011	10.59
E-1/770/0-49	18.9	.083	1.48
E-1/770/49	85.2	.018	6.25
E-2/771/0-40	29.4	.085	1.94
E-3/772/3	16	.083	1.57
S-1/784/1.2	27.2	.074	1.45
S-1/784/2.5	48.1	.055	1.76
S-1/784/3.5	13.9	.082	1.48
S-1/784/3.5	13.9	.082	1.48
S-1/784/15	1.0	.055	1.34
S-2/785/0-40	88.7	.01	10.59
S-2/785/40-50	23.8	.10	6.48
S-2/785/47-50	56	.06	2.5
S-3/786/ 0-40	15.3	.11	2.2
S-4/787/37	51.9	.061	5.0
S-4/787/40	91.3	.0085	8.67
S-5/788/33	73.1	.038	3.77
S-5/788/40-50	28.0	.08	1.80
S-7/790/8	29.1	.079	1.63
S-8/791/	67.7	.042	2.79

* wax contaminated sample

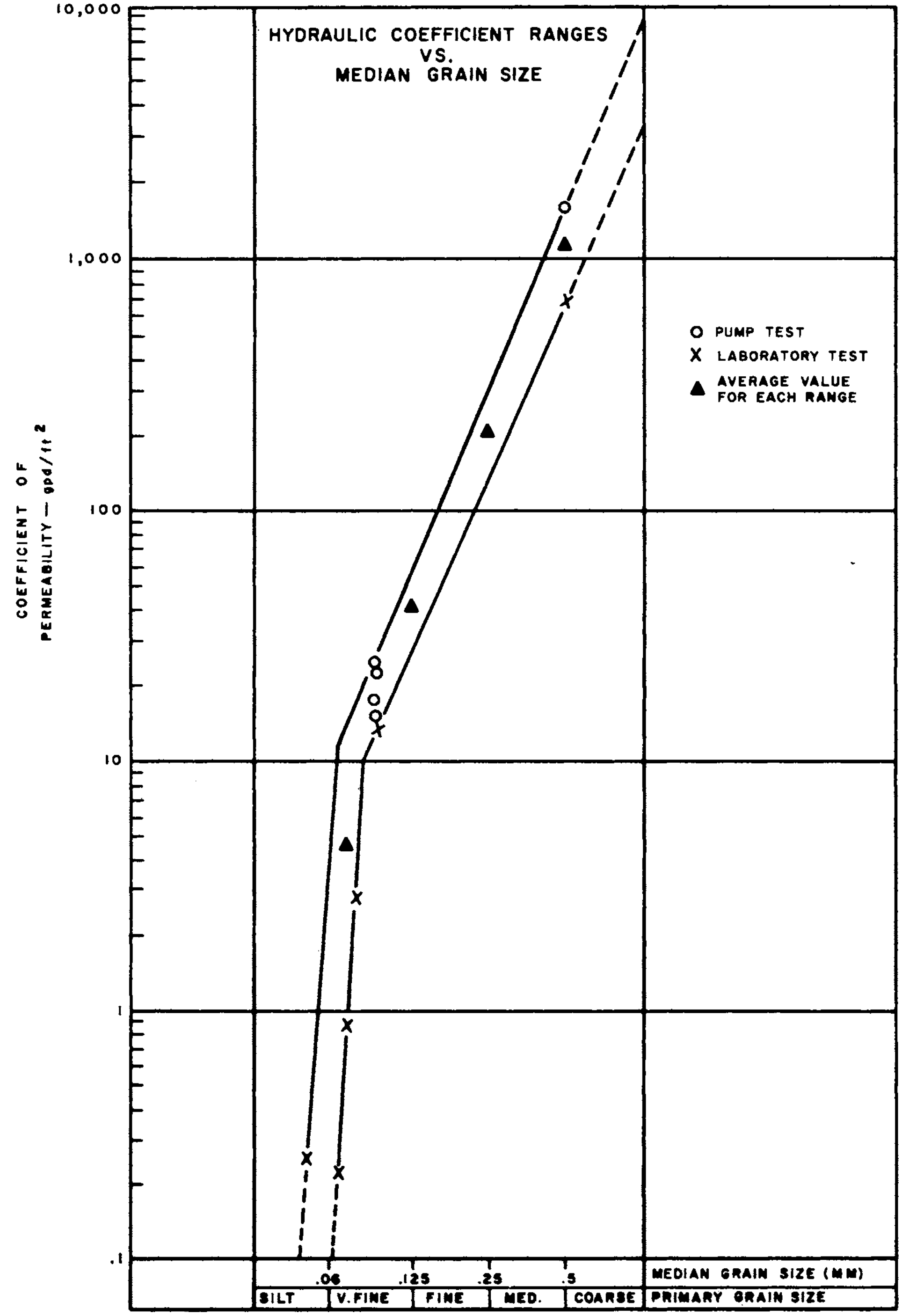


Figure 9. Theoretical Permeability Envelope Modified by the Results of this Study (From Kent, et.al, 1973)

(<.062 mm) from each sample, another permeability envelope is formed (Figure 10).

The results shown in Figure 10 imply that the permeability of unconsolidated materials with a median grain size less than 0.93 mm (Figure 9) is greatly affected by compaction of silt and clay, by the percent of organic material within the clay, and perhaps to a lesser extent, by the type of clay. Because different clay minerals exhibit different swelling properties and ion exchange capacities, identifying the clay constituents possibly would indicate one cause for rapid decrease in the permeability in addition to providing initial clay identification information for those investigatigators interested in the dispersion and distribution of dissolved ions within the impoundment ground-water system. The major clay constituents in the core samples are identified in Figure 10. Five clay minerals were identified in the samples collected from Site 13: Montmorillonite, Kaolinite, Illite, Chlorite, and Glauconite. These minerals are listed in Table 4.

Parameter Identification and Description

The model was created by employing standard geologic techniques for measuring the various physical parameters (permeability, lake surface area, and the volume of the lake) while those parameters that could not be measured were estimated (specific yield, volume of ground-water system,

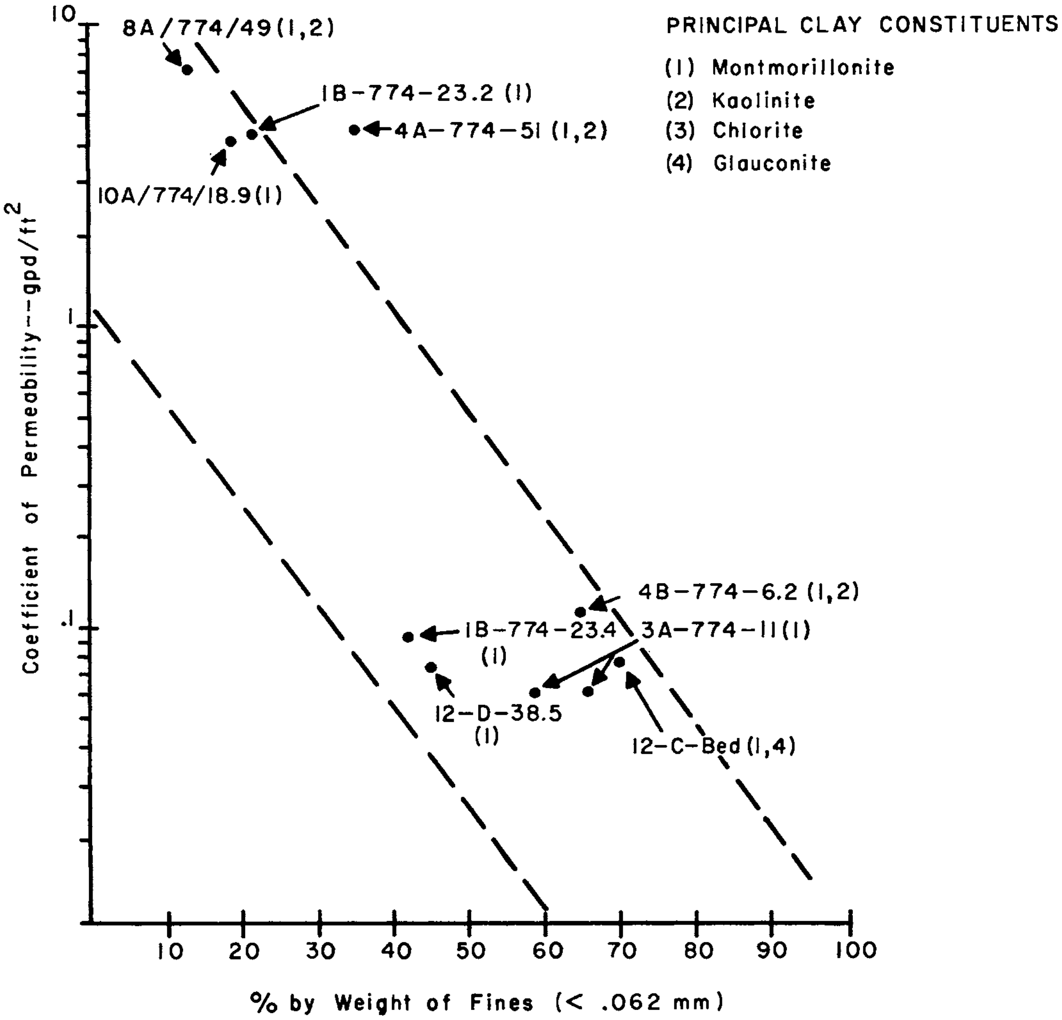


Figure 10. Theoretical Permeability Envelope Depicting the Primary Clay Constituents.

Table 4. Clay Minerals Identified at Site 13.

SAMPLE #	d- No Treatment	d- Glycolated+	MINERAL
10A-NH-18.9	14.25	17-15	**Montmorillonite**
8A-NH- 49	16.99 & 15.23 7.08	16-13(broad) 7.08	Mont. & Chlorite (002) Chlorite
1B-NH-23.4	14.73	16	Montmorillonite
3A-NV-11	14.73	17	Montmorillonite
1B-NV-23.2	16.99	22-147(broad)	Montmorillonite
10B-NH-19.2	14.25	14.4	Chlorite
12D-HBed-38.5	14.73 9.7	17 9.9	Montmorillonite Glauconite/Illite
12C-HBed- 38	14.73 9.8	15 9.8	Mont. / Chlorite Galuconite/Illite
1A-NV-24.4	14.97	15.23	Chlorite
6A-SH- .4	17 14.73 7.08	16 11.05 7.08	Mont. (?) (?) (002) Chlorite
4B-NV-6.2	16.06	16.06	Montmorillonite
1A-NH-24.2	15.23	15.5	Montmorillonite
2B-SV-1.0	15.23	7.2	Kaolinite
7B-NH-8.9	14.7	17-17	Chlor. & Mont.
4A-NH-5.1	16.36	19-14.7	Mont. & Chlor.

\+ Glycolated samples were placed in a descicator with ethylene glycol for 8 days at 88°C. Samples were then removed and run on the X-ray and bank storage). Hydrologic data collected during September and October, 1965, appear in Table 5.

The lack of continuous ground-water elevation records for a corresponding storm period made it necessary to define the physical constraints of the ground-water and lake-water systems by mathematically estimating their respective hydrologic fluctuations. The path and rate of ground-water movement were predicted by Darcy's equation. This required the identification of the hydrologic parameters of the ground-water system. Consequently, the variables in Darcy's Equation (flow, coefficient of permeability, cross-sectional area of flow, and hydraulic gradient) were measured in addition to estimating the storage volumes of the ground-water and lake compartments of the model. These data appear in Tables 2, 6 and 7. The accuracy of the values assigned to these physical parameters and converting them into mathematical expressions govern the reliability of the model response to additional input data.

The first data measured include continuous changes in lake level. The storm period in September, 1965 was selected because of the large change in lake level during that period. The surface area and the corresponding volume were measured for every contour increment on the topographic map in Figure 5 using a planimeter. The data of lake area, water level, and corresponding volume are shown in Table 6.

Table 5. Daily Summary of September 1965 Runoff Event at Site 13*

t	Month	Day	Surface area (acres)	Gage height (ft)	Rain (in)	Volume (ac-ft)	Principal spillway (ac-ft)	Rain (ac-ft)	Inflow (ac-ft)	Loss (ac-ft)
1	9	16	15.95	6.96	0.00	66.37	0.00	0.00	0.00	0.63
2	9	17	15.85	6.92	0.00	65.74	0.00	0.00	0.00	0.70
3	9	18	15.79	6.91	0.00	65.60	0.00	0.00	0.00	0.13
4	9	19	16.59	7.62	4.31	76.73	0.00	5.87	5.70	0.44
5	9	20	23.77	17.30	8.25	311.81	1.20	14.32	222.98	0.31
6	9	21	31.94	16.64	8.05	290.19	24.37	0.14	14.82	12.20
7	9	22	30.18	15.55	0.00	257.55	22.25	0.00	0.00	10.39
8	9	23	28.43	14.60	0.00	231.80	20.08	0.00	0.00	3.67
9	9	24	26.75	13.78	0.07	209.24	18.10	0.15	0.00	4.61
10	9	25	25.39	13.04	0.00	190.98	16.04	0.00	0.00	2.21
11	9	26	24.19	12.36	0.00	173.71	13.89	0.00	0.00	3.37
12	9	27	23.11	11.78	0.00	159.92	11.66	0.00	0.00	2.12
13	9	28	22.29	11.30	0.00	149.51	9.53	0.00	0.00	0.87
14	9	29	21.69	10.97	0.10	142.37	6.33	0.18	0.00	0.89
15	9	30	21.29	10.75	0.00	137.49	3.35	0.00	0.00	1.54
16	10	1	21.03	10.61	0.00	134.35	1.93	0.00	0.00	1.20
17	10	2	20.86	10.52	0.00	132.35	1.12	0.00	0.00	0.88
18	10	3	20.75	10.45	0.00	130.78	0.68	0.00	0.00	0.89
19	10	4	20.66	10.40	0.00	129.71	0.42	0.00	0.00	0.64
20	10	5	20.66	10.36	0.00	128.81	0.28	0.00	0.00	0.61
21	10	6	20.56	10.34	0.00	128.38	0.20	0.00	0.00	0.23
22	10	7	20.52	10.31	0.00	127.60	0.14	0.00	0.00	0.55
23	10	8	20.49	10.29	0.00	127.23	0.07	0.00	0.00	0.38
24	10	9	20.46	10.27	0.00	126.83	0.02	0.00	0.00	0.37
25	10	10	20.43	10.25	0.00	126.38	0.00	0.00	0.00	0.45
	Total						151.65	20.64	242.90	52.38

* From 1971 ANNUAL RESEARCH REPORT, Southern Plains Watershed Research Center, Chickasha, Oklahoma

Table 6. Calculated Data used in Constructing this Model.

Elevation	Area of Reservoir in Acres*	Surface Area of Reservoir Acres†	Accumulative Volume in Acre Feet of $X_1 \ {}_{o}\overset{E}{-}{}_{i}$ *	Accumulative Volume of X_{i}, + 1-28 Acre ft. $E_{i+(i+2)}$ †	In Acre Feet, Volume Each 2 Foot Increment *	In Acre Feet, Volume Each 2 Foot Increment†	Total Interfacing Area (A) Between X_1 and X_2 Computer Term †	Length Li
1428	52.76	56	766.8	746	101.98	.112		
1426	49.22	52	664.82	634	94.48	.095	1952	L_{28}
1424	45.26	46	570.34	539	86.61	.094	2094	L_{26}
1422	41.35	44	483.73	445	78.77	.079	1445	L_{24}
1420	37.42	37	404.96	366	71.11	.072	2917	L_{22}
1418	33.69	34	333.85	294	63.63	.062	1527	L_{20}
1416	29.94	30	270.22	232	56.31	.056	1695	L_{18}
1414	26.37	25	213.91	176	49.38	.046	1825	L_{16}
1412	23.01	22	164.53	130	43.23	.042	1467	L_{14}
1410	20.22	19	121.3	88	38.18	.031	1551	L_{12}
1408	17.96	14	83.12	57	31.39	.026	2012	L_{10}
1406	13.43	11	51.73	31	23.14	.018	1314	L_8
1404	9.71	7	28.59	13	15.67	.0099	1799	L_6
1402	5.96	3	12.92	5	8.52	.0032	1635	L_4
1400	2.56	0	4.40	0	3.48	0	1355	L_2
1398	.92	0	.92	0	.92	0		

*Calculated by the Soil Conservation Service of the U.S. Department of Agriculture.

†Calculated by the author.

Table 7. Calculated Ground-water Increments (CURVE 2-CURVE 15)*

Calculated Lake-water Increments (CURVE 1)+

H_1 or H_2	Curve 1	Curve 2	Curve 3	Curve 4	Curve 5	Curve 6	Curve 7	Curve 8	Curve 9	Curve 10	Curve 11	Curve 12	Curve 13	Curve 14	Curve 15
28	32500016	-	-	-	-	-	-	-	-	--	—	—	—	—	362659
26	27621396	-	-	-	-	-	-	-	-	--	--	--	--	311631	362383
24	23483196	-	-	-	-	-	-	-	-	—	—	--	257643	307899	354747
22	19388556	-	-	-	-	-	-	-	-	--	—	225830	257620	303688	346632
20	15647316	-	-	-	-	-	-	-	-	--	163641	221981	250881	292761	331681
18	12810996	-	-	-	-	-	-	-	-	135098	162584	215090	241100	278792	313928
16	10110276	-	-	-	-	-	-	-	105870	132990	157422	204094	227214	260718	291950
14	7681070	-	-	-	-	-	-	78952	104502	128232	149610	190448	210678	239994	267322
12	5832350	-	-	-	-	-	59305	76909	98809	119149	137473	172477	189817	214945	238369
10	3847800	-	-	-	-	42848	58358	73028	91278	108228	123498	152668	167118	186058	207578
8	2579880	-	-	-	24291	40387	52795	64531	79131	92691	104907	128243	139803	156555	172171
6	1350360	-	-	15611	23195	35267	44573	53375	64325	74495	83657	101159	109829	122393	134105
4	692280	-	6259	13752	18714	26762	32966	38834	46134	52914	59022	70690	76470	84846	92654
2	130680	2600	4625	8223	10851	14875	17977	20911	24561	27951	31005	36839	39729	43917	47821
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0

* Calculated Volume in 2-feet Increments = ($ft^3 \times 10^3$)

\+ Calculated Volume in 2-feet Increments = ft^3

The following sections describe the calculations used to define the volume and area relationships shown in Table 6. The impoundment volume was theoretically divided by a series of parallel divisions in the plane of the contour increments (Figure 11).

The volume of the lake (X1 in the program) was calculated in two feet elevation increments using the following formula for estimating the volume of an irregularly shaped trapezium with a height (h) of 4 feet:

$$V = 1/6h\ (B1 + 4M + B2)$$

where,

V = volume is ft^3

$B1$ = area (ft^2) of the base

M = area (ft^2) of the midpoint

$B2$ = area (ft^2) of the top

h = height in feet.

Each increment was calculated in the following manner:

$$V(1402\text{-}1404) = 1/6(4)*[(130680\ \text{ft}^2 + 4\ (130680\ \text{ft}^2) + 304920\ \text{ft}^2] - [(\text{lake volume } 1400\text{-}1402)]$$

$$.\ V(1402\text{-}1404) = V(1400\text{-}1404) - V(1400\text{-}1402)$$

$$V(1402\text{-}1404) = 692280\ \text{ft}^3$$

The volume of the next increment (1404-1406) was calculated similarly using areas of 1402 as B1, 1404 as M, and 1406 as B2. The volume of the lake from 1402-1404 was subtracted from the total volume instead of the volume of increment 1400-1402.

