THE WATER QUALITY PLANNING MODEL

ASHOK N. SHAHANE AND JOHN R. MALOY

South Florida Water Management District
P. O. Box V, West Palm Beach, Florida 33402 U. S. A.

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For presentation at the International Conference on Ecological Modeling
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ABSTRACT

There are three water conservation areas in the south Florida Everglades which are ecologically active water storage areas providing flood control and water supply benefits. In the development of the water use and supply plan for the region, a water management alternative called "backpumping" is considered as one of several water management schemes. In the backpumping schemes, normal eastward flow of excess water to the Atlantic Ocean is reversed by pumping it westward to the conservation areas in the wet period (May through October) to increase the water supply capability for the region of south Florida during the dry period (November through April).

The topic of this paper centers around a method for assessing the impact of various water management related backpumping schemes in one of these water conservation areas. Since water quality planning models are relatively recent, an effort was made to first examine the existing models (such as QUAL I, QUAL II, STORM, Statistical Models, Agricultural Runoff Quality-Quantity Models {known as ARM Models} and the United States Environmental Protection Agency's Storm Water Management Model) in terms of what they are designed for; what kind of information they need, etc., etc. In light of such review information, a recently developed modeling procedure for simulating spatial and time distribution of the chemical parameters in the marsh-channel system of the conservation area is presented as a case study of the water quality models. The water quality planning model with its specific set of assumptions, simplifications and input data was calibrated for the available limited chloride field data of 1974. After satisfactory calibration results, the model was then used to estimate possible

concentrations of chlorides for four years (1968-71) with different hydaulic conditions envisioned in the future backpumping schemes. A first-cut demonstration of the model output in water quality planning was conducted for Conservation Area 1 only, because of the present lack of appropriate data. Such a quantitative framework was expected to provide useful insight into chemical transport within the conservation areas in general and to assess the water quality impact of water management options in particular.

INTRODUCTION

Utilization of mathematical models in developing water resources planning policies has increased tremendously during the last two decades. Basic research during the decade (1958-68) concerned itself with the ultimate goal of estimating the hydrological system's ability to provide water for consumptive use. These models are usually called water quantity models. A Stanford Watershed Model and USDAHL sub-basin model are two examples, among many, of these types of water quantity models (see Shahane 11, 14, 15, 16 and Biswas 20)*. Further research on these water quantity models increased their capability so that they could be used directly either in setting guidelines in the planning function or in developing design criteria for managing water resources during the second decade (1968-78).

Water quality models, on the other hand, received "lip" service during the first decade (1958-68), and a few practical water quality type models were developed during the second decade (1968-78). The water quality planning models are of relatively recent origin. Comparative observations indicate that the practical use of water quality models in water resources planning has just started.

Since 1948, the South Florida Water Management District (hereafter referred to as "the District" has been involved in planning, regulating, and operating the relatively complex water system of South Florida. This system includes interconnected canals, lakes, reservoirs, groundwater (shallow and deep aquifers) and intercoastal waters covering an area of 15,500 square miles. As a part of fulfilling these responsibilities, the District has developed several mathematical models as shown in Figure 1. Each model shown in Figure 1 can be examined in terms of the practical questions that are given on the lower half of the figure.

*Numbers in parenthesis refer to bibliography

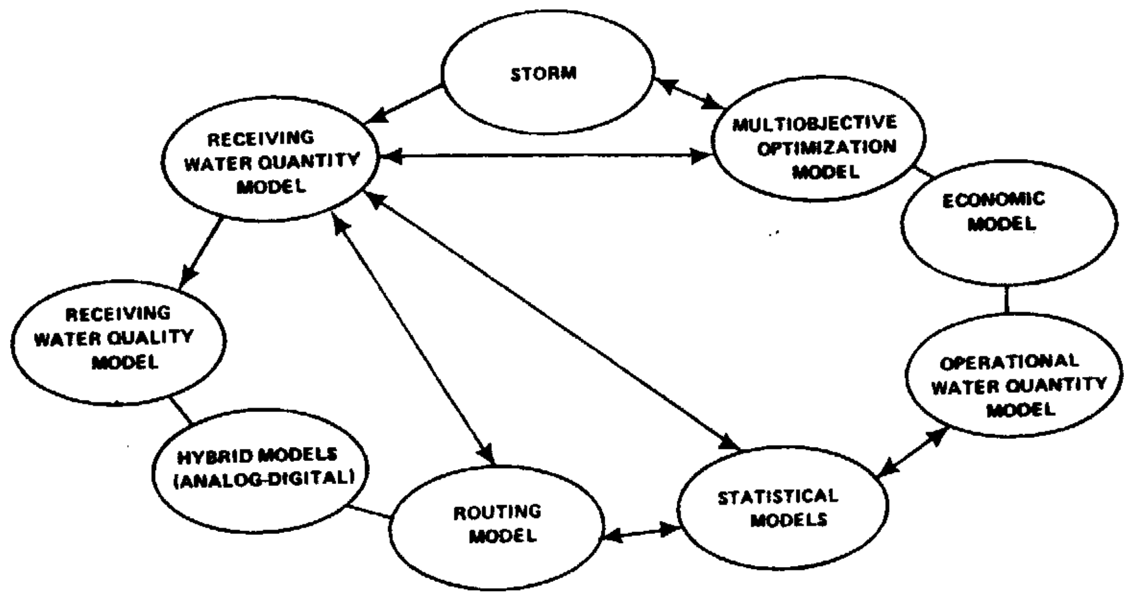
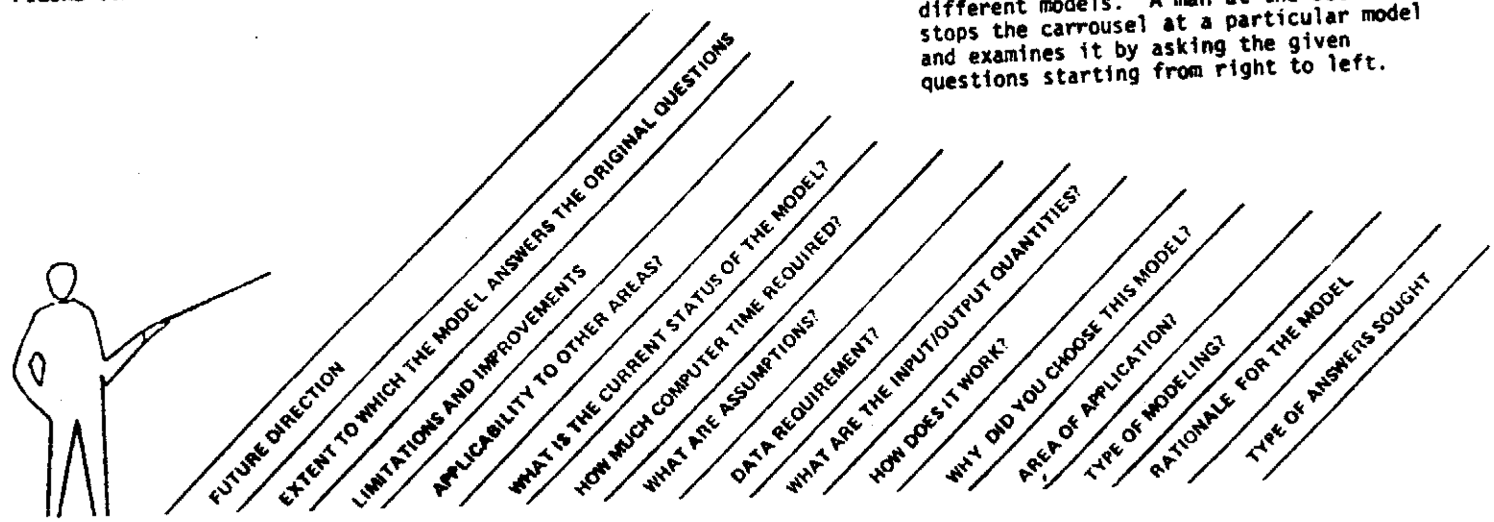


FIGURE 1. THE MODELING WORK OF THE DISTRICT

*A modeling carrousel is moving with its different models. A man at the bottom stops the carrousel at a particular model and examines it by asking the given questions starting from right to left.



This paper discusses the (a) receiving water quality model in light of the existing water quality models, and (b) application as a water quality model for the Florida Everglades Conservation Areas.

REVIEW OF THE EXISTING WATER QUALITY MODELS

Basically, water quality models are developed for assessing the water quality changes that can occur as a result of the stress (natural or man-made) imposed on the system. Since water quality changes are functions of biological, chemical, physical and many other numerous factors, these factors are first identified and then interactions between these factors are formulated. The mathematical representation of these interrelationships (reflecting the interactions) can take the form of either a simple algebraic equation tying together various factors, or a differential equation representing the change of a certain parameter as a function of other variables or more sophisticated mathematical forms such as probabilistic and stochastic models. Most of the water quality modeling efforts are first involved with formulating the concentration of a certain chemical parameter of the aquatic environment in terms of various processes responsible for causing a concentration change in that parameter. Mathematically, the identified processes are included in terms of coefficients reflecting the rate and characteristic formulation of the processes. With such generalized mathematical representation, the formulations can be applied to many different types of water systems with different forms of coefficients and rate kinetics. Although such generalized procedures look straightforward, there are many variations possible in terms of (a) the number of processes included in the formulation, (b) the type of mathematical model, (c) the category of the water system, (d) the characteristics of the chemical parameters, (e) the mathematical scheme to obtain the solution and (f) the simplifications, approximations and assumptions of the modeling methodologies. As a consequence, there exist varieties of water quality models to include these different conditions. From the standpoint of their applications in planning functions, these water quality models can be broadly listed as

1. QUAL I (using Streeter-Phelp formulations),
2. QUAL II,
3. STORM model,
4. Statistical models with probabilistic, stochastic and deterministic rationales,
5. Agricultural Runoff quality-quantity models (ARM models), and
6. EPA Storm Water Management Model

To understand the selected water quality model for the conservation areas in proper perspective, the following section briefly reviews these models in terms of what are they designed for, what kind of useful information they provide, and whether they are applicable in our specific investigations of the conservation areas.

QUAL I

The QUAL I model (which was developed by the Texas Water Development Board using the original oxygen sag equation) formulates the dissolved oxygen profile as a function of organic load, and deoxygenation and aeration rates. It is used to predict the time and spatial distribution of biochemical oxygen demand (BOD) and dissolved oxygen (DO) at the downstream side of the point of discharge. Essentially, QUAL I was developed for one dimensional flow with steady state conditions for stream and canal systems. After estimating, either in the laboratory or in the field, the rate coefficients for deoxygenation and reaeration processes, QUAL I estimates the critical time and the downstream point where minimum concentrations of dissolved oxygen can occur. Although several applications of QUAL I to various streams in the United States have been reported, a recent study of the U. S. Geological Survey and Connell Associates, Inc. of Miami have explored QUAL I model as a management tool to predict the spatial and temporal distribution of dissolved oxygen and biochemical oxygen demand in the Plantation canal of South Florida, and for the combination of the St. Johns River, Kissimmee River, Lower Florida and East Coast basins, respectively (10, 17, 24). It also should be noted that although most of the applications of QUAL I have considered the interplay of only deoxygenation and reaeration processes, formulations are available to include other dissolved oxygen related processes such as the photosynthesis, nitrification and benthic oxygen demands for estimating the impact of waste discharges on the dissolved oxygen reservoir of a stream and canal system.

QUAL II

This is a modified version of QUAL I developed by Water Resources Engineers, Inc. (WRE) of Walnut Street, California to simulate the steady state behavior of (a) chlorophyll, (b) nitrogen, (c) phosphorous, (d) coliforms, and (e) radioactive material in addition to the two parameters of dissolved oxygen and biochemical oxygen demand considered in QUAL I. The complete set of differential equations for water quality parameters of QUAL II is repeated in Table 1 for a ready reference. It is clear from the table that these formulations represent the rate of change of chemical parameters as the net interactions of dispersion, advection, constituent reactions, and various sinks, and source terms (9). An implicit type numerical technique is then applied to solve these differential equations for each of the numerous reaches constituting the river system. As an outcome, this model estimates time and spatial distribution of various parameters. Since QUAL II deals with varieties of physical, chemical and biological processes that are built into the formulations, there are relatively large numbers of constants and rate coefficients associated with this type of water quality model.

STORM Model

As a part of urban stormwater management, the STORM model was designed by Water Resources Engineers, Inc. to estimate the quantity and quality of runoff

TABLE 1

SUMMARY OF DIFFERENTIAL EQUATIONS USED IN QUAL II MODEL (Reference No. 9)

Conservative mineral (c)	$\frac{\partial c}{\partial t} = \frac{\partial(A_x D_L \frac{\partial c}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u c)}{A_x \partial x}$
Algae (A)	$\frac{\partial A}{\partial t} = \frac{\partial(A_x D_L \frac{\partial A}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u A)}{A_x \partial x} + (\mu - \rho - \frac{\sigma_1}{D}) A$
Ammonia nitrogen (N_1)	$\frac{\partial N_2}{\partial t} = \frac{\partial(A_x D_L \frac{\partial N_1}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u N_1)}{A_x \partial x} + (\alpha_1 \rho A - \beta_1 N_1 + \frac{\alpha_3}{D})$
Nitrite nitrogen (N_2)	$\frac{\partial N_1}{\partial t} = \frac{\partial(A_x D_L \frac{\partial N_2}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u N_2)}{A_x \partial x} + (\alpha_5 N_1 - \beta_2 N_2)$
Nitrate nitrogen (N_3)	$\frac{\partial N_3}{\partial t} = \frac{\partial(A_x D_L \frac{\partial N_3}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u N_3)}{A_x \partial x} + (\beta_2 N_2 - \alpha_1 \mu A)$
Phosphate phosphorus (P)	$\frac{\partial P}{\partial t} = \frac{\partial(A_x D_L \frac{\partial P}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u P)}{A_x \partial x} + (\alpha_2 (\rho - \mu) A + \frac{\sigma_2}{D})$
Biochemical oxygen demand (L)	$\frac{\partial L}{\partial t} = \frac{\partial(A_x D_L \frac{\partial L}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u L)}{A_x \partial x} - (K_1 + K_3) L$
Dissolved oxygen (ϕ)	$\frac{\partial \phi}{\partial t} = \frac{\partial(A_x D_L \frac{\partial \phi}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u \phi)}{A_x \partial x} + [K_2(\phi^* - \phi) + (\alpha_3 \mu - \alpha_4 \rho) A - K_1 L - \frac{K_4}{D} - \alpha_5 \beta_1 N_1 - \alpha_3 \beta_2 N_2]$
Coliform (F)	$\frac{\partial F}{\partial t} = \frac{\partial(A_x D_L \frac{\partial F}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u F)}{A_x \partial x} - K_5 F$
Radioactive material (R)	$\frac{\partial R}{\partial t} = \frac{\partial(A_x D_L \frac{\partial R}{\partial x})}{A_x \partial x} - \frac{\partial(A_x u R)}{A_x \partial x} - K_r R$

Note: Symbols are defined in the "notation" section from small and urban watersheds. Stormwater abatement can be investigated in terms of storage and treatment facilities (18). By considering precipitation, air temperature for rainfall/snowmelt, pollutant accumulation, land surface erosion, the amount of runoff with its associated water quality can be estimated. The water quality parameters considered in the STORM model can include up to twenty parameters some of which are suspended and settleable solids, biochemical oxygen demand (BOD), Total Nitrogen (TN), and total phosphorus (TP).

STATISTICAL MODELS

Since many professional water scientists feel that natural processes are too complex to be derived by mathematical formulations, the interrelationships can be empirically established by statistical methods. For example, a deterministic model developed by Reid, G.W. (19) using statistical technique of multiple regression analysis for storm drainage is written as

$$Y_2 = 4.8 + 0.082X_2 + 0.48X_8$$

$$Y_5 = 2.38 - 0.188 \ln K_1 + 0.310 \ln X_{10} \text{ and}$$

$$Y_6 = 2.90 + 0.00003X_1 - .0001X_3 - 0.0137X_8 - 0.741X_{11}$$

where

X_1 = population

X_2 = population density,

X_3 = number of households,

X_8 = commercial establishment,

X_{10} = streets,

X_{11} = environmental index,

Y_2 = B.O.D.

Y_5 = total nitrogen,

Y_6 = total phosphorus

ln = natural logarithm

Another interesting empirical relationship provided by Reid, G. W. (19) for the eutrophication process relates to the required nutritional dilution with eutrophication parameters as shown below:

$$Q_n = \frac{Z \cdot P}{F_n RQS_n} (1 - TL_n) - 1.44 (1 - TL_L) \times (TL_L \ 3250)$$

$$Q_p = \frac{Z \cdot P}{F_p RQS_p} (1 - TL_p) - 0.27 (1 - TL_L) (TL_L \ 1080)$$

where

Q_p or Q_n = nutritional dilution required,

Z = relative portion impounded and affected by RQS level,

TL_p or TL_n = phosphorus or nitrogen removal level expressed as a decimal,

F_p or F_n = BOD/P ratio or BOD/N ratio,

TL_L = BOD removal level expressed as a decimal,

RQS_p and RQS_n = acceptable level for phosphorus and nitrogen.

Likewise, varieties of the statistical water quality models with probabilistic and stochastic rationales are found in the literature (15, 16, 20). The criticism generally leveled against these statistical models is that they are not generalized thusly they should not be applied to any other situation. However, for setting short term planning guidelines on a regional basis, these empirical models may become more handy than a generalized solution of rigorous mathematical formulation.

AGRICULTURAL RUNOFF QUALITY-QUANTITY MODELS (ARM)

These water quality and quantity oriented models were develpped basically for describing the movement of chemicals in and across an agricultural watershed. There are two kinds of models generally used in this area. The first type uses the USDAHL-74 model of watershed hydrology which was developed by the research team of the Agricultural Research Service to estimate a runoff hydrograph for a given watershed by considering precipitation, hydrologic characteristics of soils and land use, evapotranspiration, infiltration and routing techniques (21). The estimated runoff values are then further used in the water quality model (developed by the same research team) which is called the agricultural chemical transport model (ACTMO). The net result of the combination of USDAHL 74 Model and ACTMO gives the quality and quantity of runoff from an agricultural watershed for a given rainfall distribution and hydrogeologic, climatologic and many other watershed characteristics (22). The second model, developed by Hydrocomp, Inc., of Palo Alto, California, is called Pesticide Transport and Runoff Model (PTR Model). The basic purpose of the ACTMO and PTR models is the same although the methodology is different in terms of assumptions, computational procedures and the way different hydrologic processes are included in the model. ACTMO estimates chemical transport of the pesticide carbofuran, while herbicides such as Paraquat and Dippenamid are used in the PTR model. Since most of the processes considered in the ARM model are expressed in terms of empirical equations with the characteristics of the region built into the various coefficients of the equations, the success of the model is largely dependent on the accuracy of these coefficients. Also note that the ARM models are not developed in terms of differential equations; in fact they were developed using daily accounting procedures of various interactions.

EPA STORMWATER MANAGEMENT MODEL

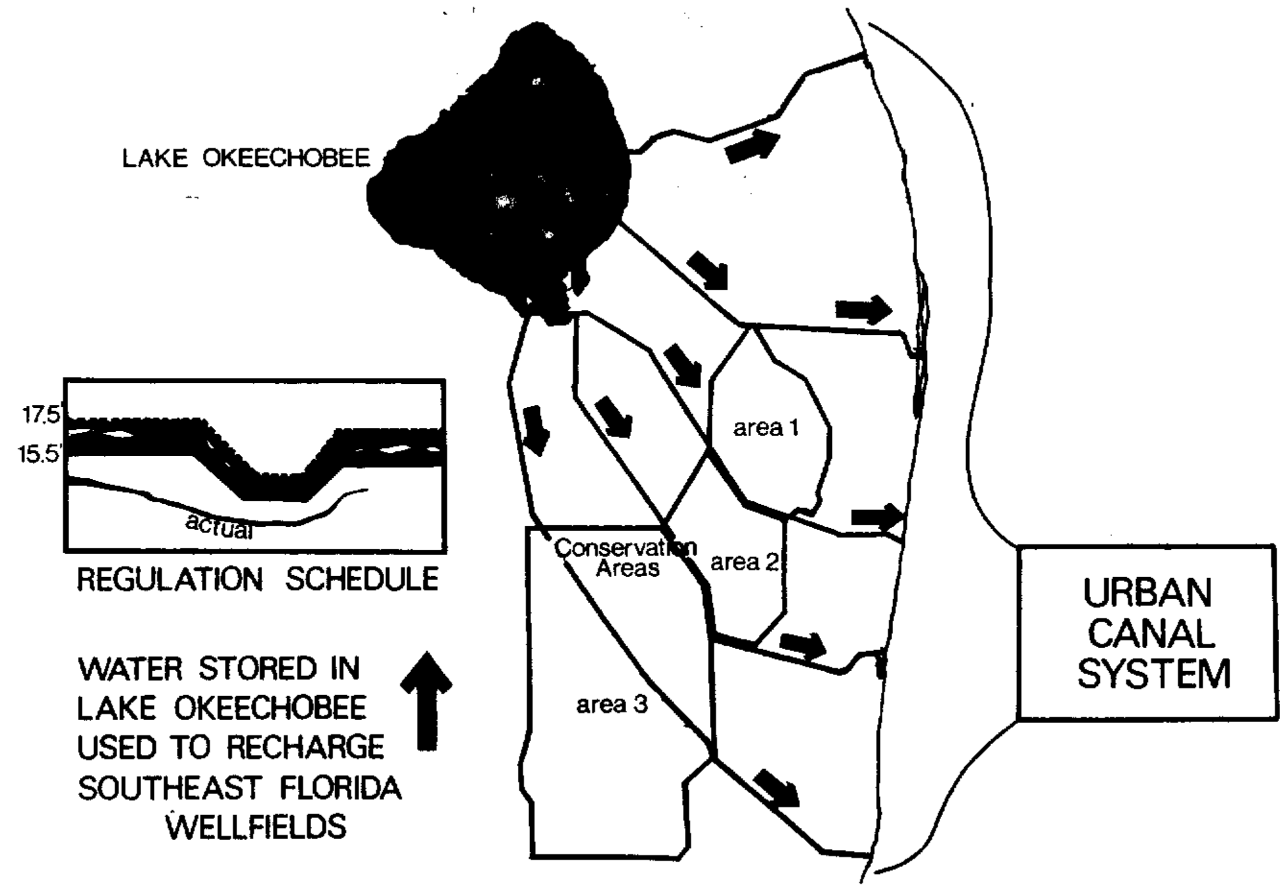
While trying to establish a generalized and uniform procedure for estimating various aspects of stormwater nationwide, the stormwater management model was developed under a combined effort by Metcalf & Eddy, Inc., Department of Environmental Engineering of the University of Florida at Gainesville, and Water Resources Engineers, Inc., under the sponsorship of the United States Environmental Protection Agency (3). Basically, this model (which is widely known as

SWIM) estimates runoff hydrographs (for a watershed from any rainfall hyetograph or multiple hyetographs) and continuous runoff quality graphs (pollutographs) on the basis of the volume of storm runoff, rainfall history, street sweeping data, land use and related data (3). As a next step, the computed hydrographs and pollutographs are routed through the simulation of the physical transport system. After finally obtaining the routed quality and quantity of stormwater, the various options for storage and treatment facilities are examined in terms of their cost effectiveness. This comprehensive model has several submodels (such as the surface runoff quantity model, dry weather flow quantity model, infiltration model, transport model, storage model, receiving water quantity model, surface runoff quality model, dry weather flow quality model, treatment model and cost-effectiveness model) which are linked together to achieve the final result of providing the optimum combination of stormwater treatment and storage facilities to minimize, in final analysis, the stormwater pollution (3). Although the SWIM model is designed for stormwater management, many concepts and procedures used in this comprehensive model seem to be useful in various contemporary environmental models and evaluations.