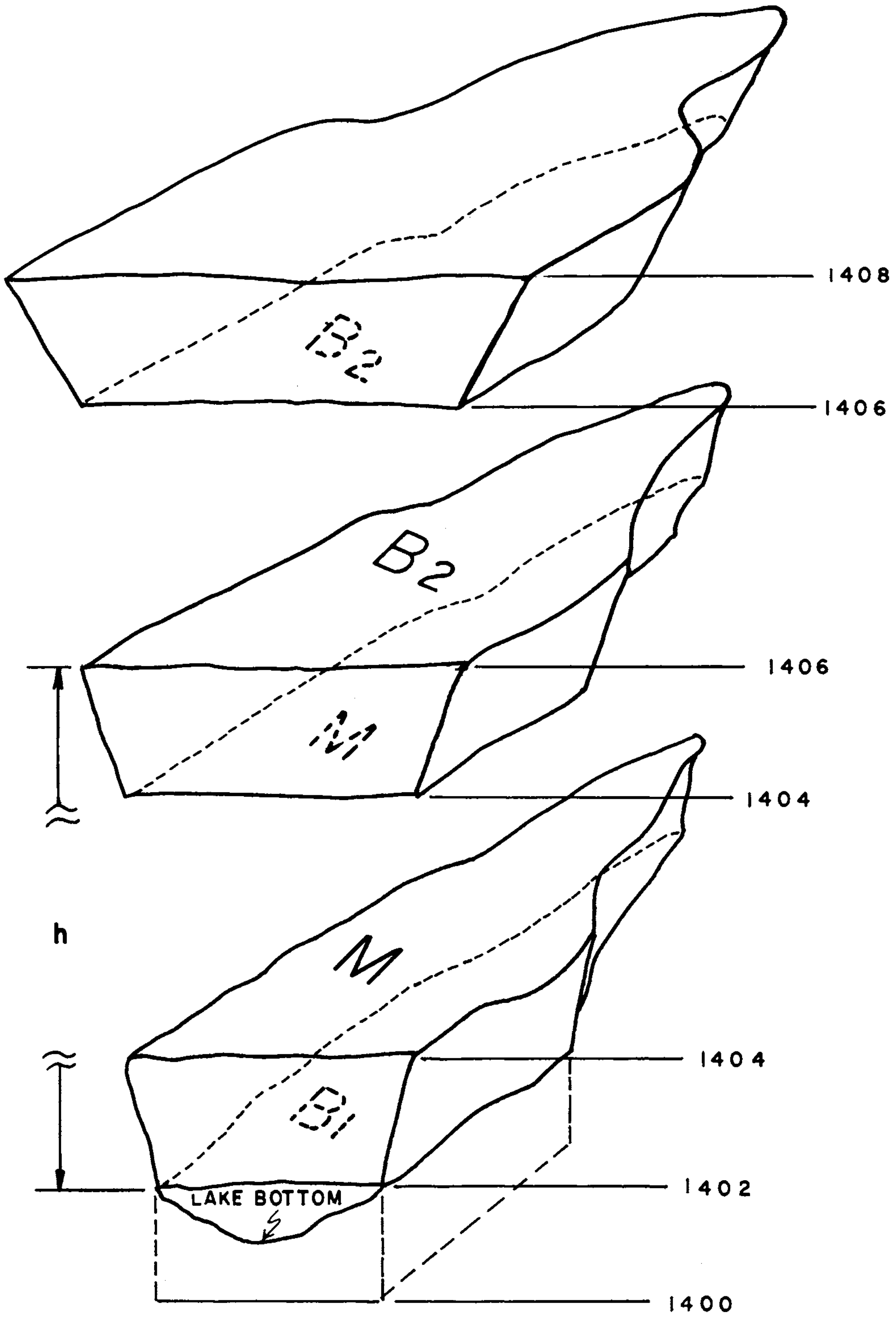


FIGURE 11. EXPLODED VIEW OF THE POND.

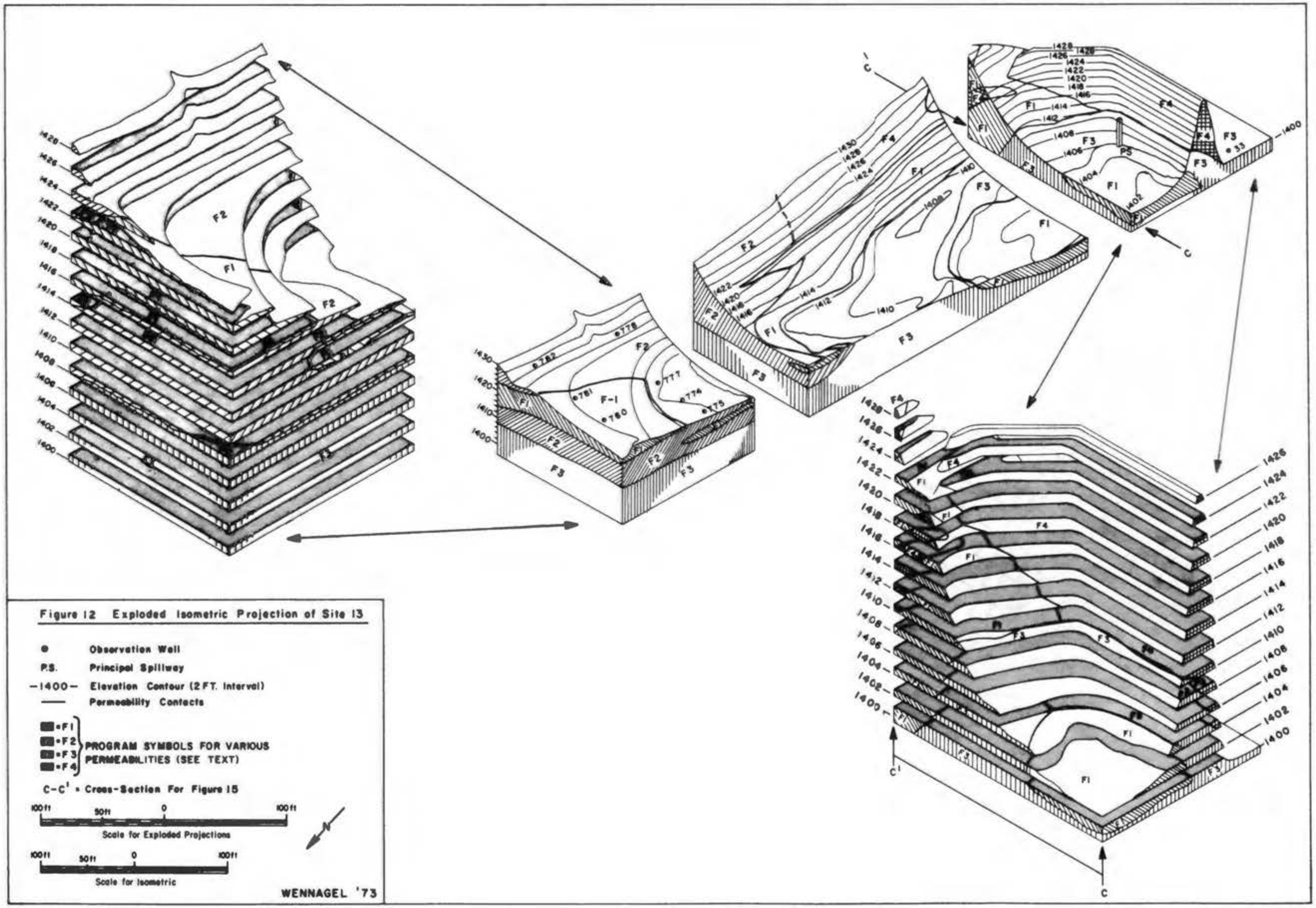


Figure 12 Exploded Isometric Projection of Site 13

● Observation Well

P.S. Principal Spillway

—1400— Elevation Contour (2 FT. Interval)

—— Permeability Contacts

▨=F1 ▨=F2 ▨=F3 ▨=F4 } PROGRAM SYMBOLS FOR VARIOUS PERMEABILITIES (SEE TEXT)

C–C' = Cross-Section For Figure 15

100ft 50ft 0 100ft

Scale for Exploded Projections

100ft 50ft 0 100ft

Scale for Isometric

N

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The remainder of the elevation increments was estimated using the Hewlett-Packard 9820A. The results, as accumulative ft^3 /2-feet elevation increments, appear in Table 7 as FUNCTION CURVE 1. The results were converted to acre/feet and then entered in Table 6.

After defining the volume of the reservoir (X1), it was necessary to estimate the boundary and the volume of the ground-water system. The base elevation was arbitrarily established at 1400 feet. The highest elevation of interest in the impoundment is 1428 feet. To match the reservoir sections, the entire ground-water system was divided into two feet elevation increments. Figure 12 illustrates that the impoundment was divided as was the lake in the plane of the elevation contours. The data for each CURVE(2-15) (Table 7) were calculated as if the saturated sediment or volume of the ground-water system were a series of enclosing envelopes divided into elevation increments of two feet each (Figure 13). The data for each CURVE i represented in Table 7, or volume increment were estimated using the following method.

The surface areas of the various lake increments (ft^2) were designated as the surface areas (Alki, Figure 13) of the ground-water envelopes. FUNCTION CURVE s (2-15) represent the accumulative volume of ground water (X2) for each 2 foot increment represented by the FUNCTION CURVE 1 which describes the accumulative volume / elevation relationship within the lake. Each volume / elevation

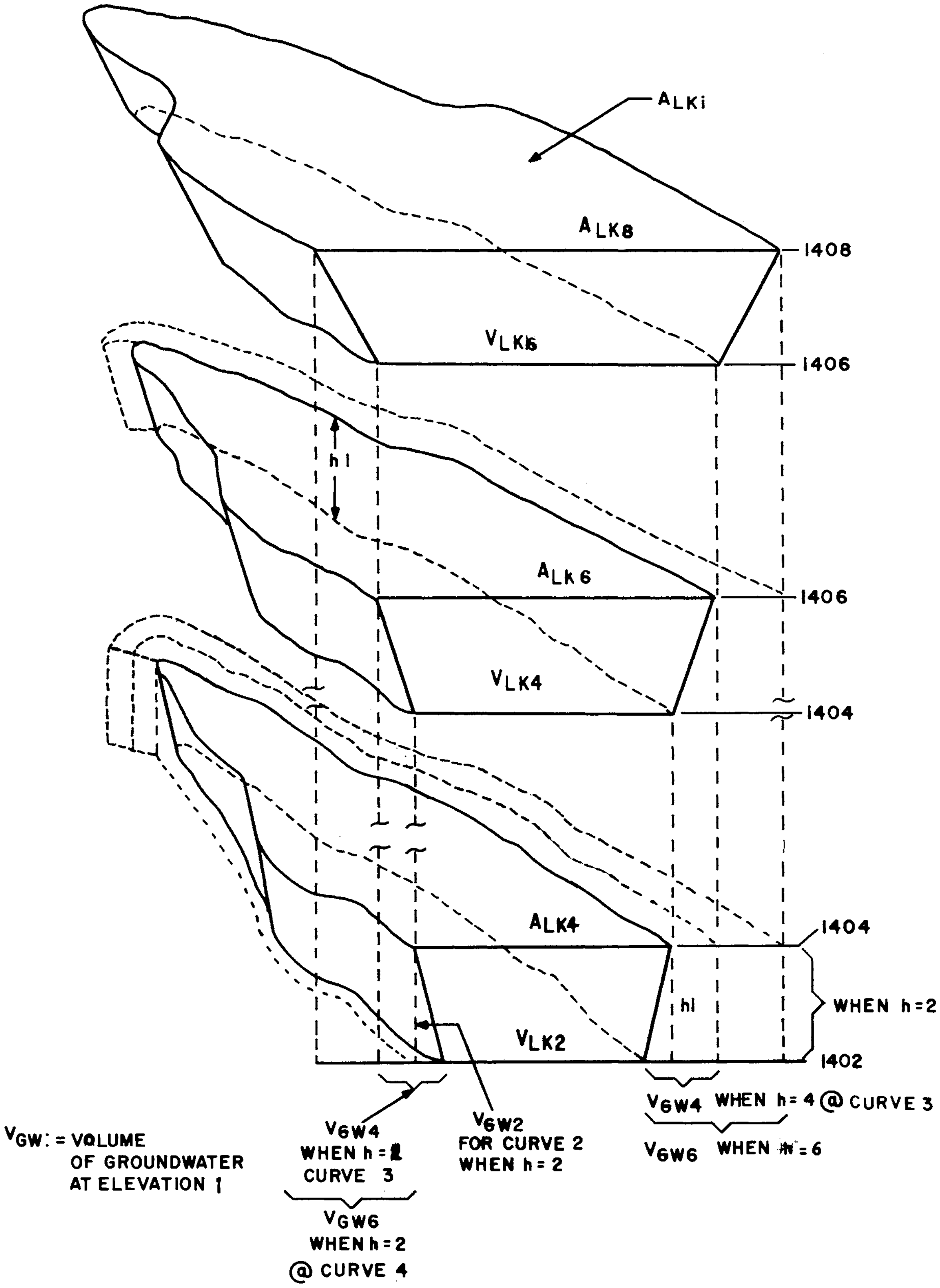


FIGURE 13. Exploded View of the Impoundment With Ground—Water Envelopes

increment of X2 was estimated by multiplying the area (ft^2) of the upper-most contour interval by the height of the increment (feet above base level) and subtracting the total volume of the lake at that elevation. Mathematically, the volumes listed in Table 7 were derived by the following formula:

$$(Alki * i) - (VLKi) = VSi * Sy = VGWi$$

Alki = Area of lake (ft^2) at maximum elevation of interest and extending radially

i = Height above base elevation in feet (2 feet, 4 feet, etc.)

VLKi = Volume of lake (X1) at height (i) of interest above base elevation

Vsi = Volume of sediments at height i

VGWi = Volume of ground water at height i

Sy = Specific Yield.

Specific yield is a measurement of the porosity when the aquifer is unconfined, as is the material at Site 13, and approximates the available storages in the aquifer. Multiplying the total volume of the permeable material by Sy approximates quantity of water available for exchange within the system. Typical values for unconsolidated fine grained sediments range $.0005 \leq Sy \leq .1$ (Te Chow, 1964; Todd, 1959). The sediments at Site 13 are well-sorted, fine grained sand highly dispersed with clay. Therefore the number .001 was designated as the average specific yield for the sediments at Site 13.

Thus the volume increments (FUNCTION CURVE 2-15) define the actual quantity of exchangeable water within the ground-water system and appear in the program. The response of the system is dependent upon specific yield (Sy). Since the storage coefficients for the various sediments at Site 13 are determined experimentally, the sediment volume increments (Table 7) must be multiplied by the new Sy coefficients and inserted into the model. A comparison was made between the results of simulations with various Sy coefficients. The results of these comparisons will be discussed later.

Therefore, the elevation and the location of each well determine the FUNCTION CURVE used for further computations in the model. Every FUNCTION CURVE defines a discrete portion of the ground-water system. As the elevation (H1) increases the surface area used to define the lake water / ground-water exchange area increases. As the surface area increases, the volume of water required to raise ground-water elevation (H2) any elevation increment also increases. Each volume increment includes the volume of the preceding increments in the calculations. Each CURVE (2-15) represents the relationship between the total (accumulative) volume of water in the ground-water compartment (X2) and the corresponding height (H2) of the ground water at any given distance from the lake-water / ground-water interface. H1 = AFGEN (CURVE i,X2) is the computer statement for this relationship. The elevation (between two contour intervals) of any observation well automatically establishes CURVE i. CURVE(S) 1-15 are graphically represented in Figure 14.

After the exchangeable volume of the ground-water compartment had been estimated, the parameters in Darcy's Equation (permeability coefficient, area, hydraulic gradient, length of travel) were determined and converted into the proper mathematical form for this model. The permeability and cross-sectional area of flow in each elevation increment are combined into a single constant, Ci. This equation appears in the program as,

$$Ci = \frac{[(AiF1 * F1)+(AiF2 * F2)+(AiF3 * F3)+(AiF4 *F4)]}{Li}$$

where F1, F2, F3, F4 are the coefficients of permeability in $ft^3/.1day/ft^2$. Li represents the length in feet measured horizontally from the midpoint between each contour interval (i and i +1). Ai is area of the contour increment i with the permeability Fi. In the program, the symbols F1,F2,F3,and F4 represent 1/10 the various permeabilities of the sediments in Table 2. Dividing the permeabilities by 10 is necessary because the computer calculates each step of the integration at .1(t), or .1 day. The total quantity of water transferred in 1t equals 10 x F1 F2 F3 and F4.

Obviously, the distances between each lake interface increment and the observation well (Li's at any elevation increment) are different for each observation well because the distance varies from one contour interval to another. Figure 15 illustrates this point and depicts the real data

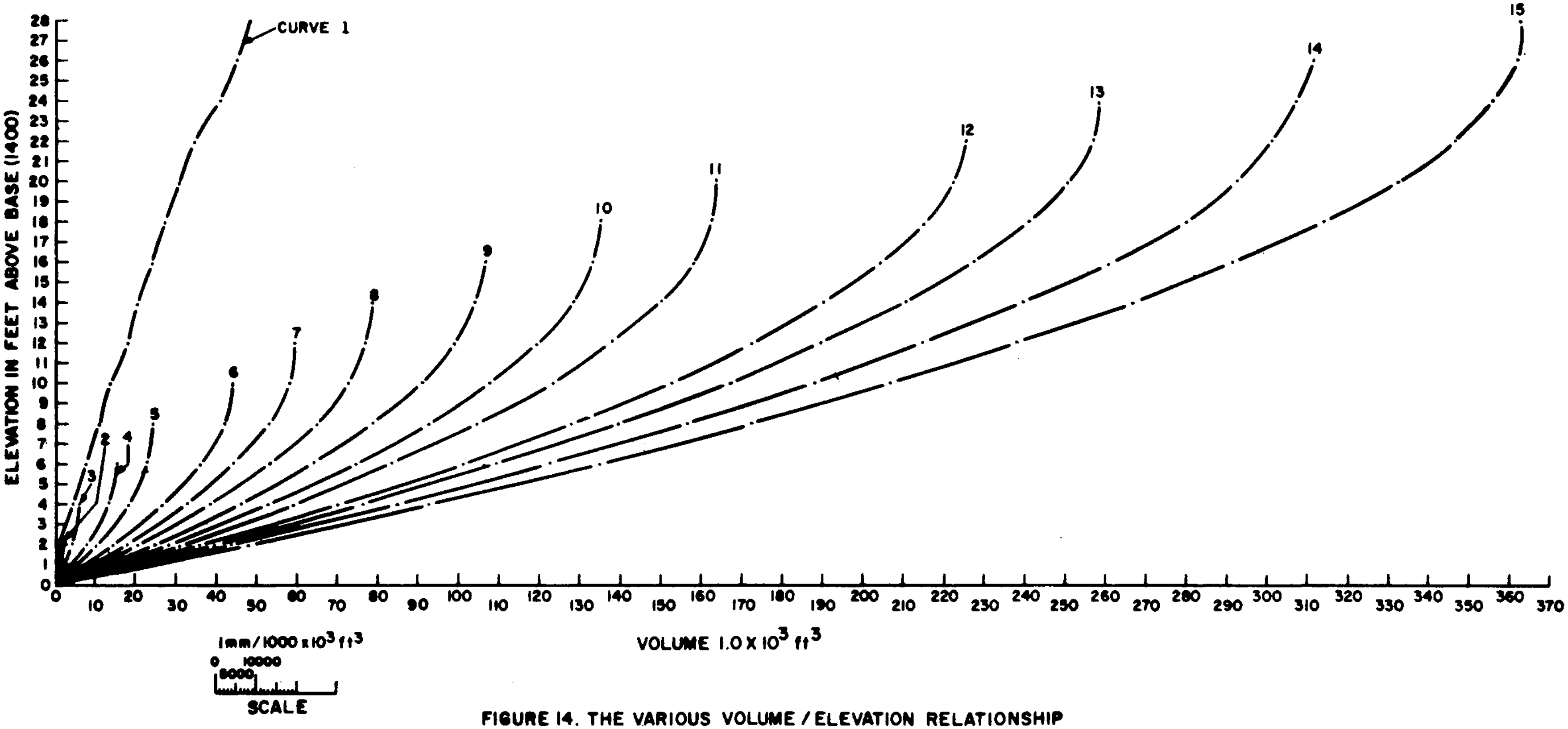


FIGURE 14. THE VARIOUS VOLUME / ELEVATION RELATIONSHIP
(FUNCTION CURV(E)S 1-15).

as the computer assimilates them. Step simulation converts the lake bed into a series of small step increments. The Ai's or the areas used in the formulas were initially figured as the average perimeter between any 2 contours (i and i+1) * 2 feet in elevation. The perimeters, or contour lines of the lake basin, are actually the circumferences of the previously defined envelopes used for calculating the volume of X2. In the program these areas are the numbers that appear in the sets of Ci equations (Appendix A). Figure 15 is a cross-sectional view that illustrates the relationship of the parameters of X2. The parameters are illustrated as being two-dimensional when actually the parameters CURVE i, X2, X1, and pav[i-(i+2)], are three-dimensional and the program is written accordingly. The ratio of ground-water to ground-water elevation for any increment is defined by the FUNCTION CURVE(2-15). The FUNCTION CURVE defining this relationship is dictated by the position of the observation well (Figure 15).