THE WATER QUALITY PLANNING MODEL

THE NEED FOR THE MODEL:

Backpumping was considered as one of several water management schemes in the development of the water supply and water use plan for the lower east coast of south Florida. Basically, backpumping means that excess water (which is normally discharged eastward to the ocean through the existing canals) is pumped westward to selected areas (in our case, the conservation areas) during the wet period to increase the water supply capability for the region of south Florida during the dry period. This concept of backpumping is ullustrated in Figure 1. In the upper portion of Figure 1, the direction of the arrows indicates normal



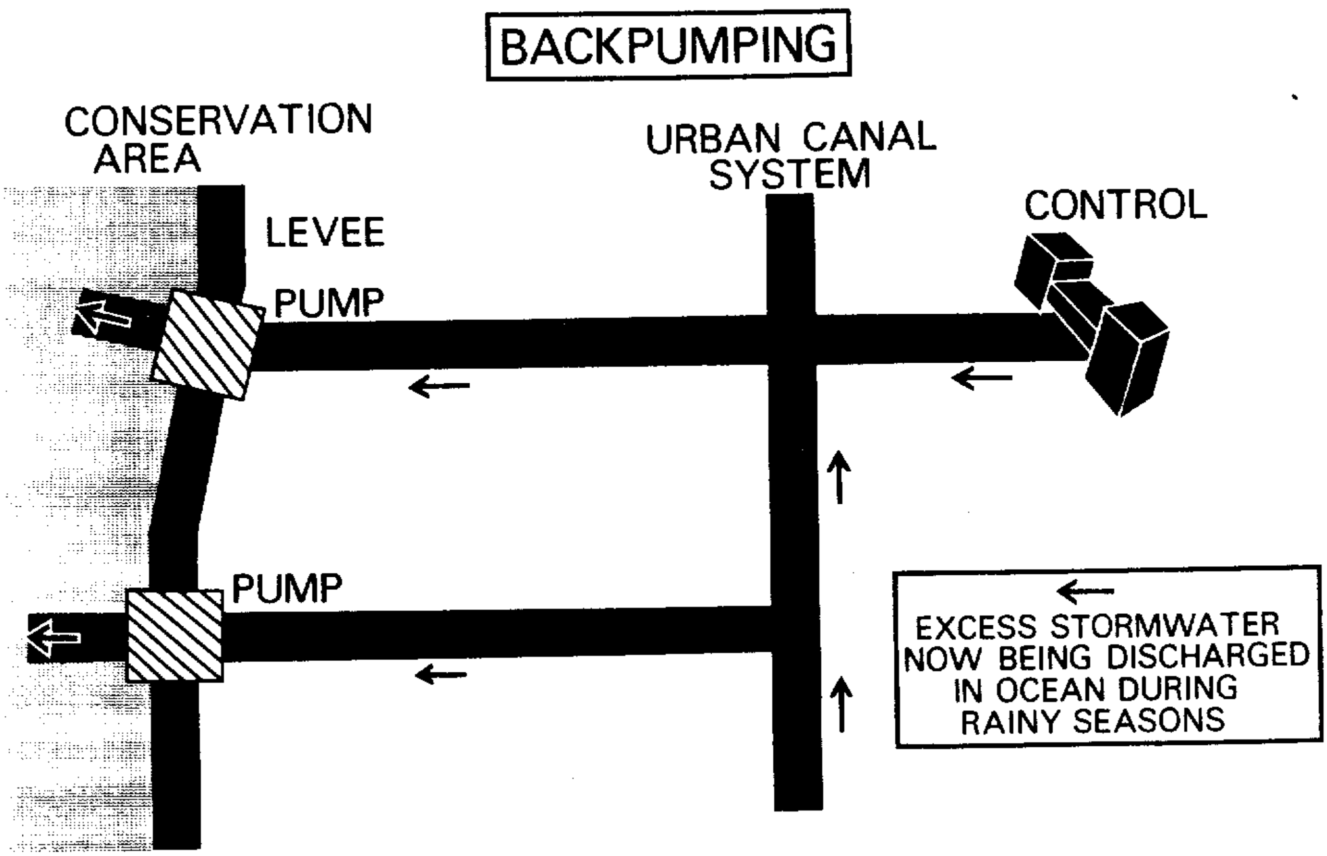


Figure 2. Comparison of Normal and Backpumping Flow Directions.

eastward flow of water from Lake Okeechobee to the ocean through the existing canal system. The lower portion of the figure represents pumping of water westward to the conservation areas of the Everglades for increasing storage capacity of the region in addition to providing flood protection to some urban areas. Although the inherent goals of the backpumping scheme are sound from a water quantity viewpoint, there are some points that need considerable environmental assessment. One of these points relates to the water quality impact of the backpumped water. In backpumping operations, surface water runoff from surrounding land uses and practices drains into a canal (which in turn is backpumped into the conservation area). The extent to which the conservation area is affected from a water quality standpoint becomes a matter of great significance in evaluating the overall effectiveness and trade-offs of future backpumping schemes. The water quality impact assessment of future backpumping schemes must be completed on a timely basis to facilitate the comparative evaluation of this alternative with other possible water management alternatives. These two points create the basic need for a water quality planning model which can estimate the spatial and time distribution of selected chemical constituents (in our case at present chlorides) in the conservation areas for the expected future inputs of different backpumping schemes.

FACTORS IN THE SELECTION OF THE MODEL

Considering the foregoing characteristics of the existing water quality model, the receiving water quality part of the EPA Stormwater Management Model appears to be more applicable for the following reasons:

1. Since QUAL I is designed primarily for stream and canal systems to handle only two chemical parameters (such as dissolved oxygen and biochemical oxygen demand) and since our water system consists largely of a marsh with feeding canals, QUAL I is not directly applicable to analyze the distribution of chlorides and dissolved nutrients in conservation areas.

2. Although the QUAL II model has sophisticated approach using differential equations for conservative as well as nonconservative parameters, the coefficients and rate constants of the equations cannot be adequately determined by the existing limited water quality data base. Because of such a limitation, it cannot be adequately used as a management tool to analyze backpumping schemes at the present time:

3. As mentioned earlier, the STORM model was developed specifically to estimate quantity and quality of surface runoff from a given watershed only at an outlet of the watershed. As a result, our specific objective of estimating temporal and spatial distribution of chemical parameters in the Conservation Areas cannot be fulfilled by the STORM model although its useful role is utilized in other aspects of backpumping analysis.

4. Lack of sufficient water quality data has prevented the availability of well-established statistical models interrelating various water quality parameters at different points in the conservation areas.

5. ARM models do include sophisticated scientific bases in their water quantity and quality counterparts. In other words, before the water quality part is developed for conservation areas, its water quantity counterpart should be ready. Since neither the Stanford Watershed Model nor the USDAHL 7 Hydrology Model has been available for three conservation areas due to many conceptual difficulties, ARM models are not considered as a logical choice.

6. In spite of the fact that the EPA Stormwater Model was developed for urban stormwater movement and although this comprehensive model has varieties of pieces built into it, the methodology of the receiving water quantity model and the receiving water quality model can be separately developed. Furthermore, the receiving water quantity model was recently applied to the three conservation areas and the hydraulic output (which becomes part of the input data set for the receiving water quality model) is available. This is one of the main reasons why the EPA SWIM Model is more suitable in our water quality investigations of

backpumping schemes. Furthermore, the network analysis implied in the receiving water quality model enables us to obtain the wanted information regarding temporal and spatial distribution of chemical constituents for various backpumping inputs. It can also be shown that some of the peculiaritiesof conservation areas may be included by modifying the basic concepts of the receiving water quality model.

DESCRIPTION OF THE MODEL

Since the selected water quality model is related to a network analysis, the area under investigation needs to be represented in terms of a link-node system as shown in Figure 3. The circles are called nodes and the line joining two nodes representsa link. The number of nodes, links and area contained in the conservation area are given in Figure 3. Additional points to be remembered are as follows:

1. The link number appears on each link,

2. The purpose of showing a directional arrow on the link is to represent it easily in a computer simulation. The direction shown does not necessarily represent the direction of flow through the link. For example, if the velocity and discharge for a particular day through link 20 of Conservation Area 1 are positive, then flow takes place from node 5 to node 12; however, if in the next day both are negative, then flow occurs from node 12 to node 5 (see Figure 2).

3. Solid lines represent hypothetical links (usually in the marshes) whereas dotted lines represent existing canals, channels or ditches.

4. External inputs through existing water control structures are shown by external arrows (e.g. S-5A and S-6).

5. The rationale for selection of a particular type of network for the conservation areas is tied to the water quantity model. Since the water quality model uses the output of the water quantity model, the same network for the water quantity model is used in the quality model in order to maintain uniformity and continuity in these two related models. Furthermore,

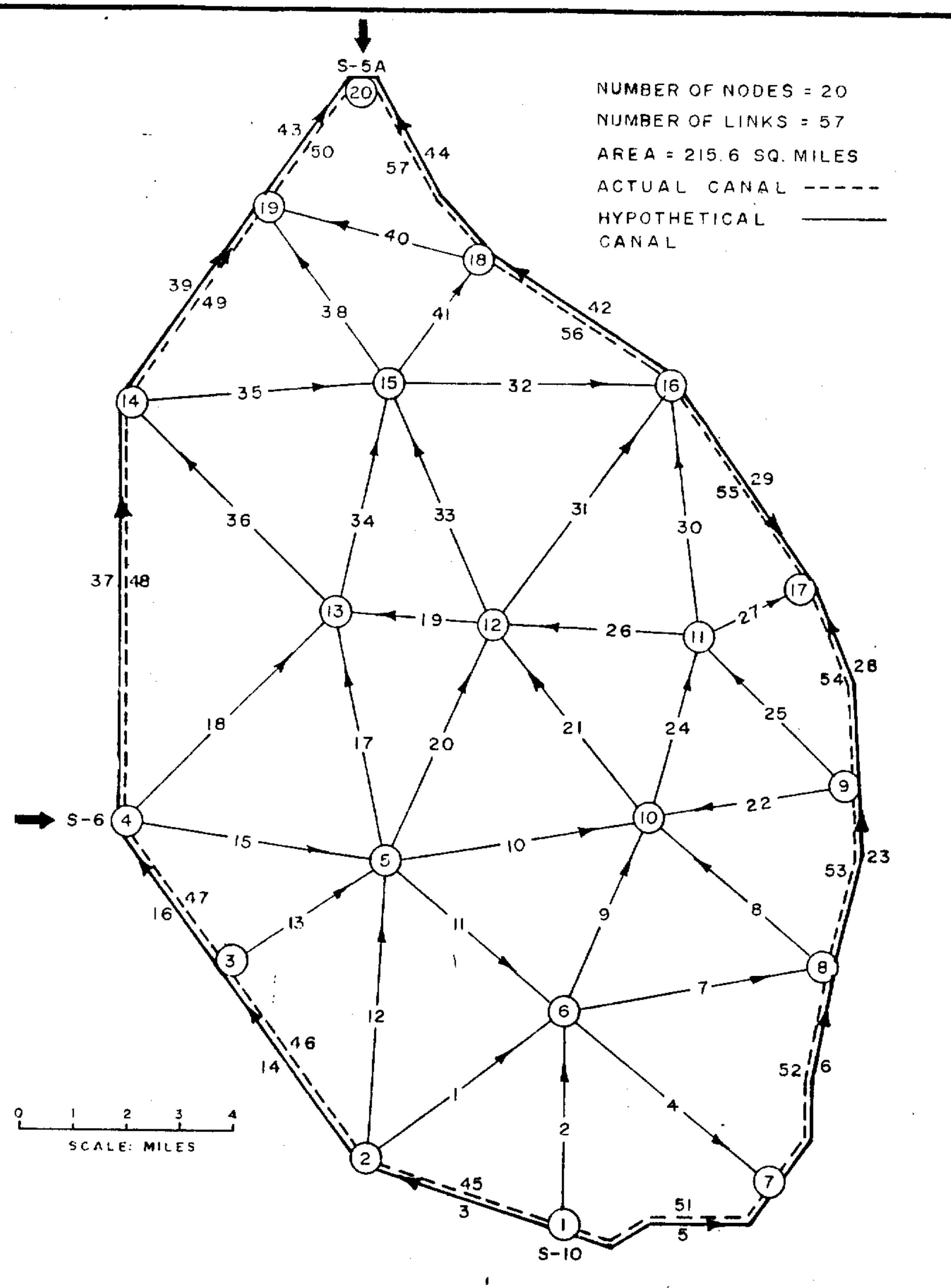
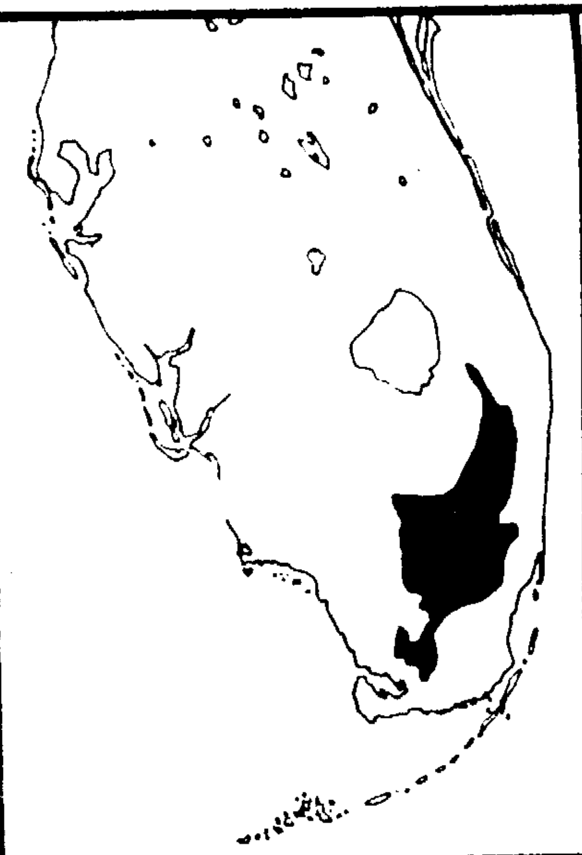