A time delayed response of an observation well water height to a rapid increase in lake elevation is expected because of the resistance to flow (governed by permeability K) between the compartments as defined by Ci. The difference in heights of lake level (H1) and ground-water level (H2) provides the driving force as was previously stated. The computer must vary the proper areas, according to the change in states X1 and X2.

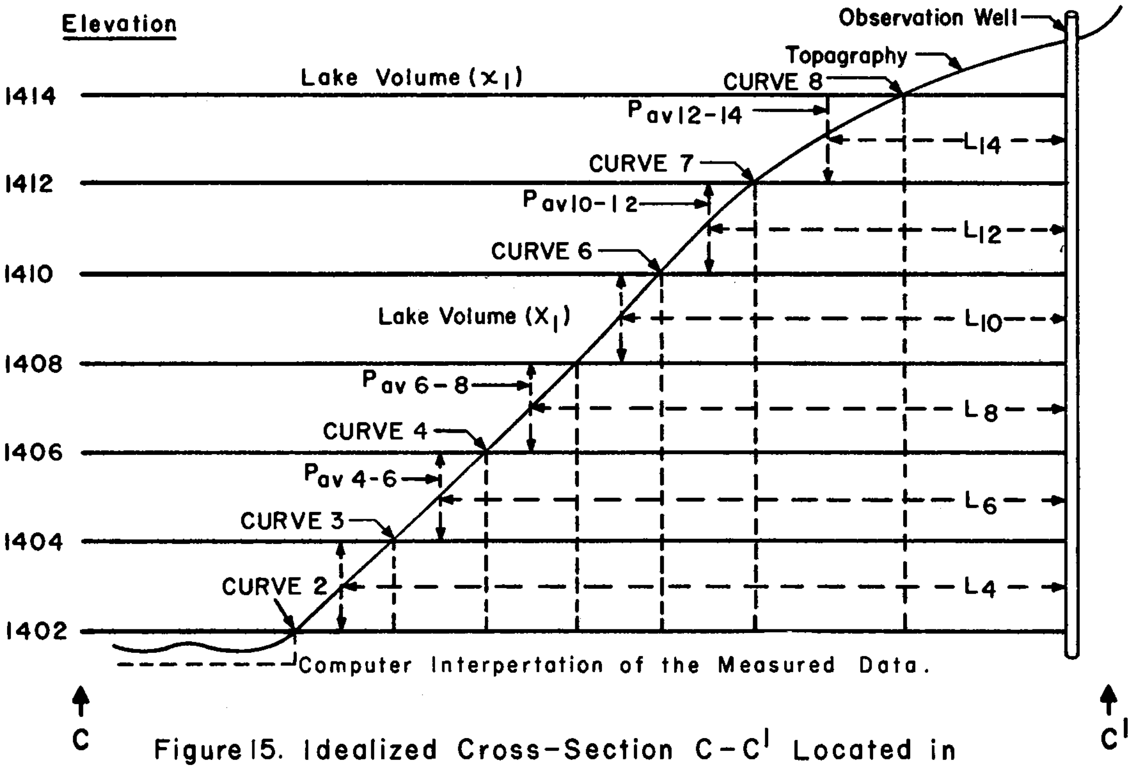


Figure 15. Idealized Cross-Section C-C' Located in Figure 12.

The symbols D1 and D2 represent the accumulative area of seepage between the lake and the ground-water system as determined from CURVE(s) 2-15. The elevation of the lake (H1) and the elevation of the ground-water (H2) are used in the Darcy equation to describe the direction and the gradient of flow at the impoundment boundary. D1 represents the total area of lake bottom and perimeter covered by water. D2 is the total area of the lake bottom and perimeter where water may flow or seep from the ground into the lake. D1 may equal D2; but since the dynamic response of the lake is more rapid than the response of the ground-water, D1 will not always be equal to D2, creating an unequal flow (mathematically) between X1 and X2 in the program. Two additional terms (QT1 and QT2) were employed to correct this problem.

Because the volumetric units of the model fluxes must be equal, the permeability coefficients of the sediments appear in the model as $ft^3/day/ft^2$ although they are reported as $gallons/day/ft^2$. The program symbol Q12, is the flux ($ft^3/t/ft^2$) from X1 to X2 if $H2<H1$. Q21 is the program symbol defining the flux ($ft^3/t/ft^2$) from X2 to X1 if $H1<H2$. When X1 increases, H1 increases. Q12 increases and the compartment X1 responds accordingly. However, since Q12 and therefore D1 are not part of the X2 compartment equation, X2 does not receive the total flux defined by Q21. Even though the driving forces, or changes in H1 and H2, indicate a flow from X1 to X2, H2 has not increased sufficiently to increase

D2 which mathematically increases the flow into the compartment. However, QT1 and QT2 compensate for this inequality and return the model to donor controlled functions for flux control.

Q02 (flux from outside the system into X2), and Q20 (ground-water flux from X2 to outside the system by seepage and flow through the dam) represent flows estimated by measuring the permeabilities and areas of the sediments at the cross-sections A-A' and B-B' (Figure 6). The areas of the cross-sections (ft^2) were measured by a planimeter and then entered into the program.

The program symbol Q10 describes a flow of water through the dam (GTD) and under the dam (GUD). Q10 estimates the water that passes from X1 through the dam and is lost from the system. More accurate formulas describing the flow of water under and through earthen dams exist (Te Chow, 1964) but the following expressions were employed to simplify the mathematics:

$$Q10 = GTD + GUD$$

where:

$$GUD = (11250*F3*H1)/100$$

$$GTD = (DA*H1*100)$$

GUD is a term which defines the flow of water from the lake under the dam through a cross-sectional area of $11250 ft^2$ with a permeability of F3. The driving force is H1 and the average length of travel is 100ft. GTD, like the other fluxes in the system is governed by Darcy's principle. Obviously the areas will vary with the amount of water in the impoundment area.

The term DA automatically supplies the well with the proper area in the equation by the same principle used in determining D1 or D2 The driving force is H1. The physical parameters are established by the following equation:

$$DA = \sum_{o-i} A1 + A2 + A3 \ldots\ldots Ai$$

A = (K*A) / L

K = F1, or F2, or F3, or F4, or F5

A = Cross-section area of dam (Figure 8) at any 2' increment

L = Length of ground-water travel from the inside surface of the dam to the cross-section B-B'.

Since the model incorporates this term as a loss from the system, L is approximated. After the water leaves the system, its direction is of no importance and therefore a rough approximation these measurements is sufficient.

Evaporation is a major source of water loss in the southwestern portion of Oklahoma. The program symbol PEV represents the water lost from the lake (X1) by evaporation. Mathematical relationships have been suggested for calculating evaporation from lake surfaces through the year (DeCoursey, 1965). However, because the formulae are quite complex, the evaporation component in this preliminary model is reduced to a simple expression. Once the other parameters of the model are properly measured or adjusted, and an ample supply of data collected, the accuracy of the proposed evaporation formulas can be tested with the model by evaluating the response of the lake level when the values of the EV term are altered.

The symbol PS (Principal Spillway) introduces an expression which estimates the flow through a sharp-edged orifice from a reservoir. The discharge from the principal spillway (PS) at Site 13 is calculated from:

$$V = CD\ A\ (2gh)^{1/2} \quad .$$

The resulting program statement of this equation is:

$\therefore$ PS = Q actual = SQRT(2*(32.2)*G)*PSA*CD

Q = flow in ft^3/day

CD = .6 = experimental coefficient (Sobersky and Acosta, 1964)

g = 32.2 ft./sec. = gravitation constant

h = G = (H1 - 10.2) = height in feet above principal spillway orifice

A = .8 ft^2 = PSA = area of orifice in ft^2

or,

PS = .8 * .60 /64.4*h .

PS (computer symbol PSS) is a flux in volumetric units/t, (ft /day). PSAFT is the discharge (PS) converted to "real" or actual reservoir discharge in acre-feet/day. In the program, G is a limiting function. The principal spillway only functions when H1 > 10.2, the elevation of the principal spillway. The statements,

```
IF(H1.LE.10.2)  G = 0
IF(H1.GT.10.2)  G = (H1-10.2),
```

provide the limiting controls for G. An approximate 20% deviation occurs between the simulated results and the measured outflow in Table 5. The spillway acts like a siphon when the entire orifice is submerged and consequently conducts more water. This relationship may be refined by future investigations.

ES is the program symbol for the flow out of the lake through the emergency spillway. The formula defines the flow of water over an open spillway (Streeter, 1966). The equation is included in the program. Again a limiting function is incorporated in the formula because ES only operates when H1 is greater than 23.2 feet.

The STEP functions (program symbols SP1 and SP2) generate runoff into the lake by adding the estimated volume (ft^3) of water needed to raise the lake elevation to the "real" or measured elevation during the periods of runoff listed in Table 6. The numbers in the program are cubic feet of water added to the pond. SP1 and SP2 are time functions telling the computer when to add the appropriate quantities of water to the lake. Simulating runoff for longer periods of time requires a different arrangement. A time related function similar to H1 = AFGN(CURVE 1, X1) could generate a hydrograph vs ft(t), or runoff vs ft(t), or rainfall vs ft(t) if the relationship of rainfall to runoff, or runoff to lake level were mathematically known. When more precise data become available, calculating and entering these functions into the model will be areas for future research.

CHAPTER VI

THE RESULTS OF MODEL SIMULATIONS

Limitations of Simulation

A systems model is not a copy of a real ecosystem. Any mathematical model only simulates those functions defined within the program. The results of any mathematical simulation are as valid as the parameters and functions used in defining the system. The measured dynamics (data) of a real system can be duplicated by the model when the various parameter coefficients are systematically altered in the model program adjusting any errors or deviations from the real data (lake level and ground-water level responses).

For example, a reservoir drains at a given rate (X1 =dX/dt). The loss from the reservoir is controlled by seepage under the dam and evaporation. Inflow is assumed constant for a specific time period. If the simulated rate of change in reservoir elevation does match the plotted rate of change in the the real system, the user can vary one, two or all three of the parameters until the simulation results compare with the real system data. However, if the parameters are altered beyond reasonable physical limits for such parameters or if they are altered without supporting hypotheses or evidence, the model is not a good representation of the real system even though the output data from the simulation match the real data.

When systematically evaluating the sensitivity of the system by adjusting the various parameters (one per simulation) and by noting the response of the system, the modeler can isolate the resulting effects and the significance each variable has on the system. In the first sets of simulations, only the permeabilities (K or F1 F2 F3 F4) were changed. The specific yield value (.001) was assumed to be constant as was the base flux (Q02 + Q20).

The model was designed to simulate conditions at Site 13 during 24 days in September and October, 1965 when unusually high rainfall caused flash flooding in the reservoir. During the storm period (Table 5) lake elevation data and the ground-water level in Well No. 32 were the only continuous measurements made of the system. Well No. 32 can be used to estimate the quantity of water constantly leaving the system through dam seepage but will not indicate the fluctuation of bank storage adjacent to the impoundment basin. Consequently, lake elevations were the data used to calibrate and analyze the results of each simulation.

Interpretation of the Results

Figure 16 depicts the results of the first simulation. The parameters most significantly affecting model response at any time and the corrections introduced to improve model response, also appear in Figure 16. Initial simulation

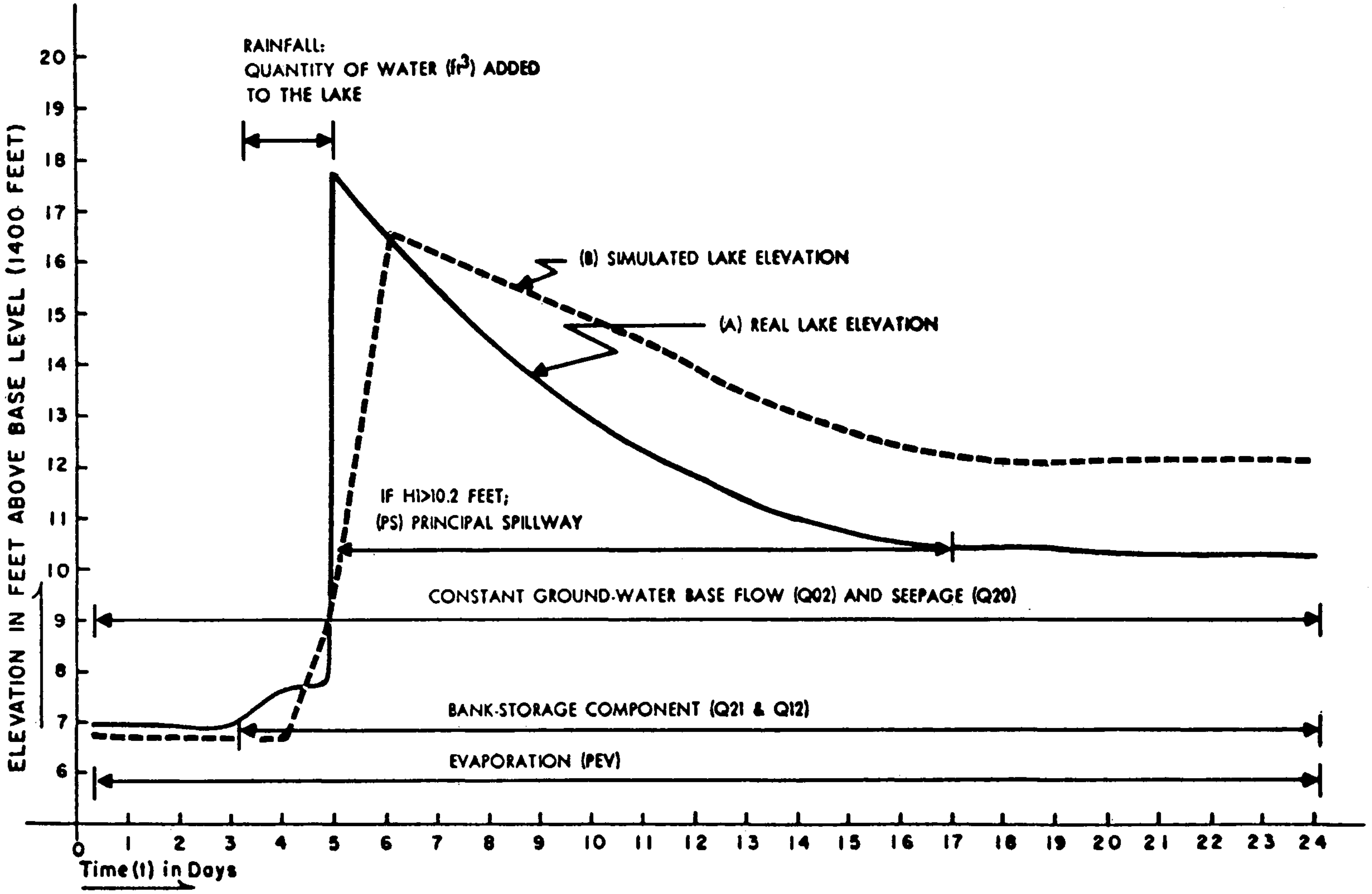


FIGURE 16. THE RESULT OF THE FIRST SIMULATION AND PRIMARY FLOW FUNCTIONS.

included the adjustment of the paramaters in order to obtain the best fit portion of the hydrograph curve representing the time period prior to and including peak stored volume (day 5) of the storm event. For model stability, evaporation (PEV), ground-water base flow (Q02), and downstream seepage (Q20) were considered constant throughout the period represented by the hydrograph (Figure 16). Base flow and seepage were determined using an assumed coefficient of permeability (constant throughout test) and the average gradient represented by initial conditions.

Drive for the initial system was rainfall described in terms of runoff within the watershed. The only loss from the initial system when $H1 < 10.2$ is by evaporation (EV). This parameter establishes a .05 ft/t decrease in elevation of the lake which approximates the correct loss from the reservoir. The accuracy of the simulation is illustrated by comparing the slope of the plotted simulated lake elevation data (B) with the slope of the plotted real lake elevation (A) from $t = 0$(days) to $t = 4$(days), and from $t=20$(days) to $t = 24$(days).

The best-fit parameters, obtained in the first stage of model simulation, were included as constants in the second stage of model simulation. The response of ground-water elevation to bank storage (Q21 and Q12) was further adjusted in the second stage of simulation by noting the local ground-water gradients and by varying coefficients of permeability and specific yield. Therefore, comparisons of simulated lake level curves with the real lake level were restricted to the time period from initial rainfall to the terminous (day 24) of the hydrograph recession curve (Figure 16).

The average difference in elevation between H1 and H2 was calculated using more recent data collected from ground-water observation wells by the Agricultural Research Service. Because these ground-water levels were not measured continuously and therefore do not correspond with the lake level during any one time period, it was necessary to extrapolate new ground-water levels for the initial conditions. The difference in ground-water elevation was converted to a volume difference for each observation well by the appropriate FUNCTION CURVE. These differences were extrapolated to the initial conditions of lake level in the model. For example, if H2 was an average of 10 feet higher than H1 for any given t, and if H1 in the model at t = 0 was 7.0 feet, the corresponding H2 was assumed to be 17.0 feet at t = 0. H1 and H2 at t = 0, were not changed throughout the simulations in order to duplicate the same conditions at the pond for each successive simulation at any time.

The following procedure was employed to evaluate the effects of permeability and specific yield changes on the model. Figure 17 illustrates the percent cumulative area of the various permeable materials at Site 13. The predominant permeability at Site 13 is $< 10 \text{gpd/ft}^2$. The sediment permeabilities at Site 13 range from ($< .1 \text{gpd/ft}^2$) for

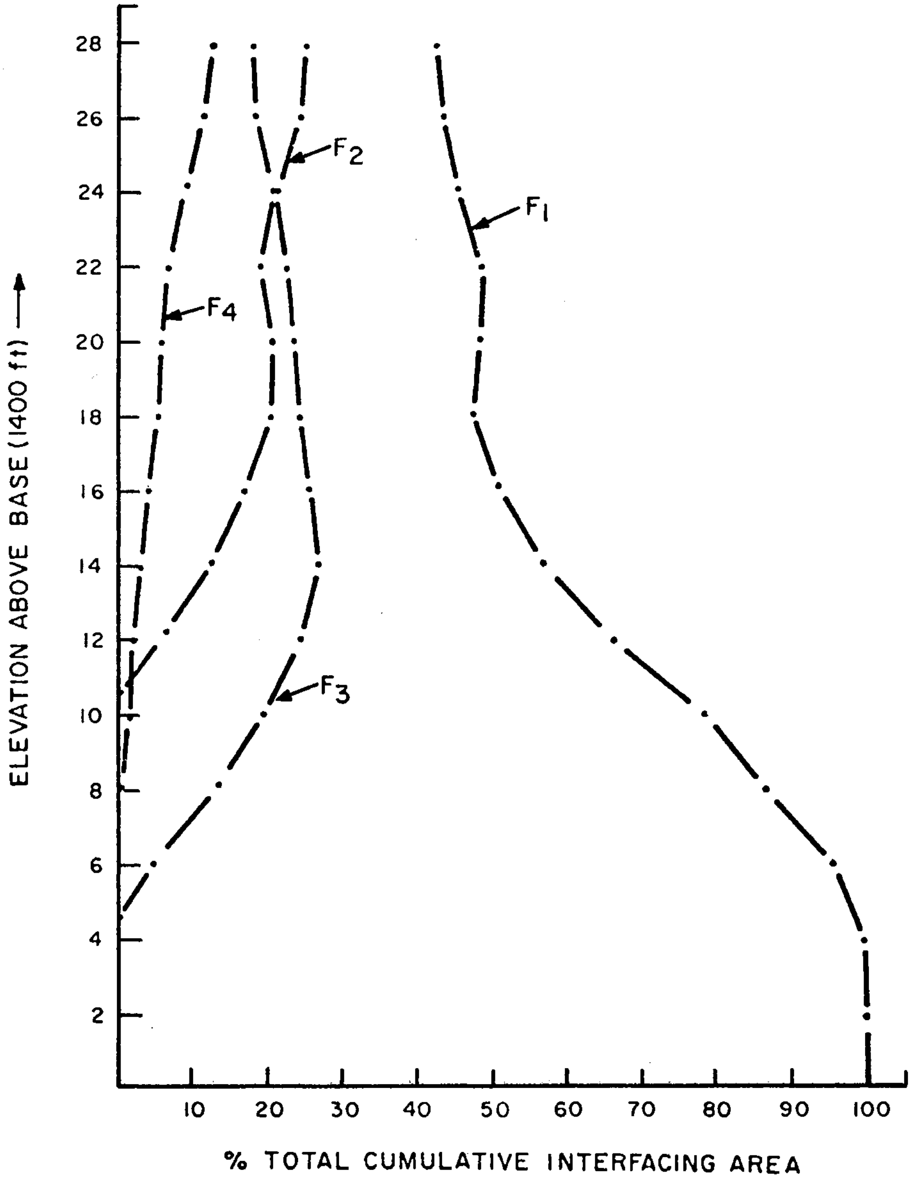


Figure 17. % Total Cumulative Interfacing Area Between The Ground-Water And The Lake-Water Systems For Each Permeability F_1, F_2, F_3, F_4.

various clay deposits to 41.86gpd/ft^2 for some silty sands (Table 2). Most of the sediments are rather impermeable considering the permeability ranges and the percent of the total sediments in each range listed in Figure 6 and shown in Figure 17. To best exemplify the effects of permeability on bank storage, homogeneous permeability was assumed throughout the sediments with a constant specific yield. Homogeneity was assured by letting F1=F2=F3=F4= the permeability selected in ft^3/ft^2/day. The permeabilities selected were 1.2 ft^3/ft^2/day (minimum permeability measured), 9.0 ft^3/ft^2/day (maximum permeability measured), and 6.4 ft^3/ft^2/day (calculated average permeability). Non-homogeneity was demonstrated by varying permeabilities within each permeability range (F1, F2, F3,or F4). However, the results of varying each permeability within its defined range did not alter the response of either the lake elevation or the ground-water elevation significantly. This lack of response under non-homogeneous conditions indicates that the range of permeabilities for each Fi symbol and the area of the impoundment within a given permeability range is reasonably close to the actual range and area of each permeability within the real impoundment. Consequently, only one simulation of non-homogeneous conditions was performed.

Figures 18, 19, and 20, depict the response of the lake elevation to a maximum permeability (homogeneous conditions, F1-F4=9.0ft^3/day), to minimum permeability (homogeneous conditions, F1-F4=1.2ft^3/day , to a calculated average

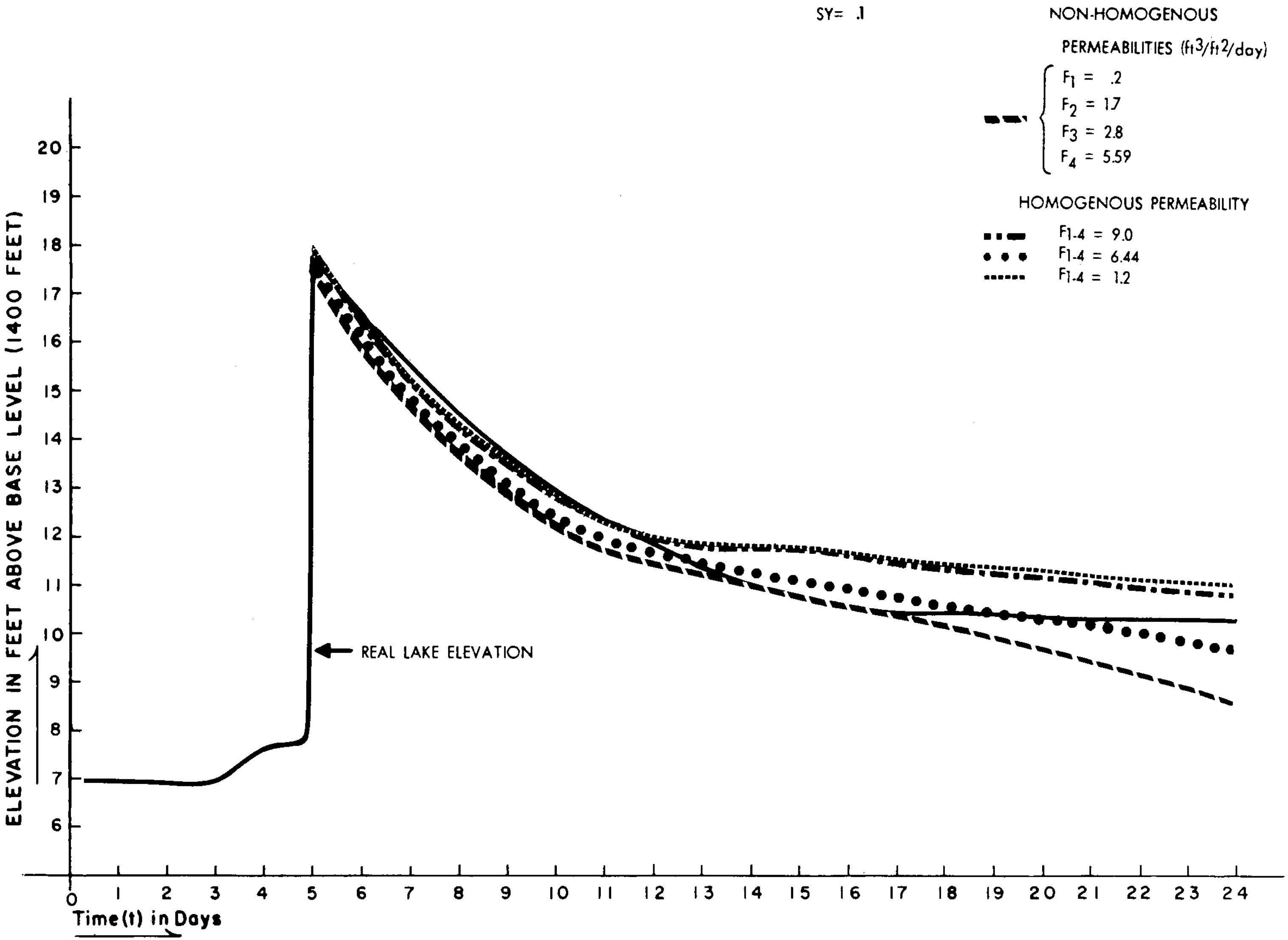


FIGURE 18. SIMULATED LAKE-ELEVATION RESPONSE TO VARIOUS PERMEABILITIES WITH A SPECIFIC YIELD COEFFICIENT OF .1.

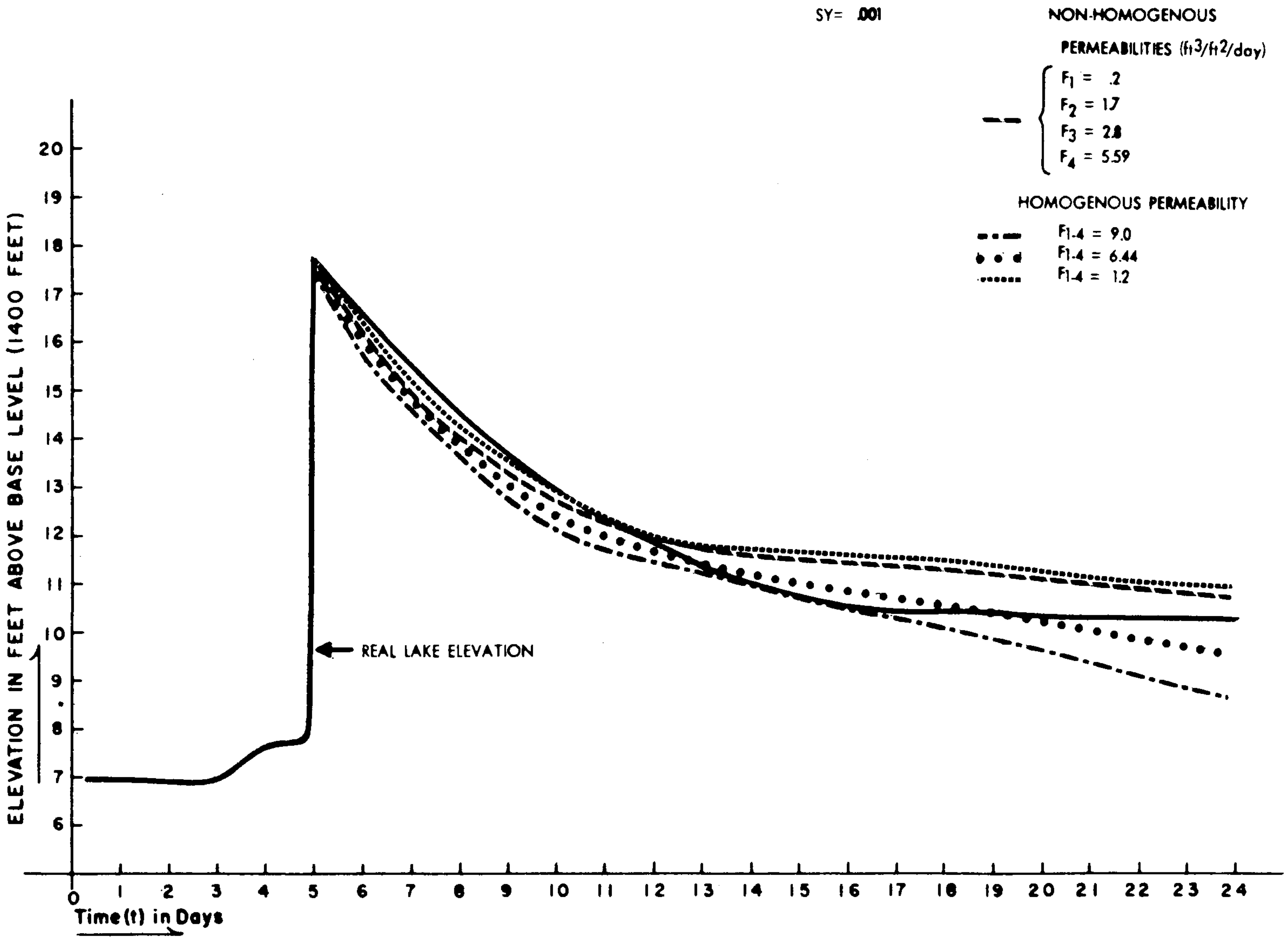


FIGURE 19. SIMULATED LAKE-ELEVATION RESPONSE TO VARIOUS PERMEABILITIES WITH A SPECIFIC YIELD COEFFICIENT OF .001.

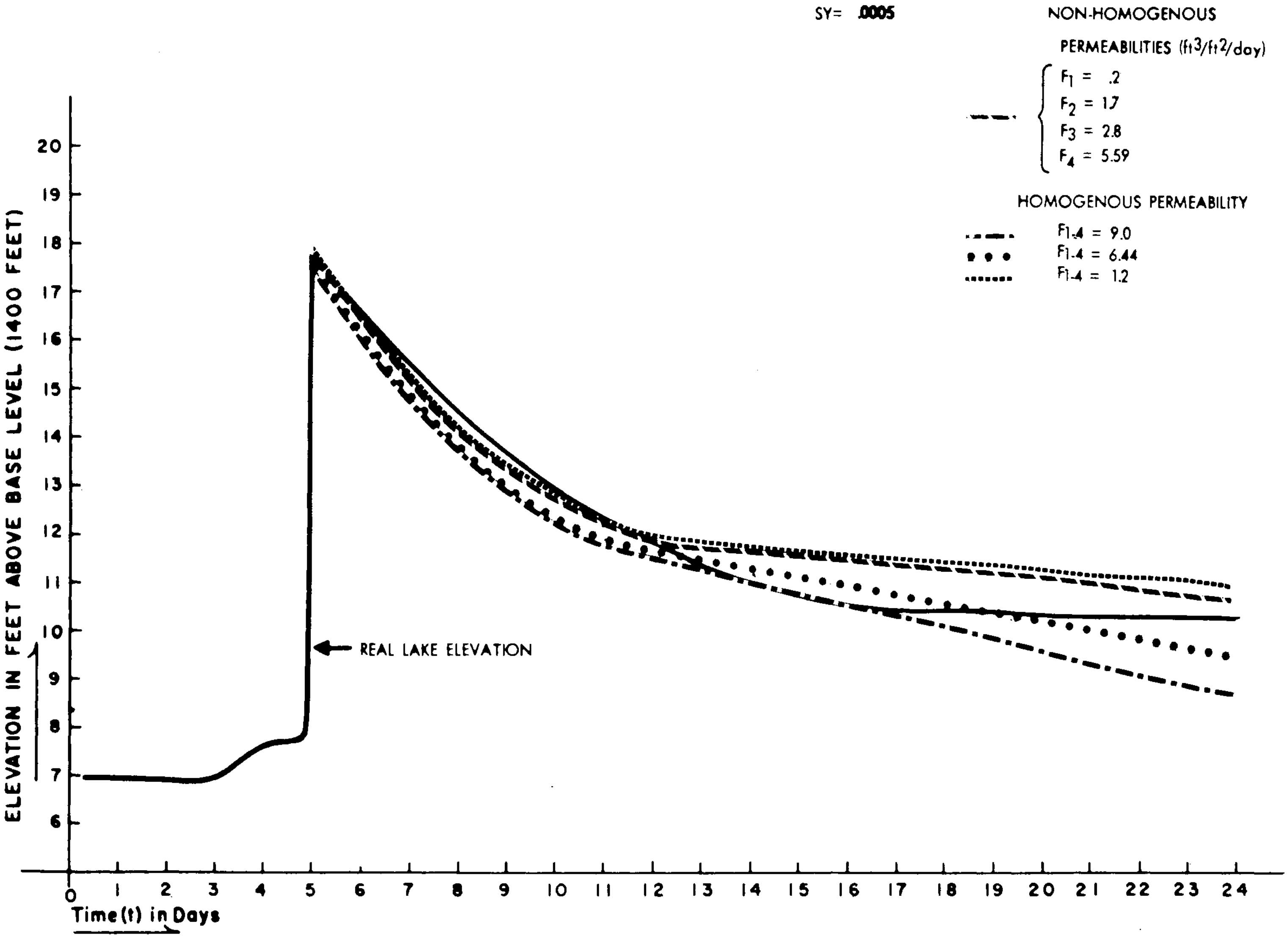


FIGURE 20. SIMULATED LAKE-ELEVATION RESPONSE TO VARIOUS PERMEABILITIES WITH A SPECIFIC YIELD COEFFICIENT OF .0005.

permeability (homogeneous conditions, F1-F4=6.4ft^3/day), and to one set of permeabilities (non-homogeneous conditions, F1=.2,F2=1.7,F3=2.8,F4=5.59ft^3/day). The model was run three times with the same permeabilities at different specific yield values (.0005,.001,.1). Varying the specific yield coefficients did not alter the simulated lake elevation significantly (Figures 18,19,20). Therefore, lake elevation is sensitive to variations of the permeabilities within the system and not to variations of specific yield.

The ground-water system responds to both permeability and specific yield changes. Figures 21 through 27 depict the results of ground-water elevation to bank-storage influence at three observation well locations (Wells 777, I75, and 18) under the previously described parameter variations.

Well #777 is located farthest from the interfacing area. Well #18 is located closest to the interfacing area. Both wells are depicted on the topographic map in Figure 5. Well #I75, an imaginary observation well, is introduced into the program to illustrate how the program can be used to optimize observation well locations prior to drilling. The only parameters changed in the imaginary observation well simulations were distances between the well and the inundated area of the lake. The effect of distance between any observation well and the lake is represented in Figure 28 by comparing the ground-water response of Well #777 and Well #18. The well nearest to the

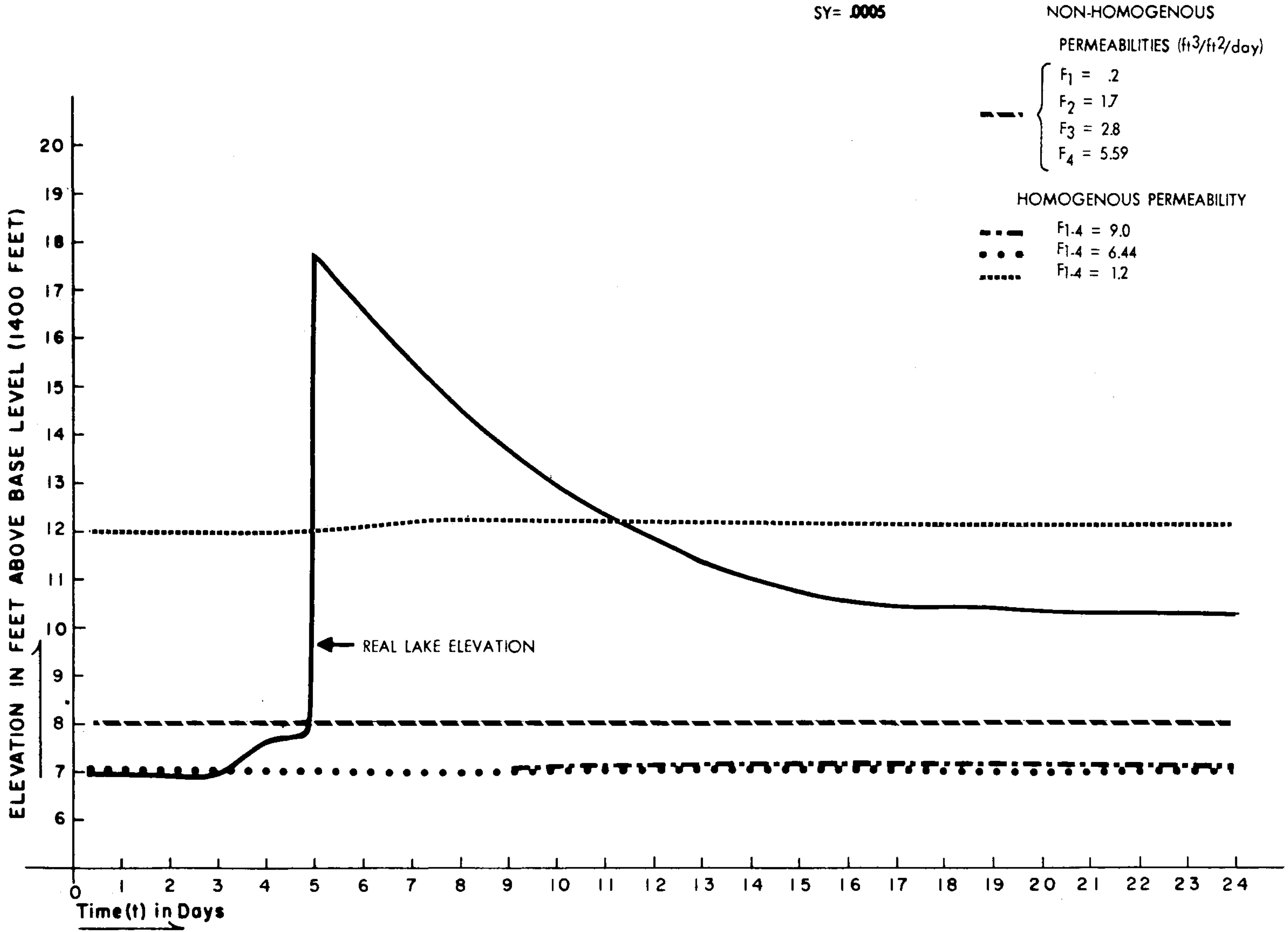


FIGURE 21. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .0005 AT OBSERVATION WELL # 777.