Figure 3 LINK-NODE REPRESENTATION OF CONSERVATION AREA I



Everglades Marshes, Sloughs & Tree Islands

FORMATION

The Everglades was formed as a result of climatic change to a wetter climate, the filling of Lake Okeechobee with fresh water and the seasonal accumulation of rainfall in the shallow bedrock basin underlying the Everglades. Area is formed into a shallow, wide drainage depression draining from Lake Okeechobee and fed by rainfall

GEOLOGY

Holocene sediments of peat, muck, and marl overlying Pleistocene marine and freshwater limestones as well as shelly sands.

SOILS

Primarily organic peats with some marls 3'-9' deep.

VEGETATION

1 White Waterlilies
2 Bladderwort
3 Sedges and Grasses

VEGETATION - continued

4 Saw Grass
5 Dahoon Holly
6 Red Bays
7 Willows

WILDLIFE

Fish, deer, wading birds, aquatic mammals.

MICROCLIMATE

Tree islands experience reduced insolation, windspeed and higher humidity in interiors.

LAND USE SUITABILITY

No agricultural value at present. Good wildlife preservation. Storm water retention.

DYNAMICS

Annual flooding and periodic fires are important in maintaining marshes. Tree islands can be destroyed by severe fires or prolonged flooding

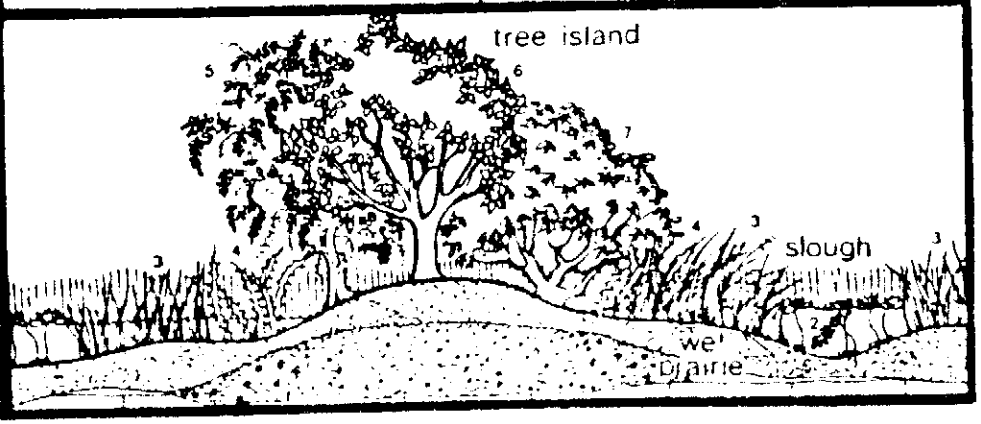


Figure 4. General Features of Conservation Areas of the Florida Everglades (25)

considering the available computer memory and realistic areal coverage, the suitable number of nodes and links are selected for the conservation areas as shown in Figure 2.

6. The area represented by Figure 3 is known as Conservation Area 1 and it is one of three conservation areas of the Florida Everglades. The general formation of these conservation areas along with the description of their geology, soils, vegetation, wildlife, micro climate, land use suitability and dynamics are given in Figure 4. As indicated in Figure 4, Area 1 is an ecologically active area with thousands of tree islands in addition to the sawgrass and slough aquatics. As shown in Figure 3, it is encircled by levees and input water through S-5A flows southward usually passing through enclosed channels, with some water going into Conservation Area 1 depending upon the relative water stages. Although the water quality model was developed for simulating the water quality as water passes through all three conservation areas, this paper presents the results of the model for Conservation Area 1.

FORMULATIONS

For a given link node representation of water system, the water quality model is primarily geared to the following basic continuity equation (3).

$$\frac{\Delta C_j}{\Delta t} = - \frac{\sum_{i=1}^{N} Q_i V_i \frac{\Delta C_{i,j}}{\Delta X_i}}{\sum_{i=1}^{N} Q_i} - K C_j \pm S_j$$

where

C_j = concentration at node j, (mg/litre)

ΔC_j = change in concentration at node j, (mg/litre),

Δt = time, (number of seconds in unit time step),

V_i = velocity of entering link, (ft/sec),

Q_i = discharge of entering link, (cu.ft./sec),

ΔX = length of entering reach, (ft.),

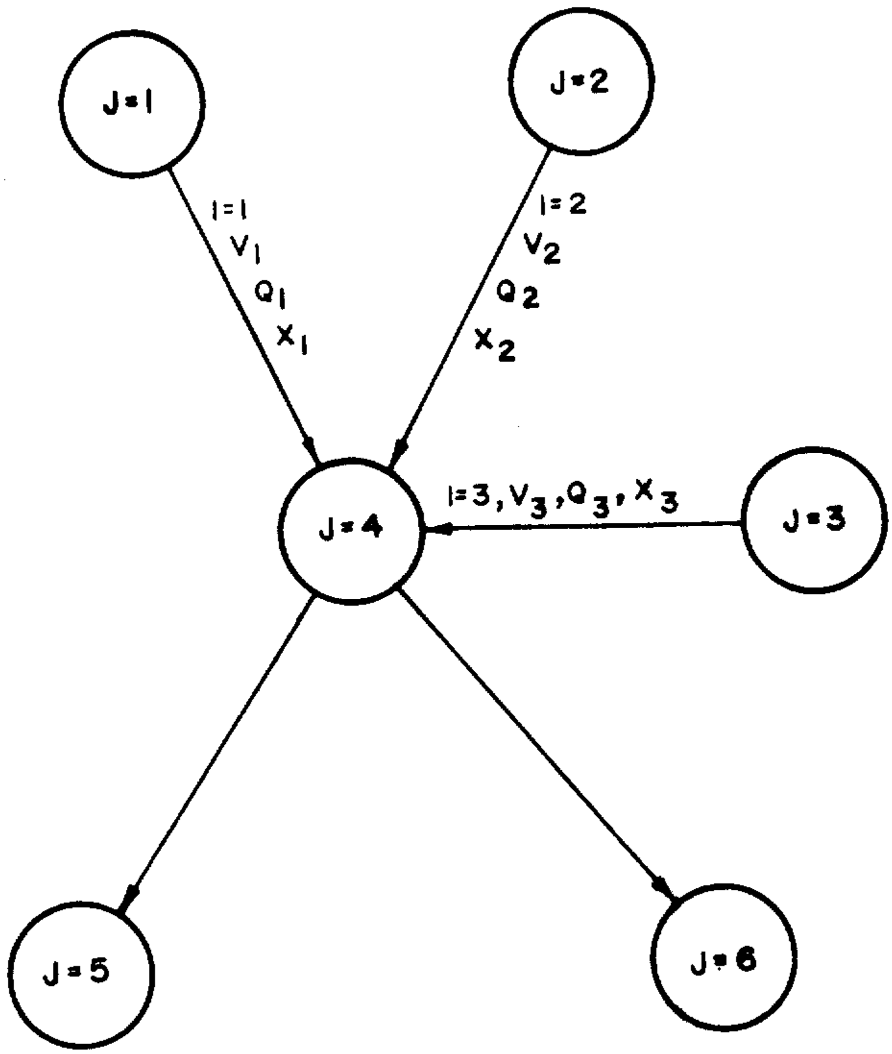


Figure 3 ILLUSTRATIVE NODE-LINK SYSTEM TO EXPLAIN THE CONTINUITY EXPRESSION OF THE WATER QUALITY MODEL

K = decay coefficient

S_j = source at node j (when +ve)

S_j = sink at node j (when -ve)

N = total number of incoming links at a given node J

i = incoming link

$\Delta C_{i,j}$ = concentration gradient in the incoming link at node j

= (concentration at node j) - (concentration of upstream node i).

To understand the working of this basic continuity equation, an illustrative node-link system is presented in Figure 5. There are six nodes with node No. 4 as a central node where change in concentration during Δt time is sought. As shown in Figure 5, there are three incoming links (which are only to be considered) and two outgoing links. In addition, the velocities (V_1, V_2 and V_3), discharges (Q_1, Q_2 and Q_3) and distances (X_1, X_2 and X_3) corresponding to three incoming links are also given. Similarly, concentrations at nodes 1, 2 and 3 (C_1, C_2 and C_3) are also required. Using such information, equation (1) can be expanded for illustrative node-link system as shown below:

$$\frac{\Delta C_4}{\Delta t} = - \frac{[Q_1 V_1 \frac{\Delta C_1}{X_1} + Q_2 V_2 \frac{\Delta C_2}{X_2} + Q_3 V_3 \frac{\Delta C_3}{X_3}]}{Q_1 + Q_2 + Q_3} - KC_4$$

where

ΔC_4 = change in concentration at node 4

= $C_4(t+1) - C_4(t)$

C_4 = $C_4(t)$

ΔC_1 = $C_4(t) - C_1(t)$

ΔC_2 = $C_4(t) - C_2(t)$

ΔC_3 = $C_4(t) - C_3(t)$

$C_4(t)$ = concentration at node 4 of previous time step

$C_1(t)$ = concentration at node 1 of previous time step

$C_2(t)$ = concentration of current time step at node 4

K = decay coefficient

NATURE OF THE WATER QUALITY MODEL

1. The formulation around which the whole framework of the water quality model is built up is a simple and basic finite difference version of double weighted procedures in which the concentration gradient along a link is first weighted according to incoming flows and then weighted according to distance traveled along the link by inflow during a unit time step for advective transport.

2. In accordance with the generally accepted definition of the steady and unsteady state, the water quality model is based on a simple form of unsteady formulation and thus the model can estimate dynamic type water quality behavior of the water systems in light of physical, chemical and biological factors.

3. The water quality model based on the basic continuity equation includes advective transport (first term on the right hand side of Equation 1), decay process (second term of Equation 1) and combination of sources or sinks (third term of Equation 1). For example, external water quality input through rainwater or increase in concentration due to evaporation can be included in the model through the third term of sources and sinks.

4. The manner in which the receiving water quality part of the comprehensive SWIM model was developed is applicable to water conservation areas, as well as to urban, rural and other types of water systems. Furthermore, it can handle conservative (such as chlorides) and nonconservative parameters (such as dissolved nitrogen and phosphorus).

5. There is no restriction of any kind of stability criteria because the outcome of the model is not based on an iterative procedure. However, since the advective term is the double weighted average of flows and distance, time steps should be such that $\frac{(V)(\Delta t)}{X}$ is always less than, or equal to one. This puts some restriction on the model,although this restriction can be easily surmounted in several ways.

6. Computational time is relatively small as compared to that required for the water-quantity model.

7. It can be seen from Equation 1 that the receiving water quality model requires a set of velocities and discharges (for all the links) which are generated in the receiving water quantity part of the SWIM model. Thus, it becomes very essential to have the output of the receiving water quantity model available as one of the major inputs to the water quality model.

COMPUTATIONAL PROCEDURE

The basic computational procedure involved in the application of the water quality model to the conservation areas is outlined in Figure 6.

As a starting step, Conservation Area 1 is considered first. With the selected link and node representation of the conservation area (as shown in Figure 3), daily velocities and discharges for the full year of 1974 (as transferred from the water quantity model) are stored on a tape, in addition to the other necessary information such as initial concentrations of chlorides for the twenty nodes. With such information, the continuity equation of the water quality model is then used to estimate daily concentration of chlorides at the twenty nodes for the 1974 historical case. To examine the adequacy of the simulated concentrations, generated concentrations are compared with the limited available historical water quality data set. These comparisons also provide the direction in which the model should be further improved. After completion of such calibration process for Conservation Area 1, Conservation Area 2A and 3A are then handled in the same manner, except that the generated concentration and outflows at node 1 of Conservation Area 1 and 2A are then considered as input to Conservation Area 2A and 3A, respectively. In this manner, three conservation areas are integrated in the model as they are connected in reality in terms of hydraulic movement and chemical transport,

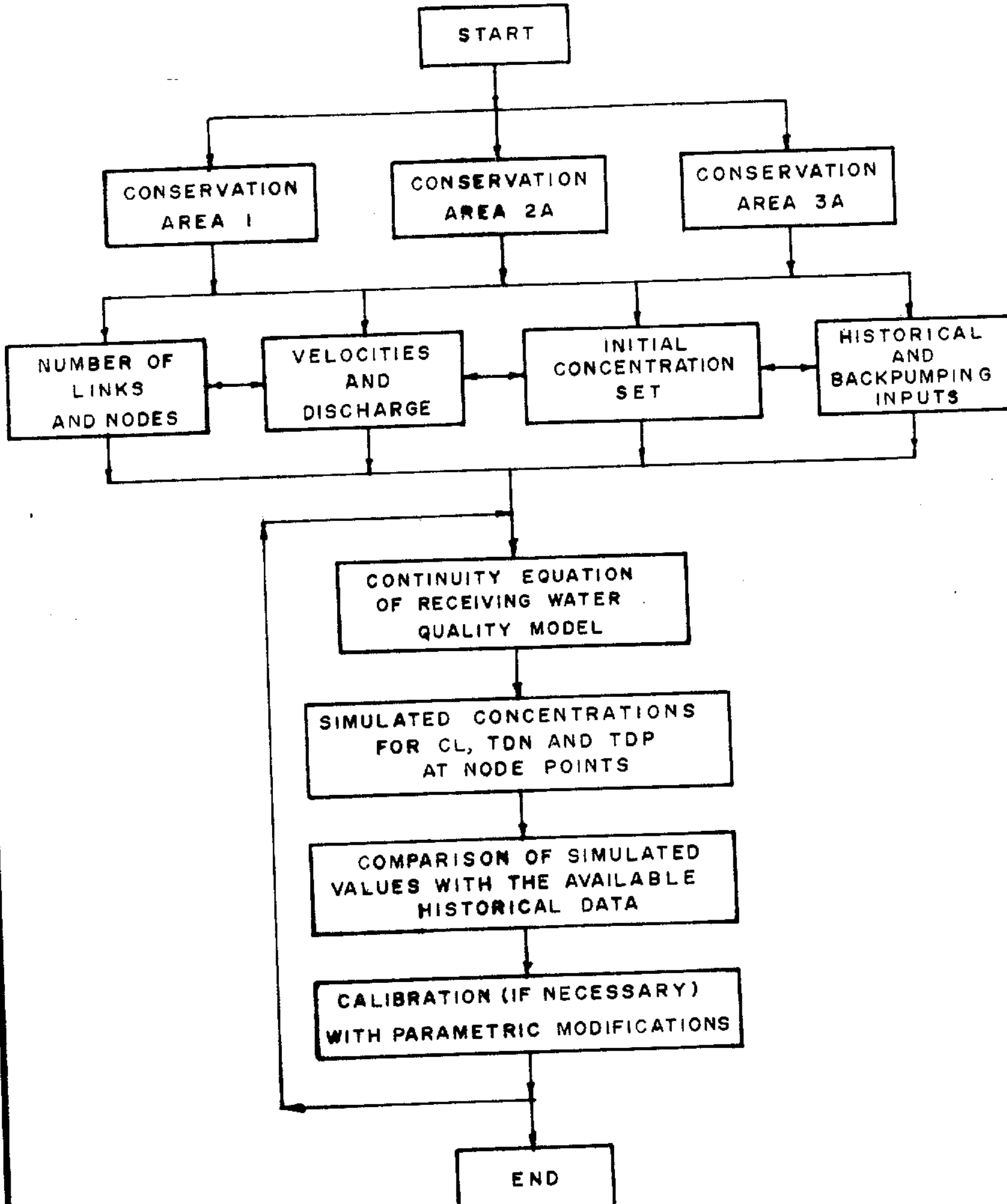


Figure 4 BASIC PROCEDURE OF THE WATER QUALITY MODEL

although the model is demonstrated only for Conservation Area 1 in this paper.

In spite of the relative simplicity of the basic equation of the water quality model, an example for a specific node is added as shown in Figure 5 to provide additional insight into various aspects of the numerical computations. The notations used in the example are as follows:

Q	Discharge in cfs
N	Number of incoming links i
V	Velocity in ft/sec
C_{up}	Initial concentration of upstream node (mg/litre),
C_j	Initial concentration at node j (mg/litre)
Length	Length of the link in ft

$$GRAD = \frac{(Q)(V)(C_j - C_{up})}{Length} \Delta t$$

$$TOTQ = \sum_{i=1}^{N} Q_i$$

$$TOTDEL = \sum_{i=1}^{N} GRAD$$

XTOT = Total change in concentration in a unit time step, (mg/litre)

$$= \frac{TOTDEL}{TOTQ}$$

XCON = Final concentration as a result of hydraulic transport, (mg/litre)

ASSUMPTIONS

1. With the considerations of the type of flow regime in conservation areas, the phenomenon of diffusion seems to have insignificant contribution in changing the concentration of selected water quality parameters. Thus, the diffusion term in the basic continuity equation is assumed to be negligible.

2. The basic continuity equation considers only incoming links to estimate the

FIGURE 7. .

A NUMERICAL EXAMPLE

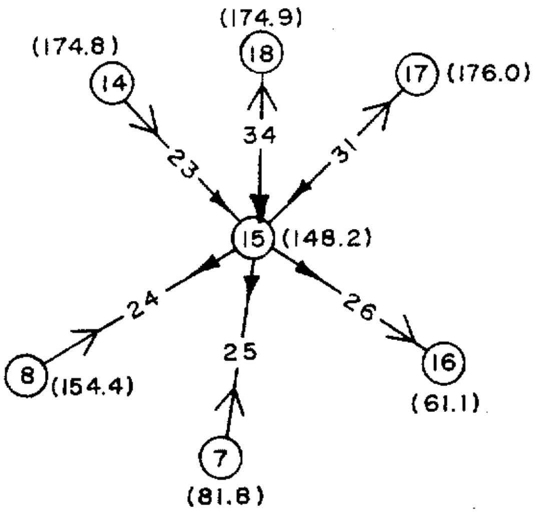
CONSERVATION AREA: CA-2A

DATE: Jan. 25, 1974

NODE # 15

TIME PERIOD: 1st 2 hours

CHEMICAL PARAMETER: CL



→ Conventional representation of a link

→ Flow direction

------ Channel link

Note: Numbers in the brackets represent concentrations at a given node for a previous time step.

LINKS	C_j (Node #)	C_{up}	LENGTH	Q	V	GRAD	REMARKS
23	148.2	174.8	19126	21.35740	.00952	-26.6	Incoming Link
24	148.2	148.2	27958	-196.24736	-.01919	-	Outgoing Link
25	148.2	148.2	26005	-14.89673	-.00659	-	Outgoing Link
26	148.2	148.2	20436	23.34822	.00722	-	Outgoing Link
31	148.2	176.0	16739	-17.80044	-.00970	-27.8	Incoming Link
34	148.2	174.9	13039	-82.74562	-.02063	-26.7	Incoming Link

TOTDEL = 29.2683674
TOTQ = 121.90346
XTOT = .2400946

$$XCON = C_j + XTOT = 148.2 + 0.24 = 148.44$$

Note: Only Incoming Links are considered in the computations for the reasons stated in the "assumption" section.

concentration change at a given node. In this technique, it is assumed that the water quality contribution of the incoming links is well mixed and the resultant concentration is passed on through the outgoing links.

3. The resultant concentration at an inlet node is assumed to be a weighted average of incoming concentration (through the controlling structure) and the computed concentrations in terms of their volumes expressed in depth units.

4. Channel nodes are assumed to be points in the main channel and thus, direct water quality contribution from rain to the channel nodes are assumed to be negligible.

5. In any period of the year (usually in the wet period), if the velocity in any link is observed to be high enough to pass the link length in a unit time step, then concentration change contributed by the advective term is assumed to be a weighted average of inflows at that node.

6. Although quantity contribution of rainfall is included in velocities and discharges of the water quantity model, the rainfall water quality inputs are included by assuming the physical mixing of surface water and rainwater. An adequate parameter to take the weighted average of rainwater quality and surface water quality is assumed to be a depth in inches.

7. The chloride concentration in the rainwater is assumed to be 5 mg/litre based on available data (4).

INPUT DATA REQUIREMENTS

As shown in Figure 4, different kinds of input data sets are required in the water quality model. These input data sets are related to;

1. Number of nodes and links considered in the network representation of the conservation areas as shown in Figure 3.

2. Starting concentrations at every node of the conservation areas .

3. Velocities and discharges for all the links and depth, and area for each of the twenty nodes.

4. Historical loading (i.e. concentration and discharge through the controlling structures) to the conservation areas.

5. Backpumped loading and the point at which the backpumped inputs are delivered in the conservation areas.

RESULTS

Within a framework of input data, assumptions, formulations and simplifications as presented earlier, the water quality model provides output for various conditions. The nature of these different sets of output is outlined in Figure 8. As shown in Figure 8, the water quality model output is generated for the following cases:

1. Historical case of 1974,

2. Four years (1968, 1969, 1970 and 1971) including wet and dry water years of 1968-1969 and 1970-1971.

3. Four years (1968, 1969, 1970 and 1971) including wet and dry water years of 1968-1969 and 1970-1971 for each of the feasible backpumping schemes.