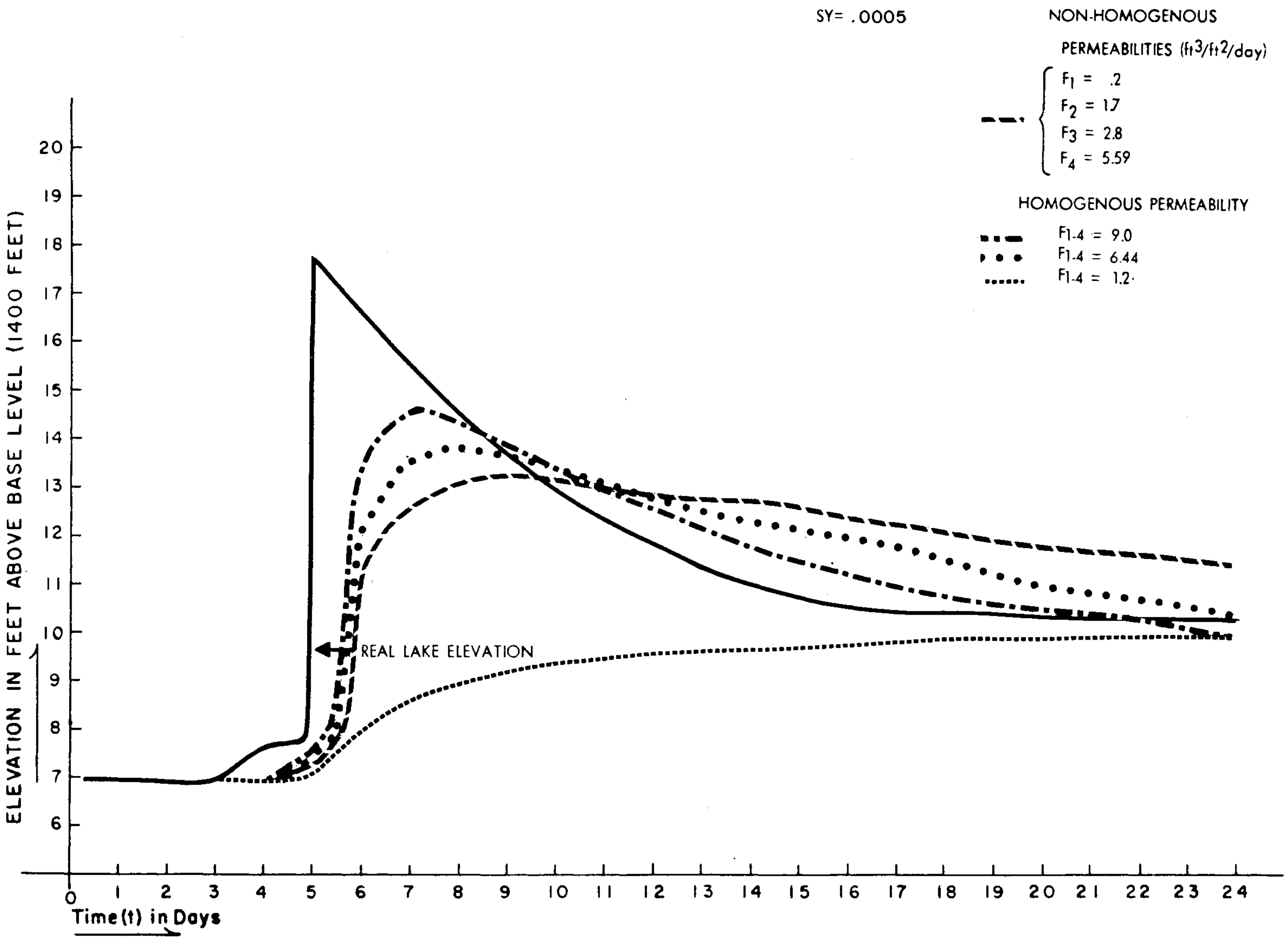


FIGURE 22. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .0005 AT OBSERVATION WELL # 175.

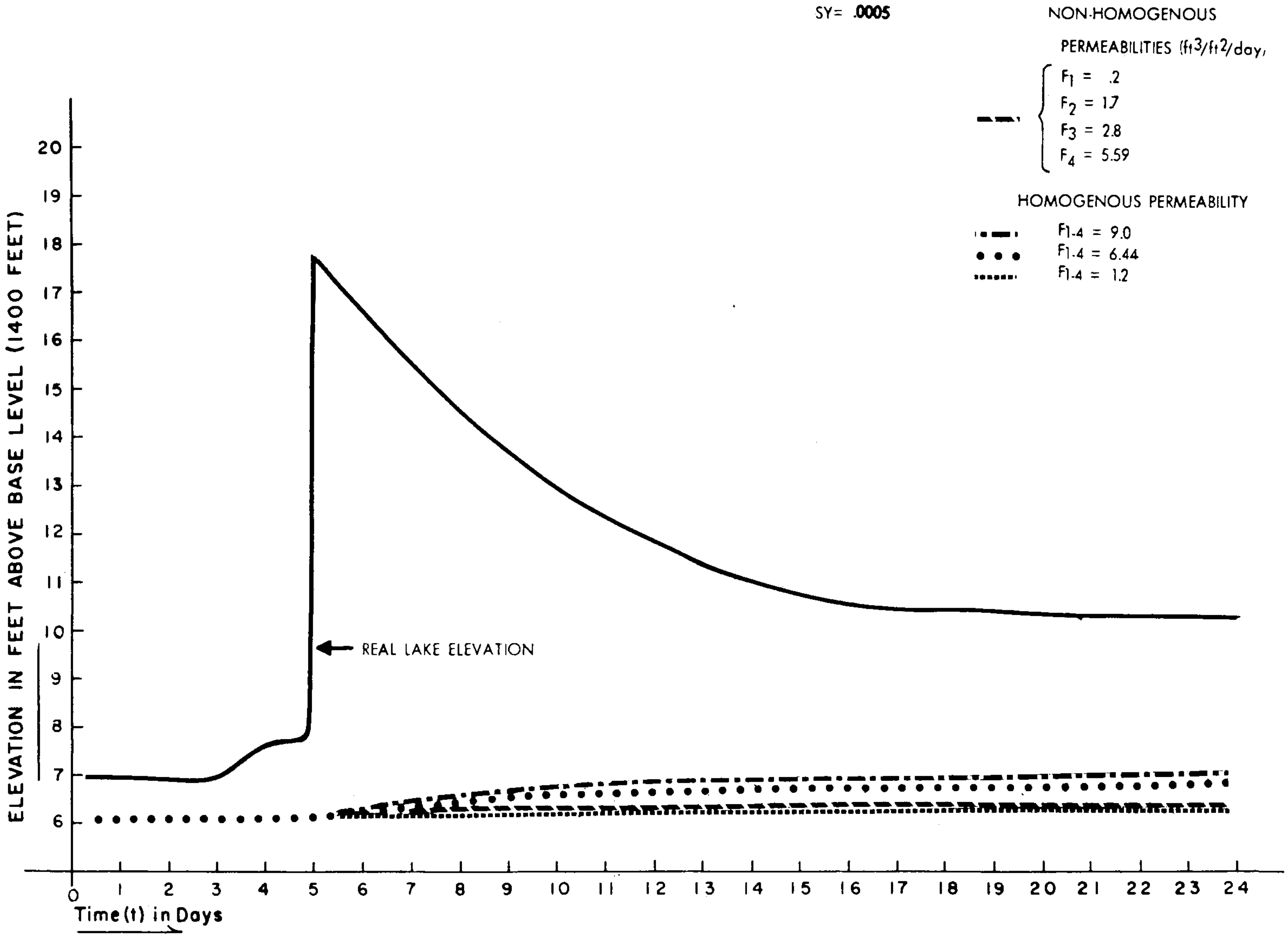


FIGURE 23. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .0005 AT OBSERVATION WELL #18.

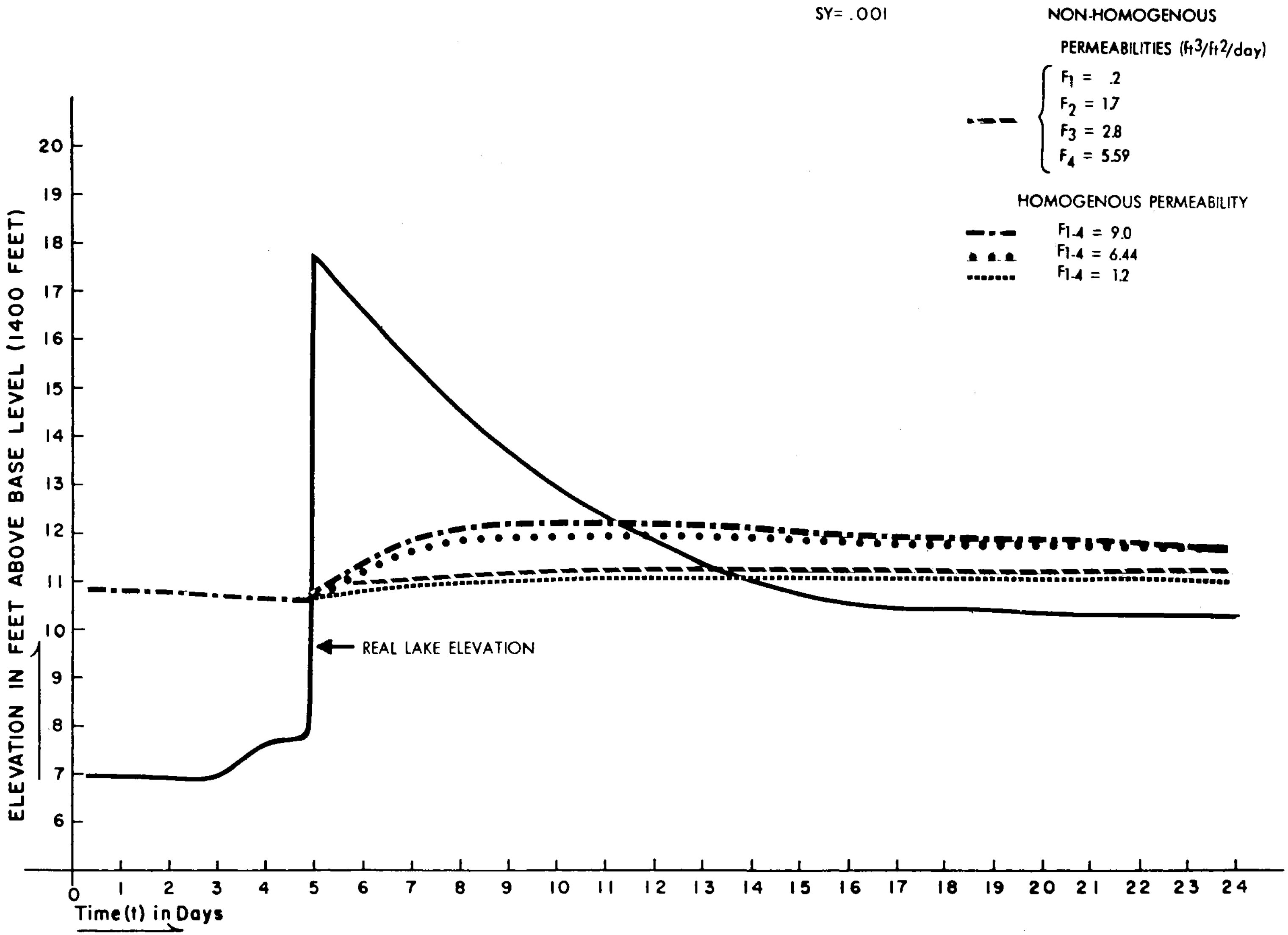


FIGURE 24. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .001 AT OBSERVATION WELL # 777.

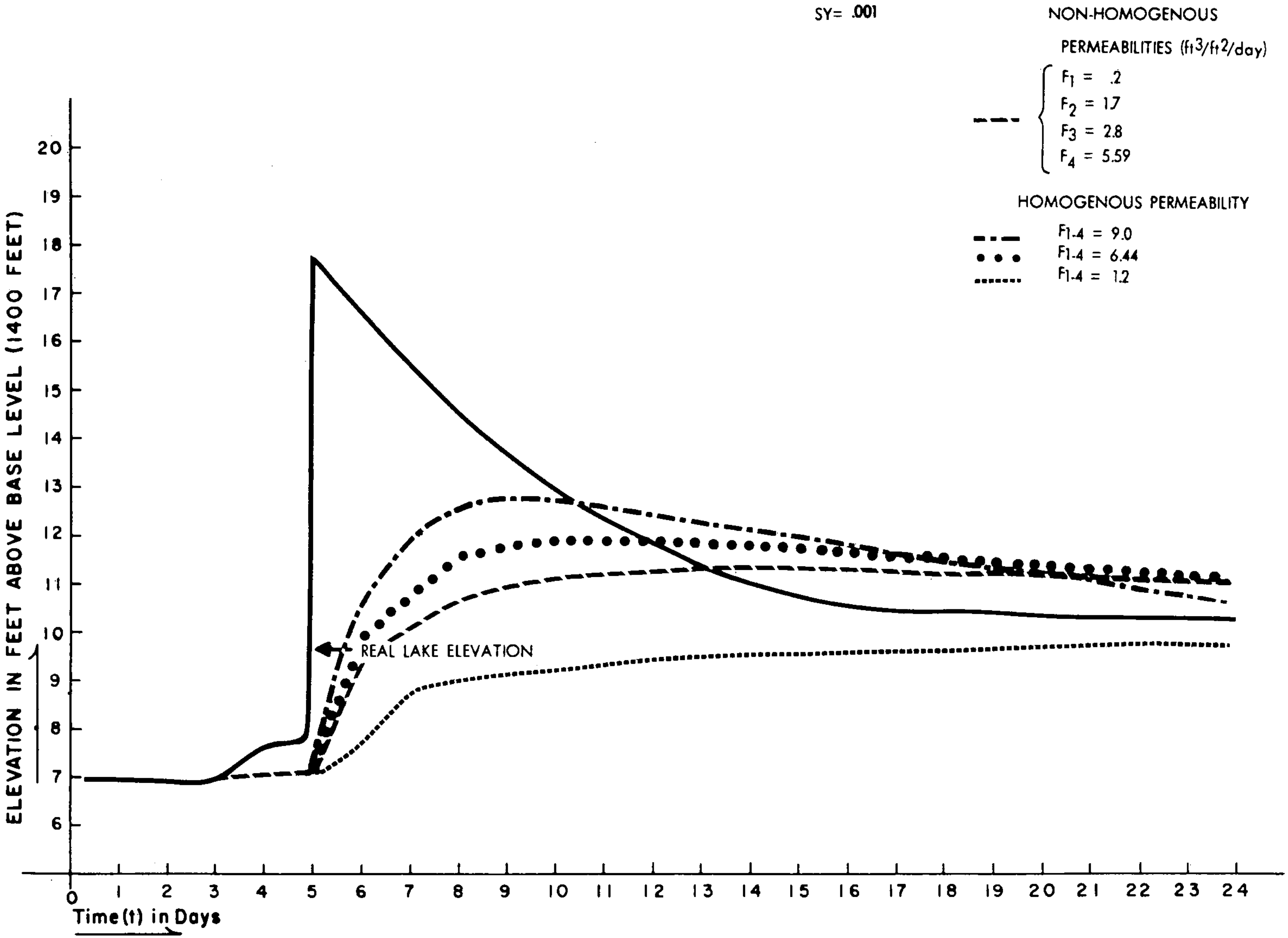


FIGURE 25. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .001 AT OBSERVATION WELL # 175.

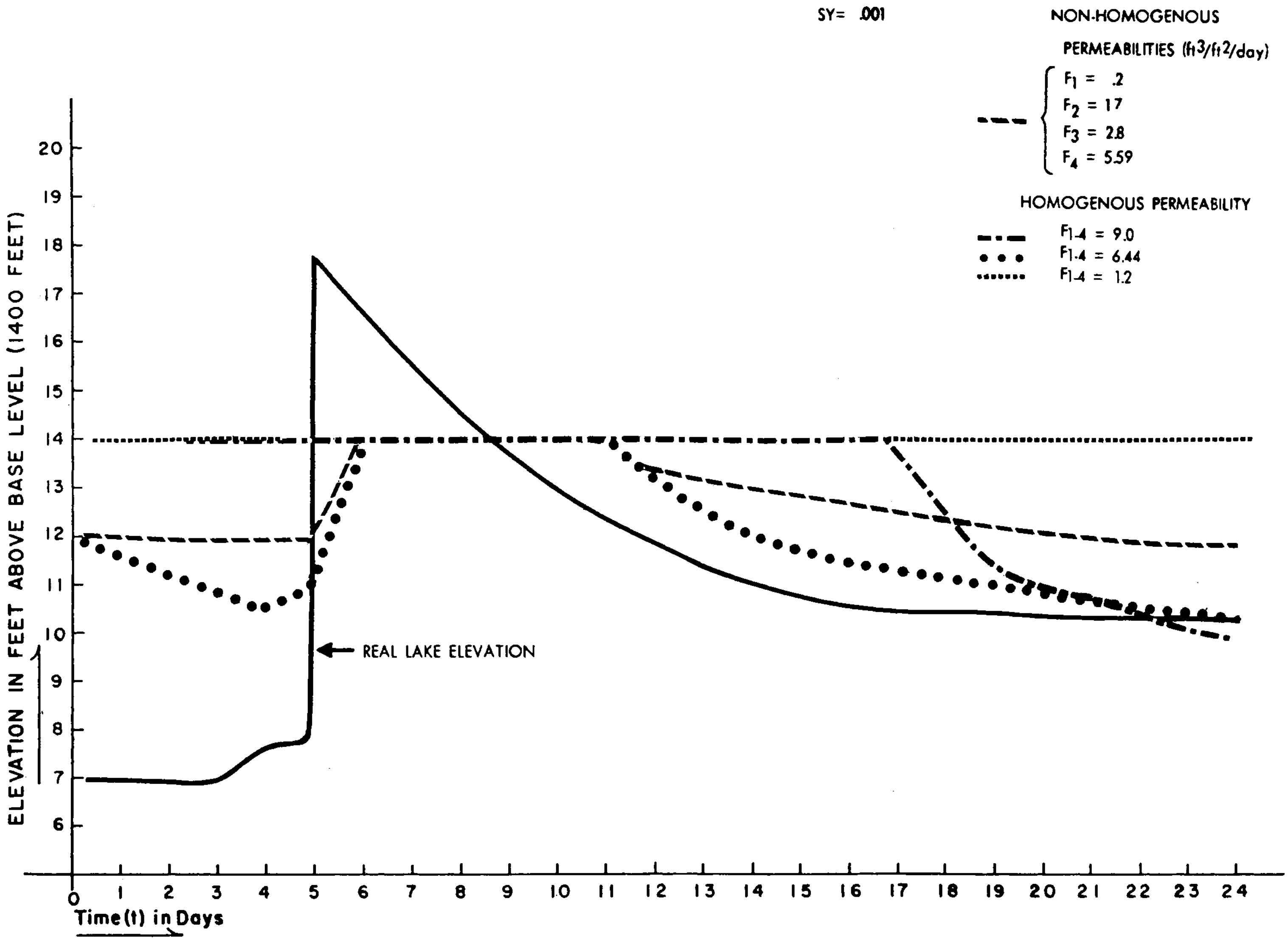


FIGURE 26. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .001 AT OBSERVATION WELL #18.

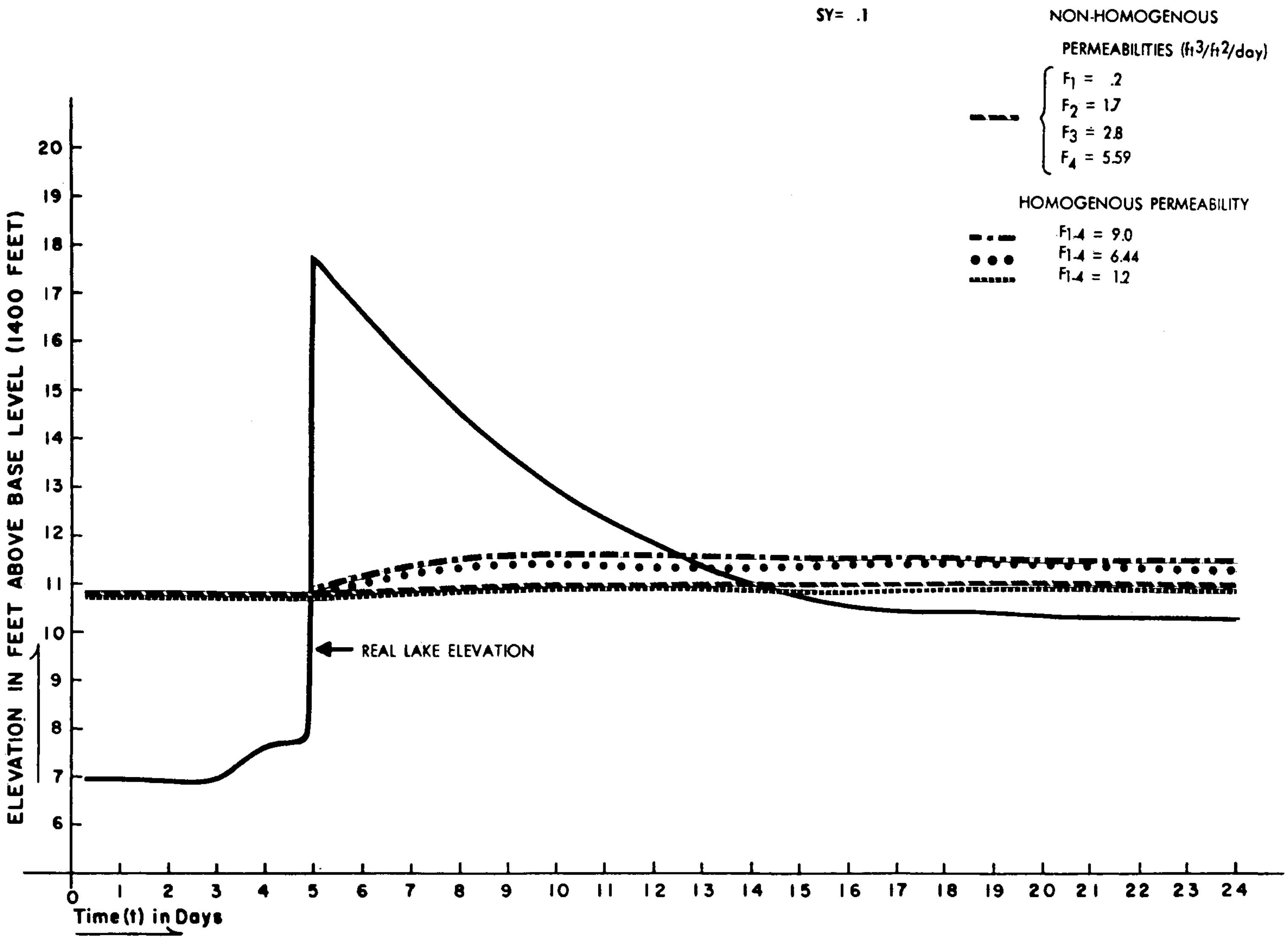


FIGURE 27. SIMULATED GROUND-WATER ELEVATION RESPONSE TO VARIOUS PERMEABILITY CHANGES WITH A SPECIFIC YIELD COEFFICIENT OF .1 AT OBSERVATION WELLS # 777, # 175, # 18 (SAME RESPONSE FOR THREE WELLS).

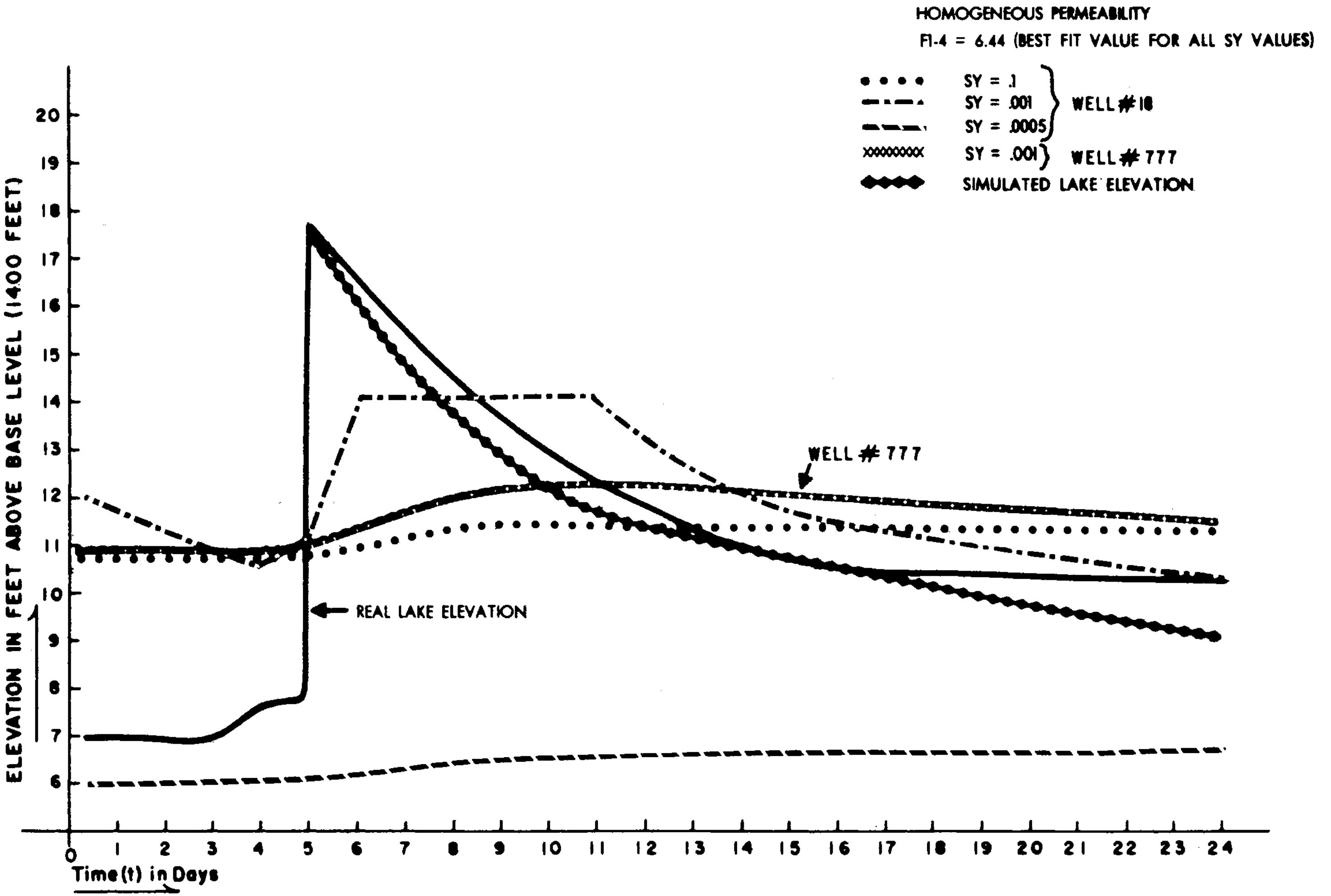


FIGURE 28. SIMULATED LAKE-ELEVATION AND GROUND-WATER ELEVATION RESPONSE TO VARIOUS SPECIFIC YIELD COEFFICIENTS (.1, .001, .0005) WITH THE CALCULATED AVERAGE PERMEABILITY OF 6.4 $ft^3/ft^2/day$ (HOMOGENEOUS CONDITION) AT OBSERVATION WELL # 18
GROUND-WATER ELEVATION RESPONSE AT OBSERVATION WELL # 777 (SY = .001, SAME PERMEABILITY) IS INCLUDED FOR COMPARISON.

lake (Well #18) responds more quickly and with a greater amplitude.

Because no real continuous ground-water data exist for comparing the simulated ground-water response to real ground-water elevation, the results are subject to verification. However once continuous data are collected, the permeabilities and the specific yield coefficients can be adjusted to elicit a more accurate ground-water response. Figure 28 summarizes the development of the model at this time. The simulated lake elevation has been adjusted to yield a reasonable response. However, the plotted ground-water elevation could be any of the three responses dependant upon the specific yield and the range of permeabilities selected. The fine adjustment of the ground-water system is left to future investigators who can compare the results of this model to additional field data and then select the appropriate permeabilities and specific yield parameters.

Adaptation of the Model to Other Systems

Ground-water and lake-water fluxes can govern the concentrations and the transfers of the nutrients and dissolved salts represented in Figure 2. The quantity of water within a system and the rate of flow within an ecosystem are the primary connections between biotic and abiotic models.

To demonstrate the compatability of this model to other systems, the following terms are introduced: GUD, GWL, GWG, GTD, GIP. These terms represent the conversion of some flux within the system to "real" values which are necessary in other models (Appendix A).

All of the following flow symbols represent quantities of water transfer in ft^3/day: GUD is the quantity of water lost under the dam. GWL is the quantity of water transferred from the lake into the ground-water system. GWG represents the water seeping into the lake from the ground-water system. GTD is the water lost from the lake through the dam. And, GIP is a flow that represents the amount of ground water coming into ground-water compartment from upstream. These flows were only approximated in this model. They are dependent upon permeability and hydraulic gradient. Flows GWL and GWG are affected to any extent by varying specific yield coefficients.

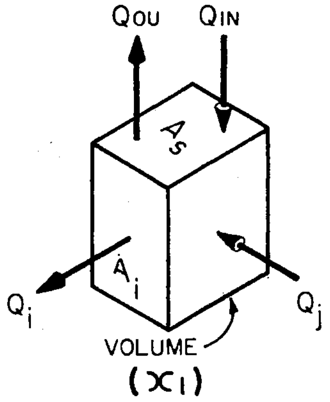
The numbers that appear in this text describe the suspected conditions at Site 13. The format of the model is applicable to other impoundment areas by substituting the parameter data of the area in question for the data of Site 13. The data necessary include: (1) FUNCTION CURVE data; (2) the permeability of the various constituents; (3) surface areas; (4) depths or total relief of reservoir.

Obviously, certain parameters like the principal spillway dimensions or function (open weir flow vs. sharp-edged orifice flow) will change to conform to the confines of the impoundment in question. At this time, the model format has not been applied to impoundment areas other than Site 13.

The concept of plotting ground-water movement can be used to trace movement of dissolved ions or compounds between the lake and the ground-water system, or to examine the filtering effects of the clay with regard to various compounds (pesticides, nitrates, phosphates, etc.) dissolved in the water. If the input parameters are reasonable, the model can be used to better understand biochemical relationships.

The biological compartments of this ecosystem model will have the interconnections between the abiotic components and biotic compartments. The aquatic ecosystem model is dependent upon an accurate mathematical simulation of the hydrology within an area.

To understand how the abiotic model is integrated with a biotic model, consider the general mass-balance equations in Figure 29. The diagram mathematically represents the interconnections employed in a comprehensive ecosystem study conducted by Water Resources Engineers Incorporated(1972). Note in equation 1 that portion labled INPUT and OUTPUT. The abiotic parameters are entered into the equation as concentrations (C) multiplied by a flow(Q) which defines the quantity of water entering (Qj) or leaving (Qi) the system. The cube represents the volume of ground water surface water in the entire ecosystem. The symbols in Figure 29 may be



$$\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ \vdots \end{bmatrix} = \begin{bmatrix} \text{TDS} \\ \text{BOD} \\ \text{DO} \\ \text{TEMP} \\ \vdots \\ \text{ALGAE} \\ \text{ZOO} \\ \text{FISH} \end{bmatrix}$$

1. *general mass balance equation for abiotic substances*

$$\frac{dVC_1}{dt} = \underbrace{\Sigma Q_i C_1}_{\text{ADVECTION}} + \underbrace{\Sigma EA\frac{dc_1}{dx}}_{\text{DIFFUSION}} + \underbrace{\Sigma Qin\,Cin}_{\text{INPUT}} - \underbrace{\Sigma Qou\,C_1}_{\text{OUTPUT}} \pm \underbrace{S_1VC_1}_{\text{SETTLING}} \pm \underbrace{K_r A_s(C_1 - C_1^*)}_{\text{REAERATION}} - \underbrace{K_{d,1}VC_1}_{\text{DECAY}}$$

$$\pm \underbrace{K_{d,2}VC_2}_{\substack{\text{TRANSFORMATION} \\ NH_3 \to NO_2 \to NO_3}} - \underbrace{\Sigma\mu_3VC_3F_{3,1}}_{\substack{\text{UPTAKE} \\ \text{BYPRODUCT}}} + \underbrace{\Sigma R_3VC_3F_{3,1}}_{\substack{\text{RESPIRATION} \\ \text{RELEASE}}}$$

2. *general mass balance equation for biota*

$$\frac{dVC_1}{dt} = \Sigma Q_i C_1 + \Sigma EA\frac{dc_1}{dx} + \Sigma Qin\,Cin - \Sigma Qou C_1 + (\underbrace{\mu_1}_{\text{GROWTH}} - \underbrace{R_1}_{\text{RESPIRATION}} - \underbrace{S_1}_{\text{SETTLE}} - \underbrace{M}_{\text{DEATH}})\,VC_1 - \underbrace{\mu_2VC_2F_{2,1}}_{\text{GRAZING}}$$

3. *phytoplankton (algae)*

$$\mu_1 = \hat{\mu}\,\theta^{T-20}\frac{L}{K_l+L}\;\frac{C}{K_c+C}\;\frac{N}{K_n+N}\;\frac{P}{K_p+P} \qquad R_1 = r\,\theta^{T-20}$$

$$S_1 = \frac{S_t}{S_o} \qquad \mu_2, C_2 = \text{Zooplankton}$$

4. *zooplankton*

$$\mu_1 = \hat{\mu}\,\theta^{T-20}\frac{\text{Algae}}{K_a+\text{Algae}} \qquad R_1 = r\,\theta^{T-20}$$

$$M_1 = \alpha + \beta\cdot\text{Toxicity} \qquad \mu_2, C_2 = \text{Fish}$$

5. *fish*

$$\mu_1 = \hat{\mu}\,\theta^{T-20}\frac{\text{Zoo}}{K_z+\text{Zoo}} \qquad R_1 = r\,\theta^{T-20}$$

$$M_1 = \alpha + \beta\cdot\text{Toxicity} \qquad \mu_2, C_2 = \text{Harvest}$$

Figure 29. Ecologic Model Formulations (From Water Resources Engineers, Inc., 1972),

equated to some terms employed in the developed impoundment model:

QOU = EV + Q10 = Evaporation + Seepage through the dam

QIN = Runoff

Qj = Q02 = Ground-water input from upstream

Qi = Q20 = Ground-water outflow.

The spatial distribution and the concentration of dissolved solids (the other components of equation 1 in Figure 29) will vary with the inter-system flows (Q21 and Q12) within the impoundment area. The system and the biota will respond accordingly to this variation. Therefore, assuming a constant flow or uniform distribution of all ionic substances within surface water or ground water in any ecosystem does not simulate the existing conditions at any variation in time.

As an example of employing this systems model in a watershed management model, consider Figure 30. Managing water resources in a given area requires an accurate estimation and prediction of surface water and ground water movement within the given area. The model constructed for this thesis could be integrated with the model shown in Figure 30 by incorporating the flows into and out of the impoundment as part of the flow within a given section of the entire watershed. Each part of the entire system is a dynamic state within its own boundaries. The impoundment, free-flowing streams, and the main river stem itself are all

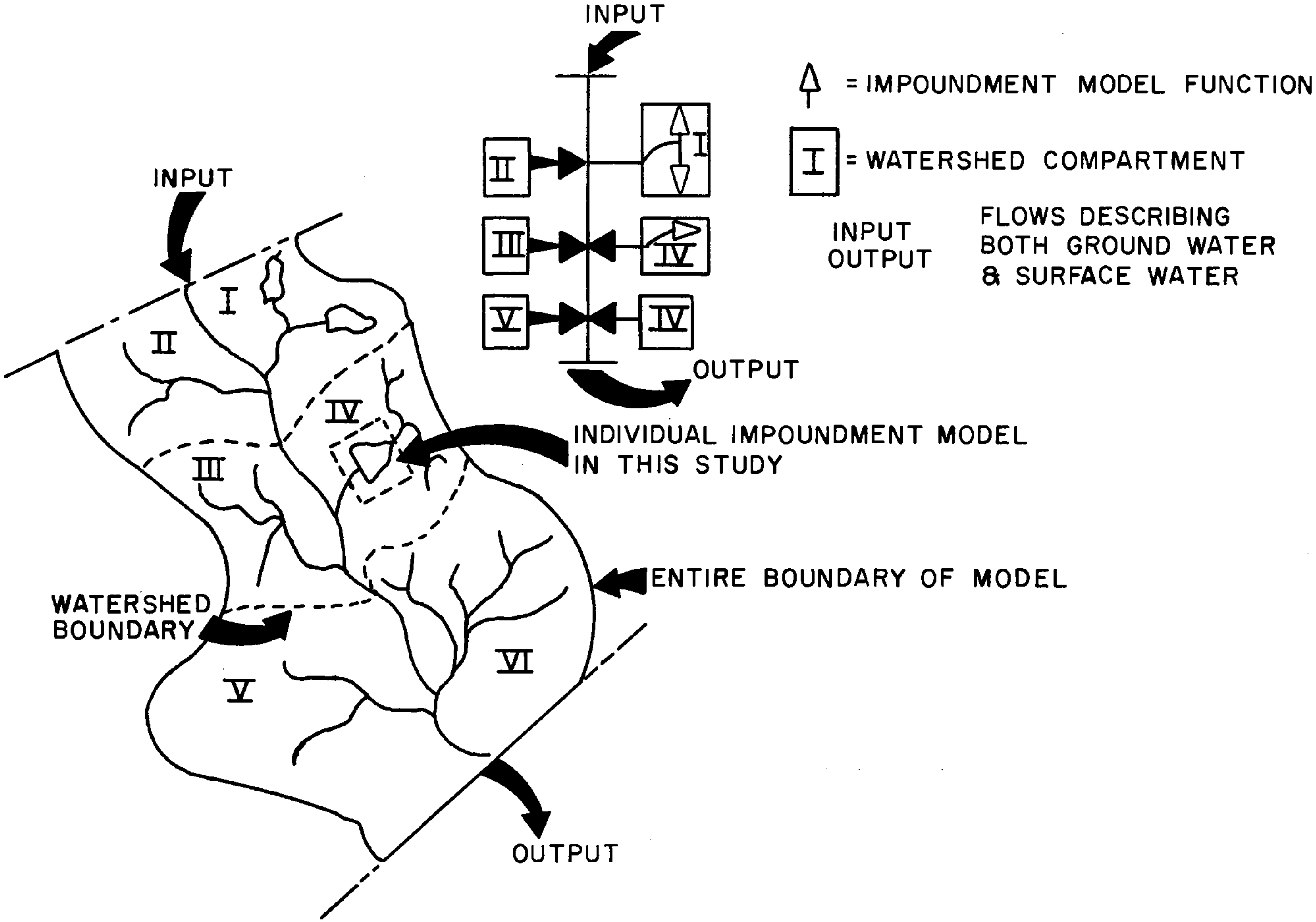


Figure 30. Theoretical Watershed Management Compartment Model.

dynamic in nature and may be modeled as a system with all of the components being smaller, more finite models. By establishing a system of flow models, the manager can have an accurate estimation of the quantity, distribution (which may be used for flood prediction or land use management criteria), and the quality of both surfacewater and groundwater within the area of interest. Establishing those relationships is an area for future investigators.

CHAPTER VII

CONCLUSION

The lake-water / ground-water system at Site 13 was modeled using standardized methods for mathematically estimating the neccessary parameters, permeabilities of the sediments, interfacing areas, specific yield coefficients, and total volumes of the lake and of the ground-water systems. The flows between the systems are defined as a function of Darcy's relationship. Simulated lake elevation results are compared to existing data. Although, simulated ground-water data are subject to verification, several traits of the systems were noted.

Simulated lake elevation is sensitive to variations of permeability but relatively insensitive to specific yield coefficient variations. The boundary conditions providing the best fit of the simulated response on the recessional portion of the lake hydrograph were homogeneous conditions using a permeability coefficient of 6.44 $ft^3/ft^2/day$ (Figure 28). However, the ground-water system responses (amplitude only) are only slightly sensitive to variations of the permeability coefficient and much more sensitive to specific yield variations (Figures 24, 25, and 26). The ground-water elevation is directly proportional to permeability and inversely proportional to changes in specific yield and to the distance between an observation well and the interfacing area of the lake. The best simulated predictions of ground-water response are shown in Figure 28. However, further verification of these predictions is needed.

REFERENCES CITED

Back, W., and Barnes, I., 1965, Relation of Electrochemical Potentials and Iron Content to Groundwater Flow Patterns: U. S. Geol. Surv. Prof. Paper 498C, pp. C1-C26.

Blackmore, A. V., 1970, The Poisenille Analogue for the Flow of Water in Wyoming Bentonite: Jorn. of Hydrology, Vol. 11, pp. 59-68.

Brindley, G. W., and Rustom, M., 1958, Adsorption and Retention of an Organic Material by Montmorillonite in the Presence of Water: American Mineralogist, Vol. 43, pp. 627-640.