Although the water quality model is designed to simulate daily concentrations of chlorides, total nitrogen (TN) and total phosphorus (TP) at all the twenty nodes of the conservation areas, only chloride results for Conservation Area 1 are presented in this paper.

CALIBRATION RESULTS

As an essential step of any modeling effort, the water quality model is calibrated in light of the available historical data set (6, 7). To do this, the output of the model is compared with the observed field data for the conservation area. Such comparisons are provided in Table 1 for Conservation

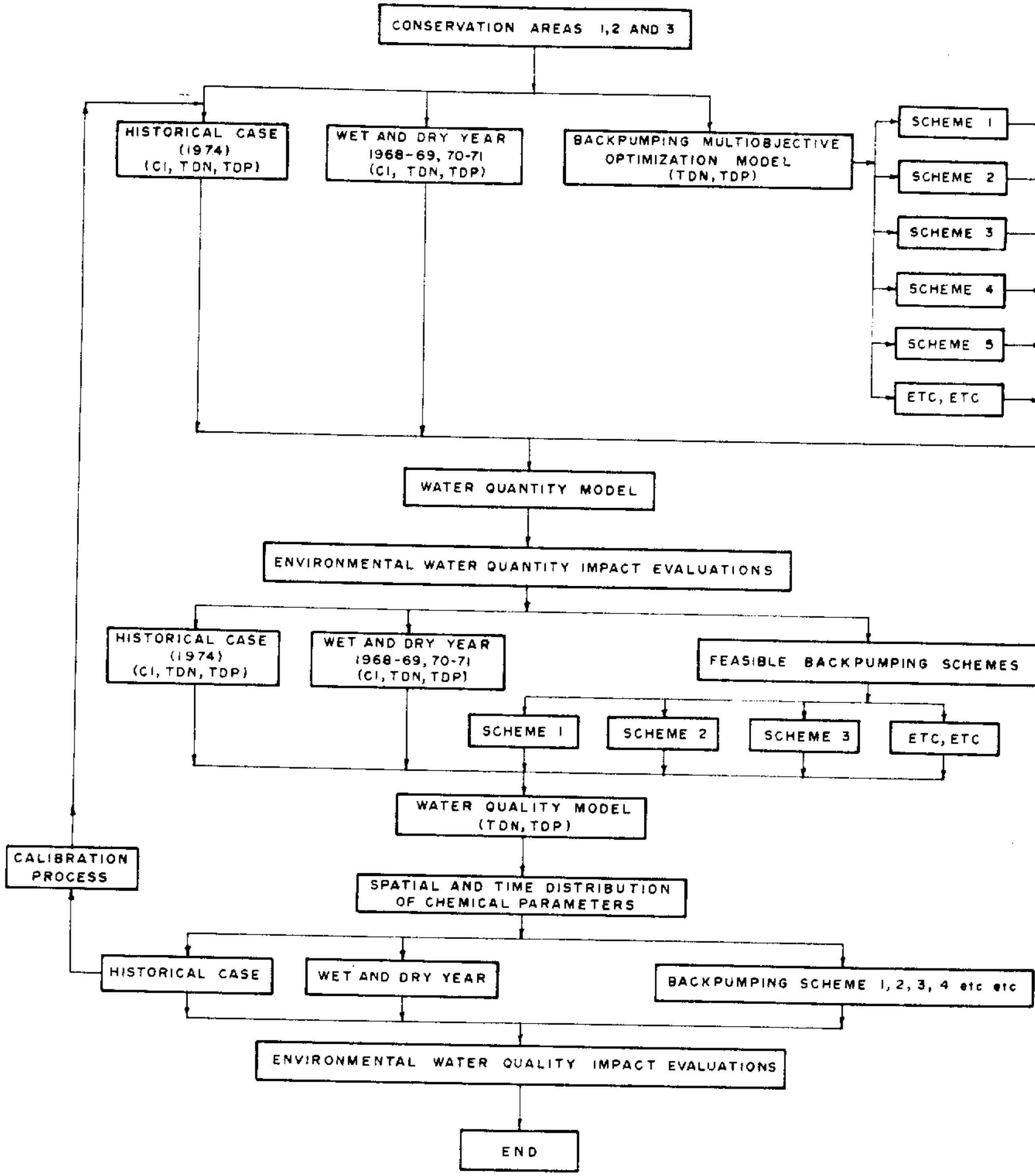


Figure 6. FLOWCHART OF THE MODELING PROCEDURE FOR FACILITATING THE WATER QUALITY — QUANTITY EVALUATION OF BACKPUMPING ALTERNATIVES

Table 1. Comparison of Simulated and Recorded Values for Chlorides for Conservation Area 1 for the Year 1974.

Date		NODE NUMBERS				
	1	5	13	12	11	15
Jan. 29, 1974	a) 159.9 b) Cl = 169	44 Cl = 40	30.8 Cl = 28	20.3 Cl = 28	22.1 Cl = 16	
Jan. 31, 1974	a) 159.3 b) Cl = 166.6	45.3 40	31.6 28	20.4 28	22.1 16	
Feb. 25, 1974	a) 166.9 b) Cl = 185.7					
Mar. 12, 1974 Mar. 13, 1974	a) 164.9 b) Cl = 196.6	45.15 45	31.1 35	20.5 35	21.15 25	46.97(Node 5+6+10) 32(Apr. 16, 1974)
Mar. 27, 1974	a) 161.1 b) Cl = 202.2				145.2(Node 14) Cl = 199.2	141.6(Node 19) Cl = 186.9
Dec. 13, 1974	a) b)	89.4 69.7	38.6 43.3	31.8 39.3	47.2 77.8	38.6 33.3

a) Simulated chloride values
b) Historical chloride data

Area 1. The comparative Table 1 along with similar tables for Conservation Areas 2 and 3 given in Reference No. 13 indicate that the model is capable of generating the chloride concentrations which are in reasonable agreement with the observed field data for the year 1974. The inclusion of rainfall quality in the computations for Conservation Area 1 appears to be very essential since the concentrations in the interior marsh nodes tend to build up in the wet period when some movement of water into the marsh occurs under the high concentration gradients.

BACKPUMPING RESULTS

After calibration runs, the water quality model is used to simulate the chloride concentrations for four years (1968-71) including a wet year (1968) and a dry year (1971) for Conservation Area 1 using the same historical inputs as observed in 1974. After a reasonable response of the model to wet and dry conditions, the model is then used for the hydraulic conditions envisioned in the backpumping schemes. Thus, the chloride time distribution (also called pollutograph) at every node of the conservation areas are estimated for four years for the backpumping schemes. All these results are compiled in Reference No. 12. Because of the limited length of the paper, the results at representative nodes are depicted in Figures 9, 10, 11, 12 and 13. To further facilitate the comparisons of these curves, Table 2 provides the areas under various curves.

DISCUSSION

PARAMETRIC SENSITIVITY ANALYSIS: As far as the chloride runs are concerned, the parametric analyses were performed on the unit time step to examine its sensitivity on the final result. In such analysis, runs were made using time step of 24 hrs., 12 hrs., 6 hrs., 4 hrs., 3 hrs., 2 hrs., and 1 hr. The water quality model based on the computations at every hour produced conceptually the most accurate results, but it took 45 minutes to generate one year of chloride concentrations. For unit time steps of 2 hrs., 3 hrs., 4 hrs., 6 hrs., 12 hrs.,

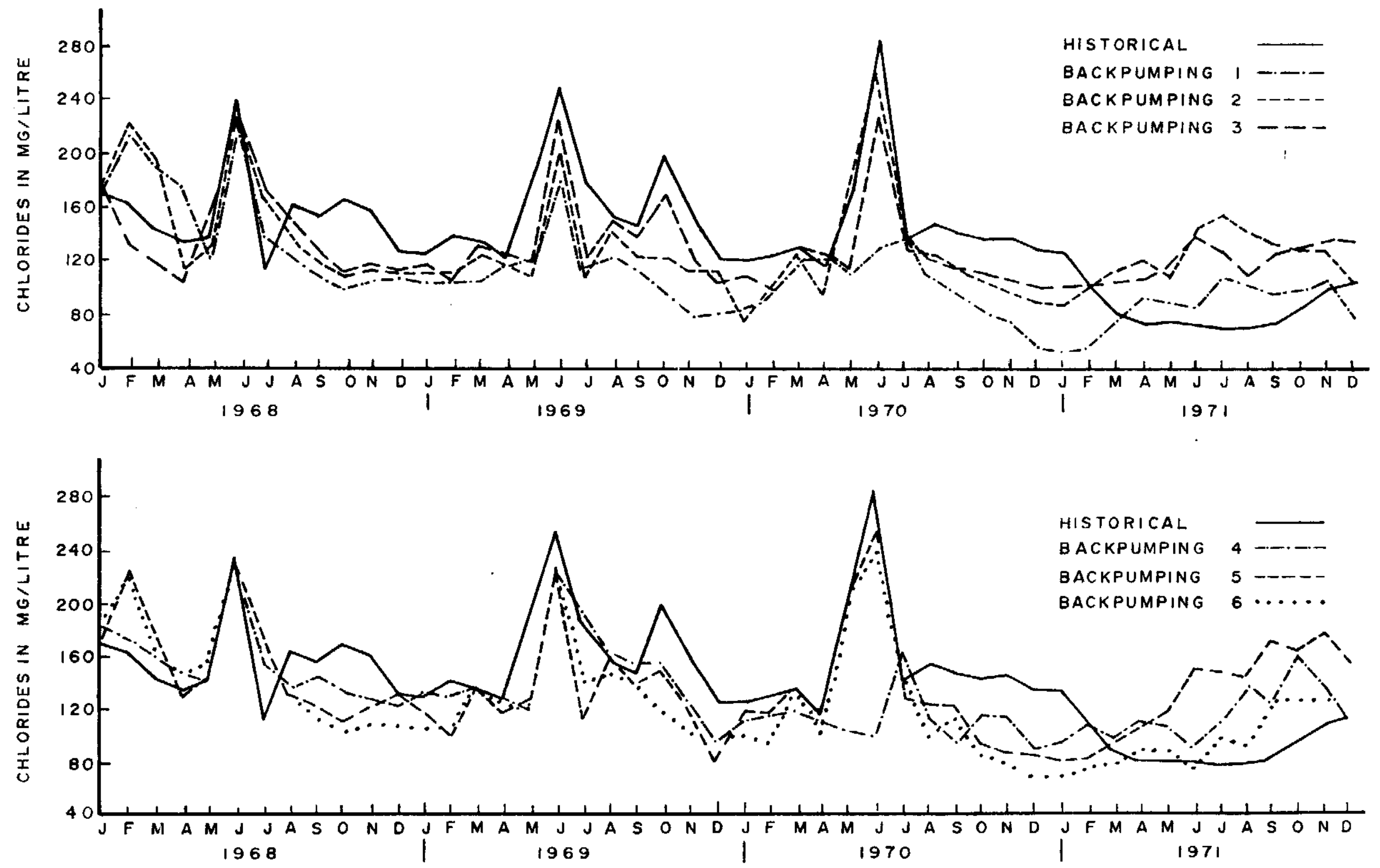


Figure 9. POLLUTOGRAPH OF CHLORIDES FOR NODE 1 OF CONSERVATION AREA 1

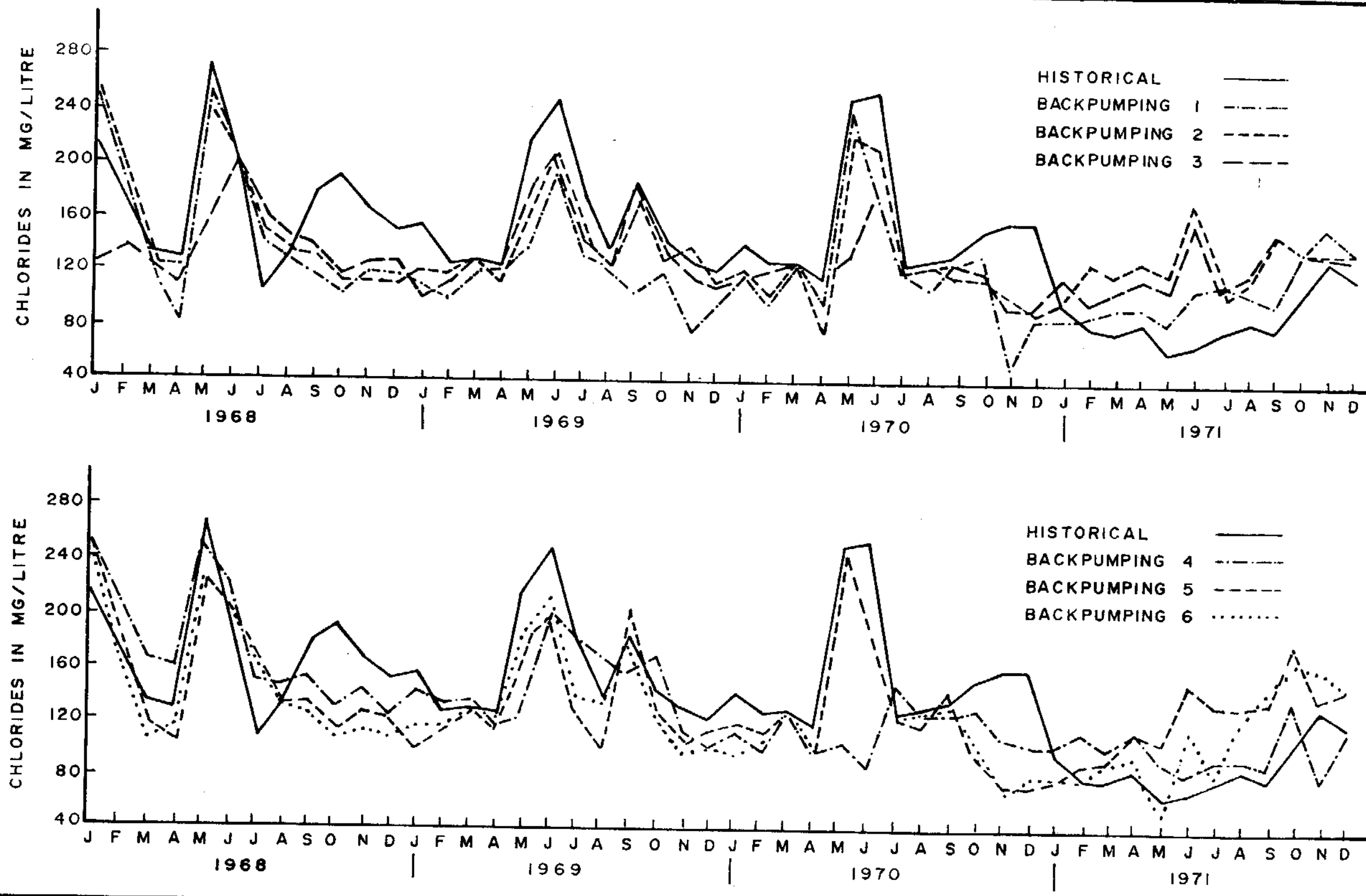


Figure 10. POLLUTOGRAPH OF CHLORIDES FOR NODE 4 OF CONSERVATION AREA I

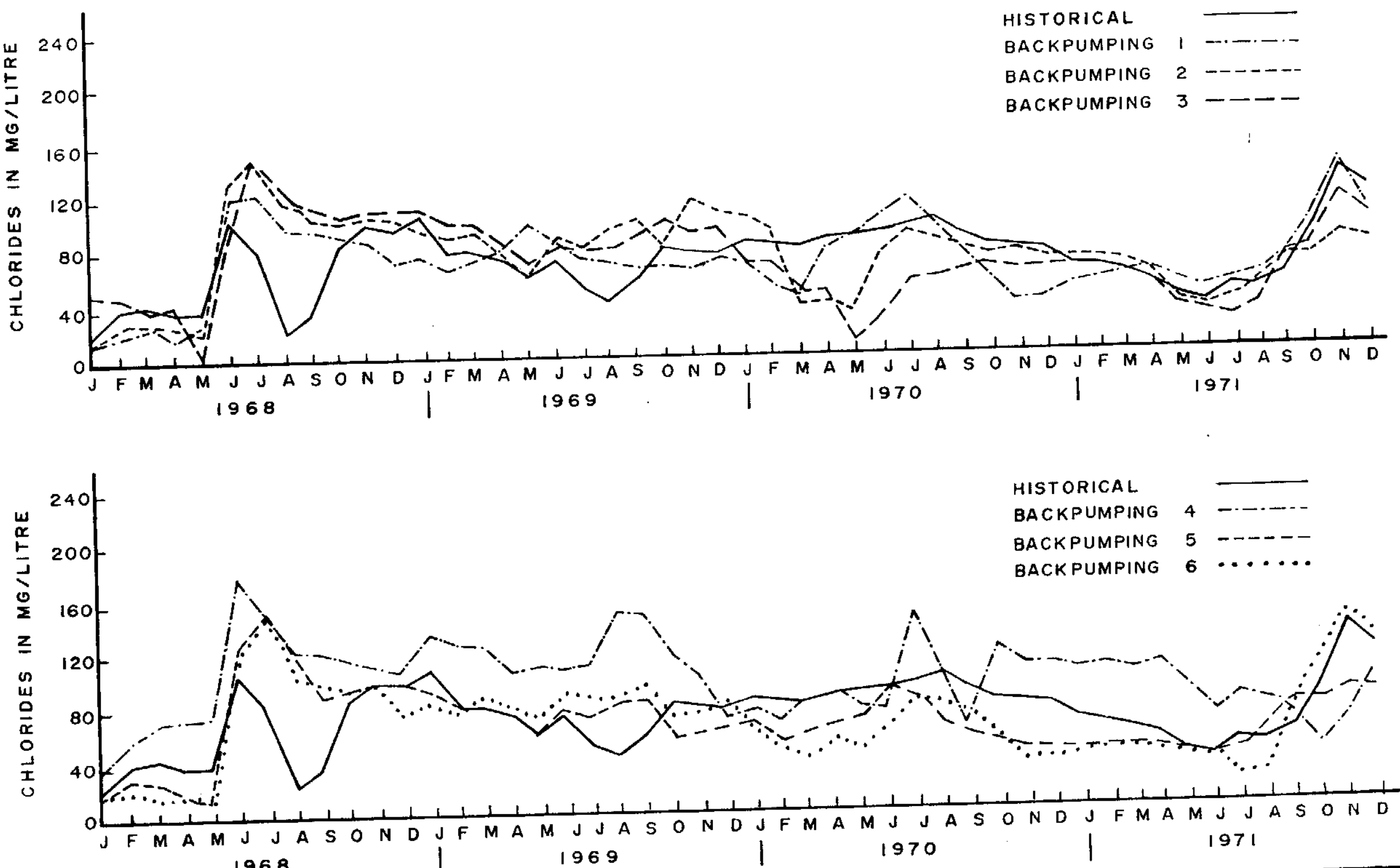


Figure 11. POLLUTOGRAPH OF CHLORIDES FOR NODE 5 OF CONSERVATION AREA I

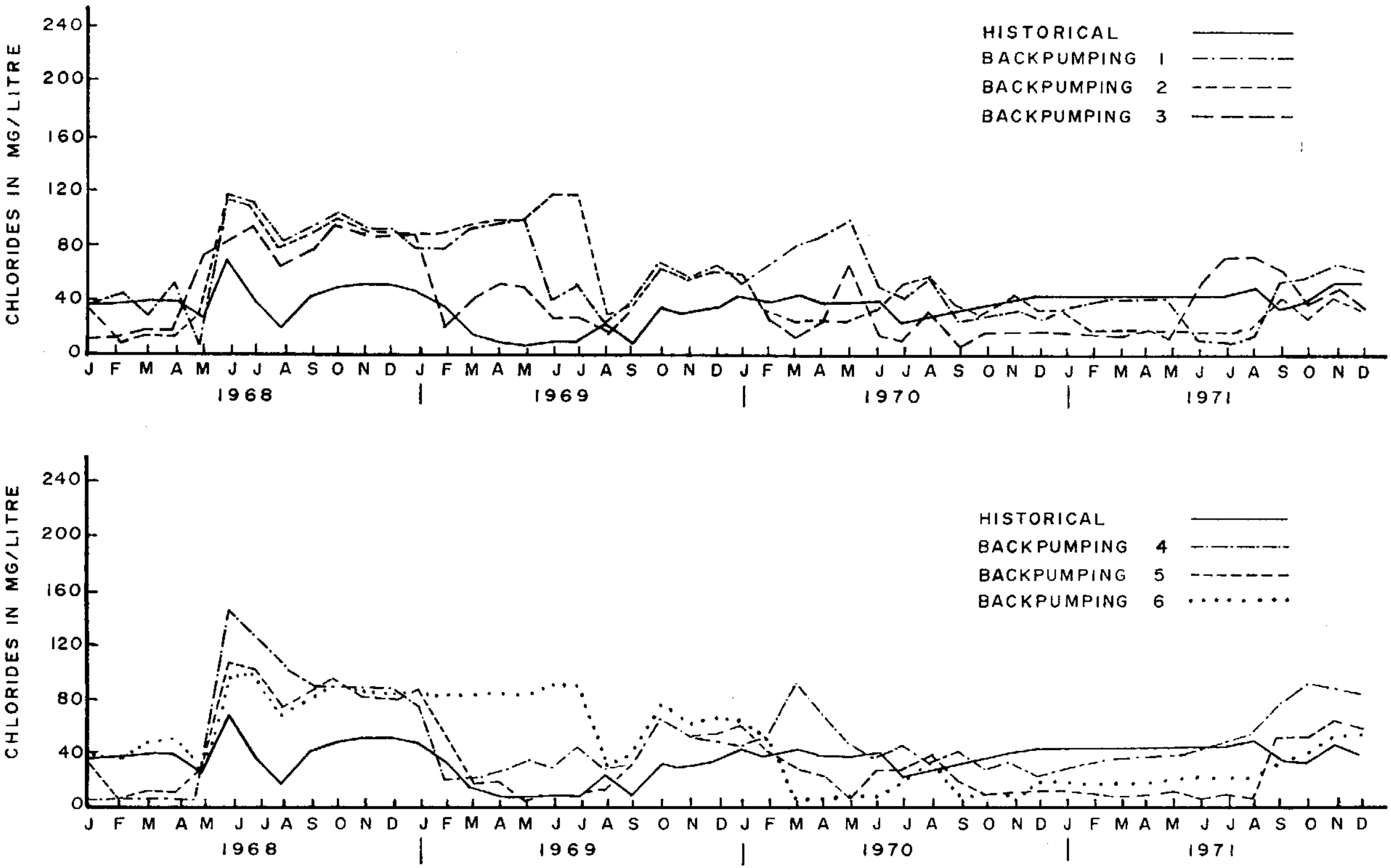


Figure 12. POLLUTOGRAPH OF CHLORIDES FOR NODE 15 OF CONSERVATION AREA 1

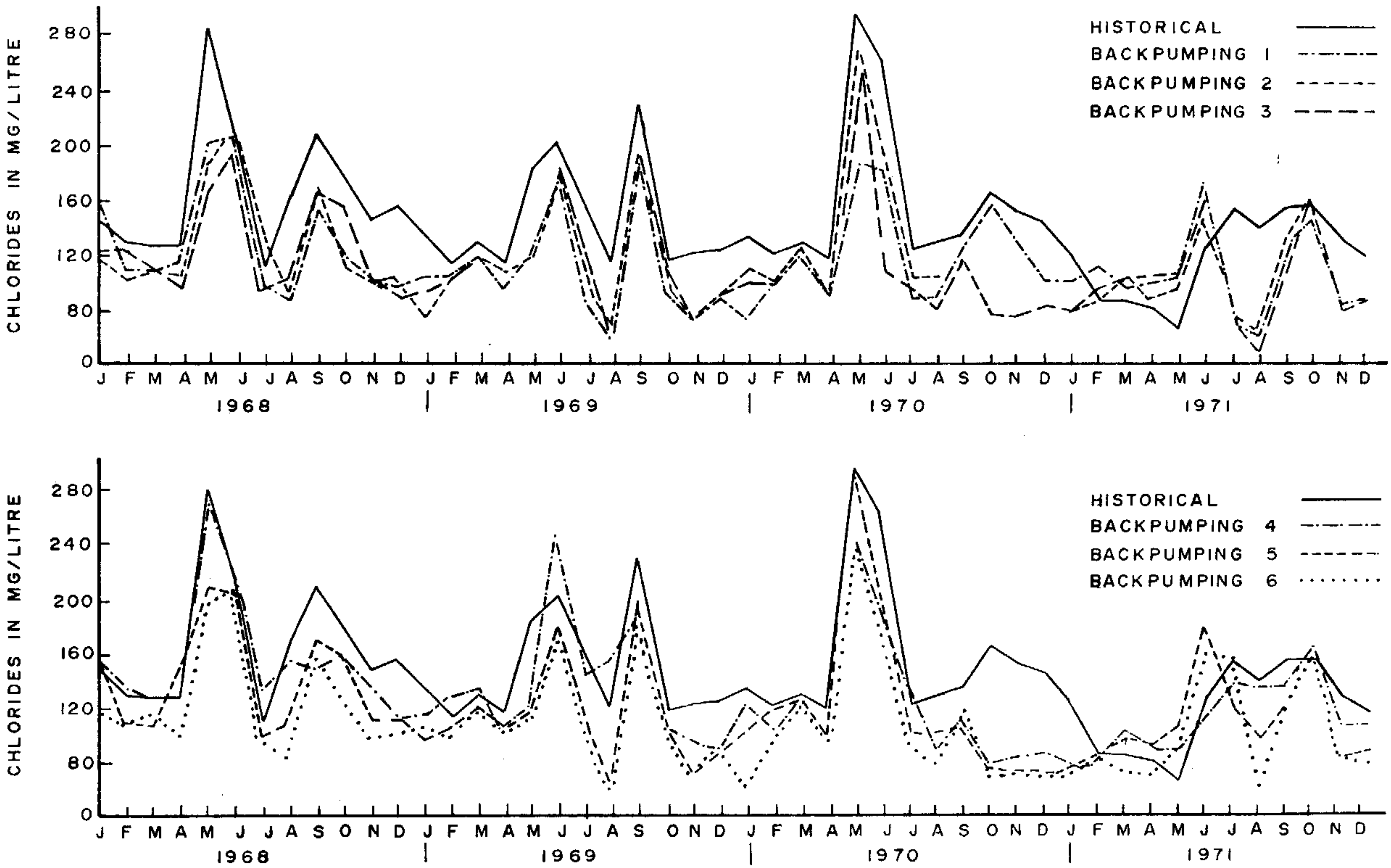


Figure 13. POLLUTOGRAPH OF CHLORIDES FOR NODE 17 OF CONSERVATION AREA 1

Cases	NODES																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Historical	57.35	58.53	60.99	62.12	41.25	38.86	58.69	58.95	62.30	20.18	22.15	13.68	14.19	62.17	20.38	63.19	63.20	65.87	65.04	69.77
B.P. #1	42.35	45.99	49.62	51.38	41.22	35.47	44.43	44.09	43.99	19.71	22.72	20.58	23.83	56.03	33.22	42.92	44.84	41.97	55.90	56.88
B.P. #2	54.05	56.19	59.16	58.67	44.26	36.59	51.50	44.24	44.22	21.76	21.53	21.04	23.08	61.62	29.53	44.99	45.31	40.59	60.61	61.54
B.P. #3	53.01	55.29	56.58	55.97	41.49	36.32	49.26	45.27	42.76	19.37	21.16	17.59	20.59	55.18	24.06	45.51	43.62	38.45	56.86	59.35
B.P. #4	51.29	50.25	53.75	56.05	57.74	52.31	52.10	51.69	53.20	30.37	27.74	24.17	30.93	61.78	29.97	56.38	53.92	57.06	63.39	65.27
B.P. #5	54.67	55.84	56.30	56.80	38.57	42.52	51.54	50.67	48.34	24.40	27.53	17.50	22.72	57.26	20.40	45.70	47.54	42.86	55.68	56.74
B.P. #6	47.38	50.26	51.90	54.13	38.58	31.59	45.84	41.64	40.56	18.05	19.55	16.70	20.18	54.63	26.51	42.55	42.49	38.54	55.58	57.35

TABLE 2. AREAS (IN INCHES) UNDER VARIOUS OUTPUT CHLORIDE CURVES FOR DIFFERENT BACKPUMPING SCHEMES IN CONSERVATION AREA 1.

and 24 hrs., the water quality model took 20 minutes, 15 minutes, 12 minutes, 10 minutes, 8 minutes, and 6 minutes, respectively. Although a time step of 24 hours provided the results which were significantly different than the most accurate results obtained for a unit step of 1 hour, comparisons of these numbers indicate clearly the necessity of trade-off considerations in selecting the optimum unit time step. Considering realistic computer time requirements without sacrificing the accuracy of the results, a time step of 2 hours was finally selected.

COMPUTER PROGRAM AND TIME REQUIREMENTS: All the computational steps of the water quality model are included in the computer program which is designed for the District's CDC 3100 computer facility. The complete listing of such a program is given in Reference No. 13. The estimated computer time requirements for various conditions are given in Table 3. It should be noted that the estimates given in Table 3 are for

a. A Chloride parameter,

b. Three conservation areas, and

c. Unit time step of 2 hours.

ANALYSIS OF THE OUTPUT IN EVALUATING BACKPUMPING SCHEMES

The hydraulic conditions in terms of the velocities and discharges of the links, depths at node points and inlet discharges as computed in the water quantity model are different for various backpumping schemes. Using these different sets of spatial and time distributions of chlorides, which can be graphically compared with historical distribution (as shown in Figures 9, 10, 11, 12 and 13) to assess quantitatively the water quality impact (adverse, status quo or beneficial) of these backpumping schemes. While examining the polluto-

Table 3. Computer time requirements of the water quality planning model for different conditions.

Case No.	Description	Computer Time
1	Historical Case of 1974	1 hour
2	Selected combination for a historical case of 1974	1 hour 40 min.
3	To create disk files of the useful output of the water quantity model	1 hour 30 min.
4	Four years including wet and dry water year of 68-69 and 70-71	6 hrs. 40 min.
5	To create disk files and to run the model for four years for a backpumping scheme	8 hrs. 10 min.

graphs at various nodes of Conservation Area 1, the following observations were made:

1. For channel nodes (i.e. Node Nos. 1, 2, 3, 4, 7, 8, 9, 14, 16, 17, 18, 19, and 20) the historical pollutograph is consequently higher than pollutographs of backpumping schemes. This is further substantiated by the values of Table 1 for these nodes.

2. For marsh nodes (i.e. Nos. 5, 6, 10, 11, 12, 13 and 15), the historical pollutograph is surpassed by some pollutographs of backpumping schemes.

3. Although an increase in chloride concentrations is observed for two or three nodes for backpumping conditions, a similar increase also occurred historically for these nodes.