Carroll, D., 1959, Ion Exchange in Clays and Other Minerals: Bul. Geol. Soc. Amer., Vol. 70, pp. 749-780.

Chen, C. W., 1970, Concepts and Utilities of Ecologic Model: Journ. of Sanitary Engr. Div. A.S.C.E., Vol. 96, No. SA5.

Chen, C. W., and Orlob, G. T., 1968, A Proposed Ecologic Model For a Eutrophying Environment: Report to the F.W.Q.A., Southwest Region, Water Resources Engineers, Inc., Walnut Creek, Calif.

Dale, M. B., 1970, Systems Analysis and Ecology: Ecology, Vol. 51, pp. 1-16.

Davidson, R. S., and Clymer, A. B., 1966, The Desirability and Applicability of Simulation Ecosystems: Ann. N. Y. Acad. Sci., Vol. 128, pp. 790-794.

Day, P. R., and Forsythe, W. M., 1957, Hydro-dynamic Dispersion of Solutes in the Soil Moisture Stream: Soil Sci. Soc. of Am. Proc., Vol. 21, pp. 477-480.

DeCoursey, D. G., 1965, Water Yield Computations: Trans. of Am. Soc. of Agriculture Engineers. Vol. 8, No. 3, pp. 367-370.

Deininger, R. A., 1973, Models for Environmental Pollution Control: Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan.

Friedland, B., and Schwartz, R. S., 1965, Linear Systems: McGraw-Hill Book Company, New York.

Garfinkel, D., 1962, Digital Computer Simulation of Ecological Systems: Nature, Vol. 194, pp. 856-857.

Garfinkel, D., MacAuthor, R. H., and Sack, R., 1964, Computer Simulation and Analysis of Simple Ecological Systems: Ann. N. Y. Acad. Sci., Vol. 115, pp. 943-951.

Garfinkel D., and Sack, R., 1964, Digital Computer Simulation of an Ecological System Based on a Modified Mass Action Law: Ecology, Vol. 45, pp. 502-507.

Grim, R. E., 1968, Clay Mineralogy: Mc Graw-Hill Co., St. Louis, Mo.

IBM, 1972, IBM Application Program, System/360 Continuous System Modeling Program User's Manual, Program Number 360A-CX-16X.

Kemper, W. D., Massland, D. E. L., and Porter, L. K., 1964, Mobility of Water Adjacent to Mineral Surfaces: Soil Sci. Soc. of Am. Proceedings, Vol. 28, pp. 164-167.

Kent, D. C., Naney, J. W., and Barnes, B. B., 1973, An Approach to Hydrogeologic Investigations of River Alluvium by the use of Computerized Data: Ground water, Vol.11, No.4, pp.30-42.

Kent, D. C. and Toetz, D., 1972, The Role of Biological Nitrogen Fixation in Lakes; A Research Proposal to the Oklahoma Water Resources Research Institute.

King, C. E., and Paulik, G. E., 1967, Dynamic Models and the Simulation of Ecologic Systems: Journ. Theor. Biol. Vol. 16, pp. 251-267.

Kittrick, J. A., and Hope, C. W., 1963, A Procedure for the Particle Size Separation of Soil for X-ray Diffraction Analysis, Soil Science, Vol. 102, pp.319-325.

Kormondy, E. J., 1969, Concepts of Ecology: Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Levings, G. W., 1971. A Ground Reconnaissance Study of the Upper Sugar Creek Watershed, Caddo County, Oklahoma, Unpublished Thesis, Department of Geology, Oklahoma State University, Stillwater, Oklahoma.

Low, P. F., 1962, Influence of Adsorbed Water on Exchangeable Ion Movement: Clays and Clay Minerals, Vol 9, pp. 219-228,

1961, Physical Chemistry of Clay-Water Interactions: Advancement in Agronomy, Vol. 13, pp. 269-327.

Martin, G. D., 1972, Optimal Control of an Oil Refinery Waste Treatment Facility: A Total Ecosystem Approach, Unpublished Thesis: Department of Mechanical Engineering, Oklahoma State University, Stillwater, Oklahoma.

Milen, L. M., and Thomson, C. B. E., 1950, Theoretical Hydrodynamics: MacMillan Company, New York, N. Y.

Odum, E. P., 1971, Fundamentals of Ecology: W. B., Saunders Company, Philadelphia, Pa.

Olsen, H. W., 1972, Liquid Movement Through Kaolinite Under Hydraulic, Electric and Osmotic Gradients: Assoc. Amer. Petrol. Geol. Bull., Vol. 56, pp. 2022-2029.

Orlob, G. T. and Shubinski, R. T., 1967, Mathematical Modeling of Water Quality in Estuarial Systems: Proceedings ASCE National Symposium on Estuarine Pollution, Stanford University, California.

Parker, R. A., 1968, Simulation of an Aquatic Ecosystem: Biometrics, Vol. 24, pp. 803-821.

Patten, B. C., 1971, Systems Analysis and Simulation in Ecology: (Academic Press, New York and London).

Pielou, E. C., 1969, An Introduction to Mathematical Ecology: Wiley-Inter-science, Addison and John Wiley and Sons, New York, New York.

Quirk, J. P., and Schofield, R. K., 1955, The Effect of Electrolyte Concentration on Soil Permeability: Soc. Soil Sci., Vol. 6, pp. 163-175.

Rutledge, R. W., 1971, Continuous Systems Modeling Program Applications: Unpub. Paper, School of Electrical Engineering, Oklahoma State University.

Sabersky, R. H., and Acosta, A. J., 1964, Fluid Flow, A First Course in Fluid Mechanics: Landis (ed.); MacMillian Company, New York.

Streeter, V. L., 1966, Fluid Mechanics: McGraw-Hill, New York, New York.

Te Chow, V., 1964, Handbook of Applied Hydrology: McGrawHill Book Company, New York, New York.

Todd, D. K., 1959, Groundwater Hydrology: John Wiley and Sons, Inc., New York, New York.

Van Dyne, G. M., 1969 , The Ecosystem Concept in Natural Resource Management: Academic Press, New York, New York and London.

Water Resources Engineers, Inc., 1972, Ecologic Simulation for Aquatic Environments: Final Report WRE-0500 - To the Office of Water Resources Research, U. S. Department of the Interior.

Watt, K., 1966, System Analysis in Ecology: Academic Press, New York, New York.

APPENDIX A

A COPY OF THE COMPLETE CSMP MODELING PROGRAM

List of Symbols Used in the Model

Ai	Interfacing area(ft^2). In the model, A1, A2,.. ..Ai (ft^2/.1day) represent the K*A/L portion of Darcy's equation for defining the flow through the dam.
C2..C28	Defines K*A/L from Darcy's equation (ft^2/.1day for every 2 feet elevation increment.
DA	Sum of Ai for any given lake elevation (H1) in ft^2/.1day.
D1	Sum of C2...C28 interfacing area increments (between lake and ground-water systems) at any given lake elevation (H1) used in determining flow Q12 at any time t.
D2	Sum of C2...C28 interfacing area increments (between lake and ground-water systems) at any given lake elevation (H1) used in determining flow Q21 at any time t.
F1	Permeability of sediments $<$10gpd/ft^2 ($<$.748ft^3/day/ft^2).
F2	Permeability of sediments 10gpd/ft^2 - 15gpd/ft^2 (.748ft^3/day/ft^2 - 1.12ft^3/day/ft^2).
F3	Permeability of sediments 15gpd/ft^2 - 20gpd/ft^2 (1.12ft^3/day/ft^2 - 1.49ft^3/day/ft^2),
F4	Permeability of sediments $>$20gpd/ft^2($>$1.49ft^3/day/ft^2).
GIP	Ground-water base flow (ft^3/.1t).
GTD	Ground-water flow (ft^3/.1t) through the dam.
GUD	Ground-water flow (ft^3/.1t) under the dam.
GWE	Preface for ground-water elevation; number that follows indicates specific observation well.
GWG	Flow (ft^3/.1t) from the ground-water system into the lake.
GWL	Flow (ft^3/.1t) from the lake into the ground-water system.
H1	Elevation (feet) of lake above base elevation elevation (1400 feet).

H2	Elevation (feet) of ground-water above base elevation (1400 feet).
PS	Flow (ft^3/.1t) through the principal spillway.
PSAFT	Flow (acre-feet) through the principal spillway.
PEV	Evaporation(ft^3/.1t).
Q20	Ground-water base flow (ft^3/.1t).
Q12	Flow (ft^3/.1t) from the lake into the ground-water system (inflow to bank-storage).
Q21	Flow (ft^3/.1t)from the ground-water system into the lake (seepage from bank-storage).
Q10	Total loss (ft^3/.1t) from the lake through seepage.
X1	Volume (ft^3) of the lake.
X2	Volume (ft^3) of the ground-water system.
L2,Li...	Horizontal distance (ft) from the interfacing area between two elevation contours and any observation well. Li's will vary with each observation well's location.