Considering these observations coupled with the information of Figures 7, 8, 9, 10 and 11 and Table 1 on the relative starting, end concentrations and relative chloride buildup for the years of 1968-70, these preliminary results indicate that the backpumping schemes seem to have a status quo type water quality. Currently a water quality sampling program of the District is underway to measure water quality parameters at the node points four times a year. Timing of these sampling trips is designed to obtain the water quality information in dry and wet periods. With such a broad set of data, the model is expected to be calibrated more precisely and its realistic response to wet and dry conditions can be better assessed in light of backpumping inputs. It is to be noted that a preliminary conclusion may be proved or disproved in further analyses when a broader field data set is available. Furthermore, the emphasis of the paper is on the methodology of using the model output in assessing the possible impact as demonstrated earlier rather than on the derived specific conclusion which is preliminary at this time.

CONCLUSIONS

Within a reasonable set of assumptions, mathematical simplifications and input information, the framework of the water quality model was developed to simulate daily chloride concentrations in the conservation areas as the water moves from Conservation Areas 1 to 3 through the integrated system of channels, marshes and controlling gate structures.

After a calibration of the model with the field data of 1974, the sensitivity of the model was further tested for the historical case of four years (1968-71) including wet and dry years. The water quality model was then extended to predict the chloride concentrations under the expected future hydraulic and hydrologic regimes of the viable backpumping schemes. The manner in which the preliminary results of the model can be utilized in assessing the relative water quality impact of backpumping schemes was demonstrated. Such assessment can be a very useful input in the continuing efforts of the District.

ACKNOWLEDGEMENTS

Since the development of the water quality planning model for the conservation areas constituted an interdisciplinary effort, several professionals within and outside the District were helpful. Dr. Wayne Huber, Associate Professor in the Environmental Sciences Department of the University of Florida is gratefully acknowledged for providing initially the valuable insights into the application of the receiving water quality part of the Stormwater Management Model to the Conservation Areas. We greatly appreciate the constant willingness, assistance and advice of Mr. Peter Rhoads, Director of the Resource Planning Department, Mr. Robert L. Hamrick, Assistant to the Department Director and Mr. Stanley Winn, Water Resources Division Director in providing valuable suggestions for developing the model to the extent possible. A District tream of geologists, chemists and biologists including Dr. Pat Gleason, Messrs. Steve Davis, Peter Stone, John Lutz, Fred Davis and Walter Dineen have provided valuable water quality field data of various kinds in addition to the practical assistance in describing the reality of water quality interactions in the conservation areas. Mr. Donald Paich provided computer programming services to run the model on the District's CDC 3100 computer. Finally, acknowledgements are also due to the staff members of the South Florida Water Management District who assisted directly or indirectly in developing the water quality planning model in its current form.

NOTATIONS

C	Concentration of chemical parameter
ΔC_j	Change in concentration at junction j
V	Velocity in ft/sec
ΔX_i	Length of the link i
K	Decay coefficient
S	Sources of sinks
j	Junction number or node number
Q	Discharge in cfs
i	Entering reach
TDN	Concentration of total dissolved nitrogen (mg/litre)
Cl	Chloride concentration, (mg/litre)
TDP	Concentration of total dissolved phosphorus (mg/litre)
X	Distance
t	Time
A_x	Cross-sectional area
D_L	Dispersion coefficient
U	Stream velocity
A	Algal biomass concentration
μ	Local specific growth rate of algae
ρ	Local respiration rate of algae
σ_1	Local settling rate for algae
D	Average stream depth
α_1	The fraction of respired algal biomass that is phosphorus
α_2	The fraction of algal biomass
α_3	The rate of oxygen production per unit of algae (photosynthesis) (This coefficient is used in the equation for dissolved oxygen)
α_4	The rate of oxygen uptake per unit of algae respired,

NOTATIONS (continued)

β_1	Rate constant for the biological oxidation of ammonia nitrogen
β_2	Rate constant for the oxidation of nitrite nitrogen
σ_2	Benthos source rate for phosphorus
K_1	Rate of decay of carbonaceous BOD
K_3	Rate of loss of carbonaceous BOD due to settling
L_1	Concentration of carbonaceous BOD
L_2	Benthic oxygen demand
K_4	Constant Benthic uptake
α_5	Rate of oxygen uptake per unit of ammonia oxidation
α_6	Rate of oxygen uptake per unit of nitrite nitrogen oxidation
K_2	Aeration rate
K_5	Coliform die-off rate
K_r	Radioactive decay rate
Δ_t	Unit time step

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