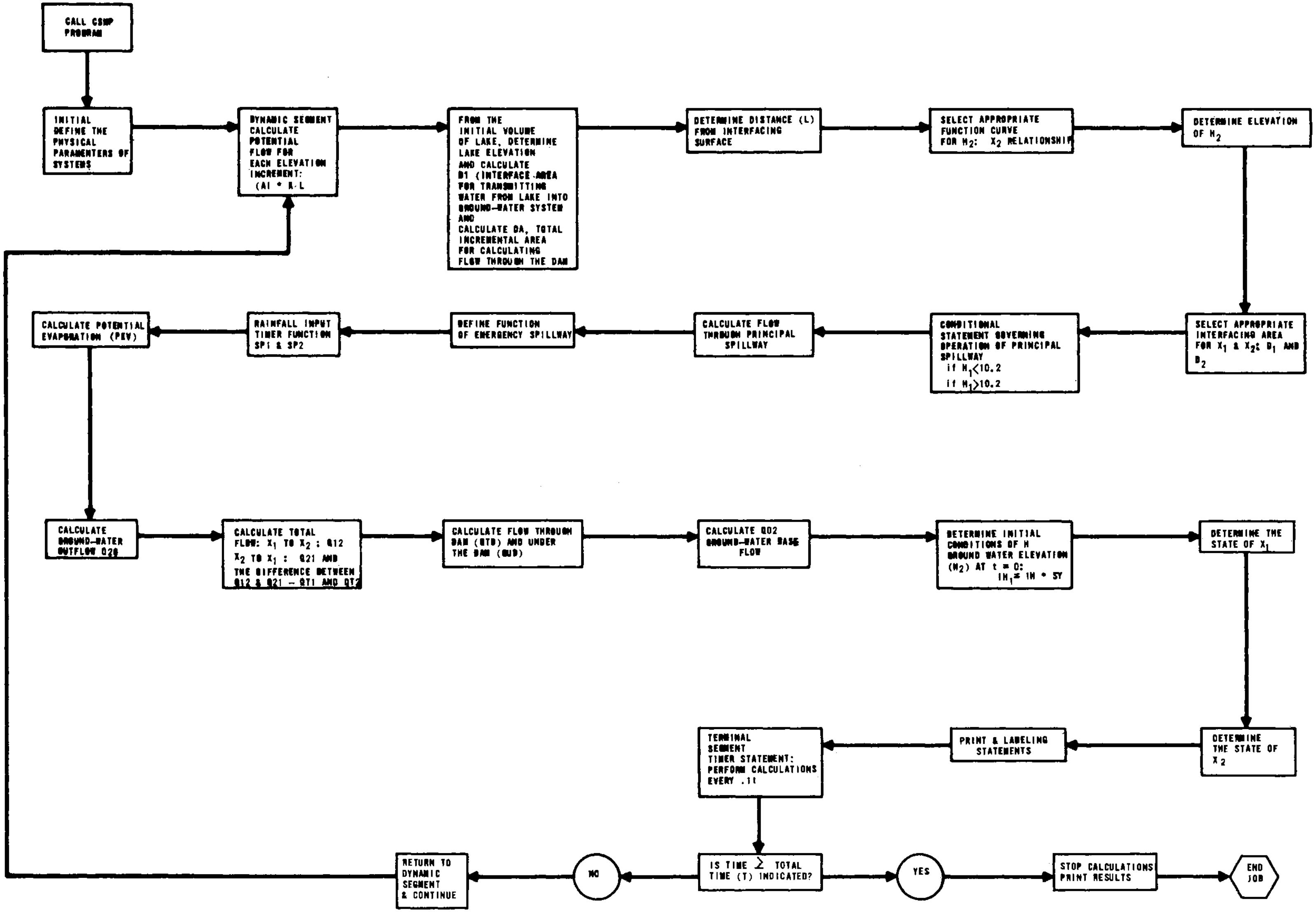


FIGURE 31. LOGIC AND BLOCK DIAGRAM FOR THE MODEL.

```
               ****CONTINUOUS SYSTEM MODELING PROGRAM****

                        *** VERSION 1.3 ***

INITIAL
PARAMETER   IC=1965120.
PARAMETER IH=94280000.
FUNCTION CURVE1=0,0,130680.,2.,692280.,4.,1350360.,6.,2579880.,8.,...
      3847800.,10.,5832350.,12.,7681070.,14.,10110276.,16.,12810996.,...
      18.,15647316.,20.,19388556.,22.,23483196.,24.,27623196.,26.,...
      32500116.,28.
      FUNCTION CURVE2=0,0,1355,2
      FUNCTION CURVE3=0,0,4625,2,6259,4
      FUNCTION CURVE4=0,0,8223,2,13752,4,15611,6
      FUNCTION CURVE5=0,0,10851,2,18714,4,23195,6,24291,8
      FUNCTION CURVE6=0,0,14975,2,26762,4,35267,6,42848,8,43979,10
      FUNCTION CURVE7=0,0,17977,2,32966,4,44573,6,52795,8,58358,10,...
      59305,12
      FUNCTION CURVE8=0,0,20911,2,38834,4,53375,6,64531,8,73028,10,...
      76909,12,78952,14
      FUNCTION CURVE9=0,0,24561,2,46134,4,64325,6,79131,8,91278,10,...
      98809,12,104502,14,105870,16
      FUNCTION CURV10=0,0,27951,2,52914,4,74495,6,92691,8,108228,10,...
      119149,12,128232,14,132990,16,135098,18
      FUNCTION CURV11=0,0,31005,2,59022,4,83657,6,104907,8,123498,...
      10,137473,12,149610,14,157422,16,162584,18,163641,20
      FUNCTION CURV12=0,0,36839,2,70690,4,101159,6,128243,8,152668,...
      10,172477,12,190448,14,204094,16,215090,18,221981,20,225830,22
      FUNCTION CURV13=0,0,39729,2,76470,4,109829,6,139803,8,167118,...
      10,189817,12,210678,14,227214,16,241100,18,250831,20,257620,22,...
      257643,24
      FUNCTION CURV14=0,0,43917,2,84846,4,122393,6,156555,8,188058,...
      10,214945,12,239994,14,260718,16,278792,18,292761,20,303688,22,...
      307899,24,311631,26
      FUNCTION CURV15=0,0,47821,2,92654,4,134105,6,172171,8,207578,...
      10,238369,12,267322,14,291950,16,313928,18,331801,20,346632,...
      22,354747,24,362383,26,362659,28
PARAMETER          PSA=.8
PARAMETER SY=.001
PARAMETER   L2=1200.,L4=1180.,L6=1130.,L8=890.,L10=660.,L12=390.,...
        L14=220.,L16=90.,L18=0.
      GWV777=X2
      GWE777=H2
PARAMETER          N=0.
PARAMETER          P=.01
      CD=.6
PARAMETER F1=.0279,F2=.17,F3=.28,F4=.559,F5=6.
DYNAMC
NOSORT
      A1 =(153*F1)/11
      A2 =(156*F1)/10.5
      A3 =(162*F1)/9
      A4 =(164*F3)/8
      A5 =(175*F3)/7.5
      A6 =(181*F3)/7
      A7 =(189*F5)/5
      A8 =(195*F5)/4.5
      A9 =(204*F5)/2.5
      A10=(279*F5)/2.25
      A11=(281*F5)/2.22
      A12=(286*F5)/2
```

```
      A13=(290*F5)/1.5
      A14=(294*F5)/1
      IF (L2. LE.0.)GO TO 40
      C2=(F1*308)/L2
      IF (L4. LE.0.)GO TO 41
      C4= (F1*( 408))/L4
      IF (L6. LE.0.)GO TO 42
      C6=(F1*(569)+F3*(45))/L6
      IF (L8. LE.0.)GO TO 43
      C8=(F1*(499)+F3*(225)+F4*(8))/L8
      IF (L10.LE.0.)GO TO 44
      C10=(F1*(554.)+F2*(0.)+F3*( 305.)+F4*(18))/L10
      IF (L12.LE.0.)GO TO 45
      C12= (F1*(382)+F2*(181)+F3*(441)+F4*(26))/L12
      IF (L14.LE.0.)GO TO 46
      C14= (F1*(187)+F2*(416.)+F3*(426)+ F4*(81.))/L14
      IF (L16.LE.0.)GO TO 47
      C16= (F1*(335)+F2*(510)+F3*(250)+F4*(130))/L16
      IF (L18.LE.0.)GO TO 48
      C18=((F1*(399)+F2*(471)+F3*(245)+F4*(125))/L18)
      IF (L20.LE.0.)GO TO 49
      C20=(F1*(599)+F2*(195)+F3*(199)+F4*(127))/L20
      IF (L22.LE.0.)GO TO 50
      C22=(F1*(658)+F2*(149)+F3*(169)+F4*(224))/L22
      IF (L24.LE.0.)GO TO 51
      C24=(F1*(428)+F2*( 475)+F3*(125)+F4*(322))/L24
      IF (L26.LE.0.)GO TO 52
      C26=(F1*(295)+F2*( 711)+F3*(92)+F4*( 337))/L26
      IF (L28.LE.0.)GO TO 53
      C28=(F1*(330)+F2*(494 )+F3*(54)+F4*(352))/L28
      GO TO 75
   40 C2=0.0
   41 C4=0.0
   42 C6=0.0
   43 C8=0.0
   44 C10=0.0
   45 C12=0.0
   46 C14=0.0
   47 C16=0.0
   48 C18=0.0
   49 C20=0.0
   50 C22=0.0
   51 C24=0.0
   52 C26=0.0
   53 C28=0.0
      H1=AFGEN(CURVE1,X1)
      GO TO 75
   75 IF (0..LT.H1.AND.H1.LE.2.)GO TO 1
      IF ( 2..LT.H1.AND.H1.LE.4. )GO TO 2
      IF ( 4..LT.H1.AND.H1.LE.6. )GO TO 3
      IF (6.LT.H1.AND.H1.LE.8.)GO TO 4
      IF (8.LT.H1.AND.H1.LE.10.)GO TO 5
      IF (10.LT.H1.AND.H1.LE.12.)GO TO 6
      IF (12.LT.H1.AND.H1.LE.14.)GO TO 7
      IF (14.LT.H1.AND.H1.LE.16.)GO TO 8
      IF (16.LT.H1.AND.H1.LE.18.)GO TO 9
      IF (18.LT.H1.AND.H1.LE.20.)GO TO 10
      IF (20.LT.H1.AND.H1.LE.22.)GO TO 11
      IF (22.LT.H1.AND.H1.LE.24.)GO TO 12
      IF (24.LT.H1.AND.H1.LE.26.)GO TO 13
      IF (26.LT.H1.AND.H1.LE.28.)GO TO 14
```

```
 1 D1=C2
   DA=A1
   GO  TO 30
 2 D1=C2+C4
   DA=A1+A2
   GO  TO 30
 3 D1=C2+C4+C6
   DA=A1+A2+A3
   GO  TO 30
 4 D1=C2+C4+C6+C8
   DA=A1+A2+A3+A4
   GO  TO 30
 5 D1=C2+C4+C6+C8+C10
   DA=A1+A2+A3+A4+A5
   GO  TO 30
 6 D1=C2+C4+C6+C8+C10+C12
   DA=A1+A2+A3+A4+A5+A6
   GO  TO 30
 7 D1=C2+C4+C6+C8+C10+C12+C14
   DA=A1+A2+A3+A4+A5+A6+A7
   GO  TO 30
 8 D1=C2+C4+C6+C8+C10+C12+C14+C16
   DA=A1+A2+A3+A4+A5+A6+A7+A8
   GO  TO 30
 9 D1=C2+C4+C6+C8+C10+C12+C14+C16+C18
   DA=A1+A2+A3+A4+A5+A6+A7+A8+A9
   GO  TO 30
10 D1=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20
   DA=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10
   GO  TO 30
11 D1=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22
   DA=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10+A11
   GO  TO 30
12 D1=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22+C24
   DA=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10+A11+A12
   GO  TO 30
13 D1=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22+C24+C26
   DA=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10+A11+A12+A13
   GO  TO 30
14 D1=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22+C24+C26+C28
   DA=A1+A2+A3+A4+A5+A6+A7+A8+A9+A10+A11+A12+A13+A14
   GO  TO 30
30 IF (L2.  LE.0.)GO  TO 59
   IF (L4.  LE.0.)GO  TO 60
   IF (L6.  LE.0.)GO  TO 61
   IF (L8.  LE.0.)GO  TO 62
   IF (L10.LE.0.)GO  TO 63
   IF (L12.LE.0.)GO  TO 64
   IF (L14.LE.0.)GO  TO 65
   IF (L16.LE.0.)GO  TO 66
   IF (L18.LE.0.)GO  TO 67
   IF (L20.LE.0.)GO  TO 68
   IF (L22.LE.0.)GO  TO 69
   IF (L24.LE.0.)GO  TO 70
   IF (L26.LE.0.)GO  TO 71
   IF (L28.LE.0.)GO  TO 72
   GO  TO 73
59 STOP
60 H2=AFGEN(CURVE2,X2)
   IF (H2.GT.2.) H2=H1
   GO  TO 80
```

```
61 H2=AFGEN(CURVE3 ,X2)
   IF (H2.GT.4.) H2=H1
   GO TO 80
62 H2=AFGEN(CURVE4,X2)
   IF (H2.GT.6.) H2=H1
   GO TO 80
63 H2=AFGEN(CURVE5,X2)
   IF (H2.GT.8.) H2=H1
   GO TO 80
64 H2=AFGEN(CURVE6,X2)
   IF (H2.GT.10.) H2=H1
   GO TO 80
65 H2=AFGEN(CURVE7,X2)
   IF (H2.GT.12.) H2=H1
   GO TO 80
66 H2=AFGEN(CURVE8,X2)
   IF (H2.GT.14.) H2=H1
   GO TO 80
67 H2=AFGEN(CURVE9,X2)
   IF (H2.GT.16.) H2=H1
   GO TO 80
68 H2=AFGEN(CURV10,X2)
   IF (H2.GT.18.) H2=H1
   GO TO 80
69 H2=AFGEN(CURV11,X2)
   IF (H2.GT.20.) H2=H1
   GO TO 80
70 H2=AFGEN(CURV12,X2)
   IF (H2.GT.22.) H2=H1
   GO TO 80
71 H2=AFGEN(CURV13,X2)
   IF (H2.GT.24.) H2=H1
   GO TO 80
72 H2=AFGEN(CURV14,X2)
   IF (H2.GT.26.) H2=H1
   GO TO 80
73 H2=AFGEN(CURV15,X2)
   IF (H2.GT.28.) H2=H1
   GO TO 80
80 IF ( 0..LT.H2.AND.H2.LE.2. )GO TO 15
   IF ( 2..LT.H2.AND.H2.LE.4. )GO TO 16
   IF (4.LT.H2.AND.H2.LE.6.)GO TO 17
   IF (6.LT.H2.AND.H2.LE.8.)GO TO 18
   IF (8.LT.H2.AND.H2.LE.10.)GO TO 19
   IF (10.LT.H2.AND.H2.LE.12.)GO TO 20
   IF (12.LT.H2.AND.H2.LE.14.)GO TO 21
   IF (14.LT.H2.AND.H2.LE.16.)GO TO 22
   IF (16.LT.H2.AND.H2.LE.18.)GO TO 23
   IF (18.LT.H2.AND.H2.LE.20.)GO TO 24
   IF (20.LT.H2.AND.H2.LE.22.)GO TO 25
   IF (22.LT.H2.AND.H2.LE.24.)GO TO 26
   IF (24.LT.H2.AND.H2.LE.26.)GO TO 27
   IF (26.LT.H2.AND.H2.LE.28.)GO TO 28
15 D2=C2
   GO TO 29
16 D2=C2+C4
   GO TO 29
17 D2=C2+C4+C6
   GO TO 29
18 D2=C2+C4+C6+C8
   GO TO 29
```

```
19 D2=C2+C4+C6+C8+C10
   GO TO 29
20 D2=C2+C4+C6+C8+C10+C12
   GO TO 29
21 D2=C2+C4+C6+C8+C10+C12+C14
   GO TO 29
22 D2=C2+C4+C6+C8+C10+C12+C14+C16
   GO TO 29
23 D2=C2+C4+C6+C8+C10+C12+C14+C16+C18
   GO TO 29
24 D2=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20
   GO TO 29
25 D2=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22
   GO TO 29
26 D2=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22+C24
   GO TO 29
27 D2=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22+C24+C26
   GO TO 29
28 D2=C2+C4+C6+C8+C10+C12+C14+C16+C18+C20+C22+C24+C26+C28
   GO TO 29
29 IF (H1.LE.10.2) G=0
   IF (H1.GT.10.2) G=H1-10.2
   PSS=SQRT(2*(32.2)*G)*PSA*CD
   PS=PSS*86.4
   PSAFT=PS/43.560
   Q=H1-23.2
   R=LIMIT(0.0,27.2,Q)
   Y=SQRT(R**3)
   ES=33.3*70.*Y
   SP1=STEP(3.0)-STEP(4.0)
   SP2=STEP(4.8)-STEP(5.0)
    EV=X1
   PEV=P*EV
   Q12=D1*(H1-H2)*10.
   Q21=D2*(H2-H1)*10.
   QT1=Q21+Q12
   QT2=Q12+Q21
   GTD=(DA*H1 )*150.
   GUD=((112500.*F3)*H1)/100.
   Q10= GUD+GTD
       Q02=((4616. *F2)+(300. *F3))*(28.-H2) *3.30
     Q20=Q02
   GWG= Q21
   GWL= Q12
   GIP=Q02
   IH1=IH*SY
   X1=INTGRL(IC,QT1-Q12-ES-PS-(PEV)-Q10+940000.*SP1+55000000.*SP2)
   X2=INTGRL(IH1,QT2-Q21+Q02-Q20)
   LAKELE=H1
   LAKVOL=X1
   IF (N.EQ.0.)GO TO 81
   IF (N.EQ.1.)GO TO 82
   IF (N.EQ.2.)GO TO 83
   IF (N.EQ.3.)GO TO 84
   IF (N.EQ.4.)GO TO 85
   IF (N.EQ.5.)GO TO 86
   IF (N.EQ.6.)GO TO 87
   IF (N.EQ.7.)GO TO 88
   IF (N.EQ.8.)GO TO 89
   IF (N.EQ.9.)GO TO 91
    IF (N.EQ.10.)GO TO 92
```

```
   81 GWV777=X2
      GWE777=H2
      GO TO 90
   82 GWV776=X2
      GWE776=H2
      GO TO 90
   83 GWV775=X2
      GWE775=H2
      GO TO 90
   84 GWV774=X2
      GWE774=H2
      GO TO 90
   85 GWV24=X2
      GWE24=H2
      GO TO 90
   86 GWE794=H2
      GWV794=X2
      GO TO 90
  87  GWV18=X2
      GWE18=H2
      GO TO 90
   88 GWVI74=X2
      GWEI74=H2
      GO TO 90
   89 GWVI76=X2
      GWEI76=H2
      GO TO 90
   91 GWVI75=X2
      GWEI75=H2
      GO TO 90
  92  GWV24=X2
      GWE24=H2
   90 CONTINUE
TERMINAL
      PRTPLOT GWE777,LAKELE
       TIMER FINTIM=30.0, OUTDEL=1.0, DELT=0.1
END
PARAMETER F1=.12,F2=.12,F3=.12,F4=.12
END
PARAMETER F1=.64,F2=.64,F3=.64,F4=.64
END
PARAMETER F1=.9,F2=.9,F3=.9,F4=.9
END
RESET PRTPLOT
      PRTPLOT GWEI75,LAKELE
PARAMETER N=9.
PARAMETER L2=115.5,L4=106.,L6=88.5,L8=67.,L10=56.,L12=19.,L14=7.5,...
      L16=0.0
PARAMETER F1=.0279,F2=.17,F3=.28,F4=.559,F5=6.
END
PARAMETER F1=.12,F2=.12,F3=.12,F4=.12
END
PARAMETER F1=.64,F2=.64,F3=.64,F4=.64
END
      RESET PRTPLOT
       PRTPLOT GWE18,LAKELE
PARAMETER  IH=94282000.
PARAMETER  L2=125.,L4=93.,L6=75.,L8=42.,L10=33.,L12=25.,L14=19.,...
       L16=14.,L18=8.,L20=3.,L22=0.
PARAMETER N=6.
PARAMETER F1=.0857,F2=.2,F3=.64,F4=3.
```

```
END
PARAMETER F1=.9,F2=.9,F3=.9,F4=.9
END
PARAMETER F1=.12,F2=.12,F3=.12,F4=.12
END
PARAMETER F1=.64,F2=.64,F3=.64,F4=.64
END
STOP
```

```
                        MINIMUM             LAKELE VERSUS TIME
                       6.8598E 00
 TIME          LAKELE      I
0.0           7.0000E 00   +
1.0000E 00    6.9527E 0C   +
2.0000E 00    6.9060E 00   +
3.0000E 00    6.8598E 0C   +
4.0000E 00    8.3209E 00   ------+
5.0000E 00    1.8545E 01   -------------------------------------------------+
6.0000E 00    1.6323E 01   ----------------------------------------+
7.0000E 00    1.5124E 01   -----------------------------------+
8.0000E 00    1.4133E 01   -------------------------------+
9.0000E 00    1.3452E 01   ----------------------------+
1.0000E 01    1.2845E 01   -------------------------+
1.1000E 01    1.2267E 01   -----------------------+
1.2000E 01    1.1947E 01   ---------------------+
1.3000E 01    1.1848E 01   ---------------------+
1.4000E 01    1.1750E 01   --------------------+
1.5000E 01    1.1653E 01   --------------------+
1.6000E 01    1.1558E C1   --------------------+
1.7000E 01    1.1464E 01   -------------------+
1.8000E 01    1.1371E 01   -------------------+
1.9000E 01    1.1279E 01   ------------------+
2.0000E 01    1.1189E 01   ------------------+
2.1000E 01    1.1099E 01   ------------------+
2.2000E 01    1.1012E 01   -----------------+
2.3000E 01    1.0925E 01   -----------------+
2.4000E 01    1.0839E 01   -----------------+
2.5000E 01    1.0755E 01   ----------------+
2.6000E 01    1.0672E 01   ----------------+
2.7000E 01    1.0589E 01   ---------------+
2.8000E 01    1.0508E 01   ---------------+
2.9000E 01    1.0429E 01   ---------------+
3.0000E 01    1.0350E 01   --------------+
```

```
                         MINIMUM             GWE777 VERSUS TIME
                        1.0735E 01
 TIME          GWE777       I
0.0           1.0797E 01    ----+
1.0000E 00    1.0784E 01    ---+
2.0000E 00    1.0771E 01    --+
3.0000E 00    1.0758E 01    -+
4.0000E 00    1.0746E 01    +
5.0000E 00    1.0761E 01    -+
6.0000E 00    1.1021E 01    ---------------------+
7.0000E 00    1.1203E 01    ----------------------------------+
8.0000E 00    1.1323E 01    -------------------------------------------+
9.0000E 00    1.1363E 01    ----------------------------------------------+
1.0000E 01    1.1389E 01    ------------------------------------------------+
1.1000E 01    1.1400E 01    -------------------------------------------------+
1.2000E 01    1.1404E 01    -------------------------------------------------+
1.3000E 01    1.1406E 01    -------------------------------------------------+
1.4000E 01    1.1407E 01    -------------------------------------------------+
1.5000E 01    1.1405E 01    -------------------------------------------------+
1.6000E 01    1.1402E 01    -------------------------------------------------+
1.7000E 01    1.1396E 01    -------------------------------------------------+
1.8000E 01    1.1389E 01    ------------------------------------------------+
1.9000E 01    1.1381E 01    ------------------------------------------------+
2.0000E 01    1.1370E 01    -----------------------------------------------+
2.1000E 01    1.1359E 01    ----------------------------------------------+
2.2000E 01    1.1347E 01    ---------------------------------------------+
2.3000E 01    1.1338E 01    --------------------------------------------+
2.4000E 01    1.1329E 01    --------------------------------------------+
2.5000E 01    1.1318E 01    -------------------------------------------+
2.6000E 01    1.1307E 01    ------------------------------------------+
2.7000E 01    1.1294E 01    -----------------------------------------+
2.8000E 01    1.1281E 01    ----------------------------------------+
2.9000E 01    1.1266E 01    ---------------------------------------+
3.0000E 01    1.1251E 01    --------------------------------------+
```

```
                          *** CSMP/360 SIMULATICN DATA ***

PARAMETER F1=.64,F2=.64,F3=.64,F4=.64

END

                                  MINIMUM              GWEI75 VERSUS TIME
                                 9.8993E 00
  TIME            GWEI75           I
 0.0             1.4000E 01      --------------------------------------------------+
 1.0000E 00      1.4000E 01      --------------------------------------------------+
 2.0000E 00      1.4000E 01      --------------------------------------------------+
 3.0000E 00      1.4000E 01      --------------------------------------------------+
 4.0000E 00      1.4000E 01      --------------------------------------------------+
 5.0000E 00      1.4000E 01      --------------------------------------------------+
 6.0000E 00      1.4000E 01      --------------------------------------------------+
 7.0000E 00      1.4000E 01      --------------------------------------------------+
 8.0000E 00      1.4000E 01      --------------------------------------------------+
 9.0000E 00      1.4000E 01      --------------------------------------------------+
 1.0000E 01      1.4000E 01      --------------------------------------------------+
 1.1000E 01      1.4000E 01      --------------------------------------------------+
 1.2000E 01      1.4000E 01      --------------------------------------------------+
 1.3000E 01      1.4000E 01      --------------------------------------------------+
 1.4000E 01      1.4000E 01      --------------------------------------------------+
 1.5000E 01      1.4000E 01      --------------------------------------------------+
 1.6000E 01      1.4000E 01      --------------------------------------------------+
 1.7000E 01      1.4000E 01      --------------------------------------------------+
 1.8000E 01      1.4000E 01      --------------------------------------------------+
 1.9000E 01      1.3116E 01      ----------------------------------------+
 2.0000E 01      1.1946E 01      -------------------------+
 2.1000E 01      1.1487E 01      -------------------+
 2.2000E 01      1.1118E 01      --------------+
 2.3000E 01      1.0966E 01      -------------+
 2.4000E 01      1.0807E 01      -----------+
 2.5000E 01      1.0643E 01      ---------+
 2.6000E 01      1.0475E 01      -------+
 2.7000E 01      1.0305E 01      ----+
 2.8000E 01      1.0134E 01      --+
 2.9000E 01      9.9822E 00      -+
 3.0000E 01      9.8993E 00      +
```

```
                      *** CSMP/360 SIMULATION DATA ***
PARAMETER F1=.64 F2=.64,F3=.63,F4=.64


 TIME          GWE18         I
0.0            7.0000E 00    +
1.0000E 00     6.9989E 00    +
2.0000E 00     6.9956E 00    +
3.0000E 00     6.9904E 00    +
4.0000E 00     6.9988E 00    +
5.0000E 00     7.2737E 00    --+
6.0000E 00     9.7505E 00    ---------------------------+
7.0000E 00     1.0871E 01    ---------------------------------------+
8.0000E 00     1.1539E 01    ---------------------------------------------+
9.0000E 00     1.1802E 01    ------------------------------------------------+
1.0000E 01     1.1931E 01    -------------------------------------------------+
1.1000E 01     1.1954E 01    -------------------------------------------------+
1.2000E 01     1.1943E 01    -------------------------------------------------+
1.3000E 01     1.1915E 01    -------------------------------------------------+
1.4000E 01     1.1872E 01    -------------------------------------------------+
1.5000E 01     1.1817E 01    ------------------------------------------------+
1.6000E 01     1.1750E 01    -----------------------------------------------+
1.7000E 01     1.1674E 01    -----------------------------------------------+
1.8000E 01     1.1589E 01    ----------------------------------------------+
1.9000E 01     1.1496E 01    ---------------------------------------------+
2.0000E 01     1.1397E 01    --------------------------------------------+
2.1000E 01     1.1292E 01    -------------------------------------------+
2.2000E 01     1.1193E 01    ------------------------------------------+
2.3000E 01     1.1122E 01    -----------------------------------------+
2.4000E 01     1.1044E 01    ----------------------------------------+
2.5000E 01     1.0960E 01    ---------------------------------------+
2.6000E 01     1.0870E 01    ---------------------------------------+
2.7000E 01     1.0775E 01    --------------------------------------+
2.8000E 01     1.0676E 01    -------------------------------------+
2.9000E 01     1.0572E 01    ------------------------------------+
3.0000E 01     1.0465E 01    ----------------------------------+
```

APPENDIX B

BASIC MATHEMATICS OF MODEL CONSTRUCTION

Basic Mathematics of Model Construction

The most common ecosystem models are constructed by biologists interested in transfers of biomass (gm/m) during some given length of time. A typical equation would be,

$$\overset{o}{X1} = \frac{dX}{dt} = X1*Q10+X2*Q21$$

This expression states that the rate of change (of the mass) of X1 is controlled by the state of X1 (total mass) times some transfer coefficient (Q10) plus the mass of another state (same measurement units) multiplied by a transfer coefficient (Q21) for any given time (t).

Note that the expression only states that a transfer occurs from one compartment (X1 or X2) to another). The mode of flux and the method of transport are not specified. The route of transfer is also not specified in the model. However, most biological models represent biomass flux through trophic levels. The method of transport is assumed to be one organism ingesting and digesting another.

The following symbols are used to describe the basic functions of a linear systems model. Fij(X,t) is the flux of energy, matter, or water from compartment i to j, while Xi and Xj, are concentrations in their respective compartments. The compartments Xi and Xj may be expressed as concentrations (e.g., milligram per liter, kilocalories per square meter), or total volume (e.g. cubic feet). The flux units (Fij(X,t)) may be milligrams per liter per day, kilocalories per square meter per year, or cubic feet per day. The flux rate is governed by Øij (transfer coefficient) which when multiplied by its respective state governs how much of the flux is transferred from Xi to Xj in one time unit t.

More simply stated, two compartments are interconnected and have an exchange of material (cubic ft. of water) during some length of time (t). Øij or Qij in the previous examples, is a number which when multiplied by the states tells the modeler the rate or how fast the transfer occurs, e.g., 25 ft /hr vs. 25 ft /day.

A major distinction exists between biological models and abiotic models in determining transfer coefficients and intercompartmental flows. In the biological model, the symbol Qij is a number which, when multiplied times its respective state (Xi), produces a flow rate or transfer of biomass from that state per unit (t). The same flow (Xi*Qij) may appear twice in the set of state equations representing a portion of an ecosystem (providing the system is not uni-directional), once as a positive flow (Xi*Qij) in the state equation of Xj (since the flow denoxes a positive transfer, or an increase in the state of Xj), and once as a negative flow (-Xi*Qij) in the state equation of Xi (denoting a decrease in the state Xi).

Biological models are constructed by estimating the biomass of one compartment (each compartment of the model generally represents a different species) at a time t (defined as an initial t, or t = 0) and then repeating the measuring process again at another time t + n. The following equation defines the flux Fij (flow from X1 to Xj),

$$Fij(X, (t+n)) = Xi(t+n) - Xi(t).$$

The transfer coefficient for this expression generally is found,

$$Qij(t) = Fij(x,t+n)/n,$$

where,

t = unit of time (initially, t = 0)

n = total number of t units

therefore,

$$XiQij(t) = Fij(t) .$$

The most common mathematical expressions for flows in ecological compartment models are as follows:

(1) Fij = k (constant). Flow from compartment i to j does not change with time (t) or system state.

(2) Fij = QijXi. Flow to j is proportional to the content of state i. The donor compartment only is controlling.

(3) Fij = QijXj. The receiving compartment alone regulates the flow.

These three functions represent linear flows which are common to hydrologic and ecologic models. Nonlinear flows also occur but they are not discussed here (Patten, 1971).

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