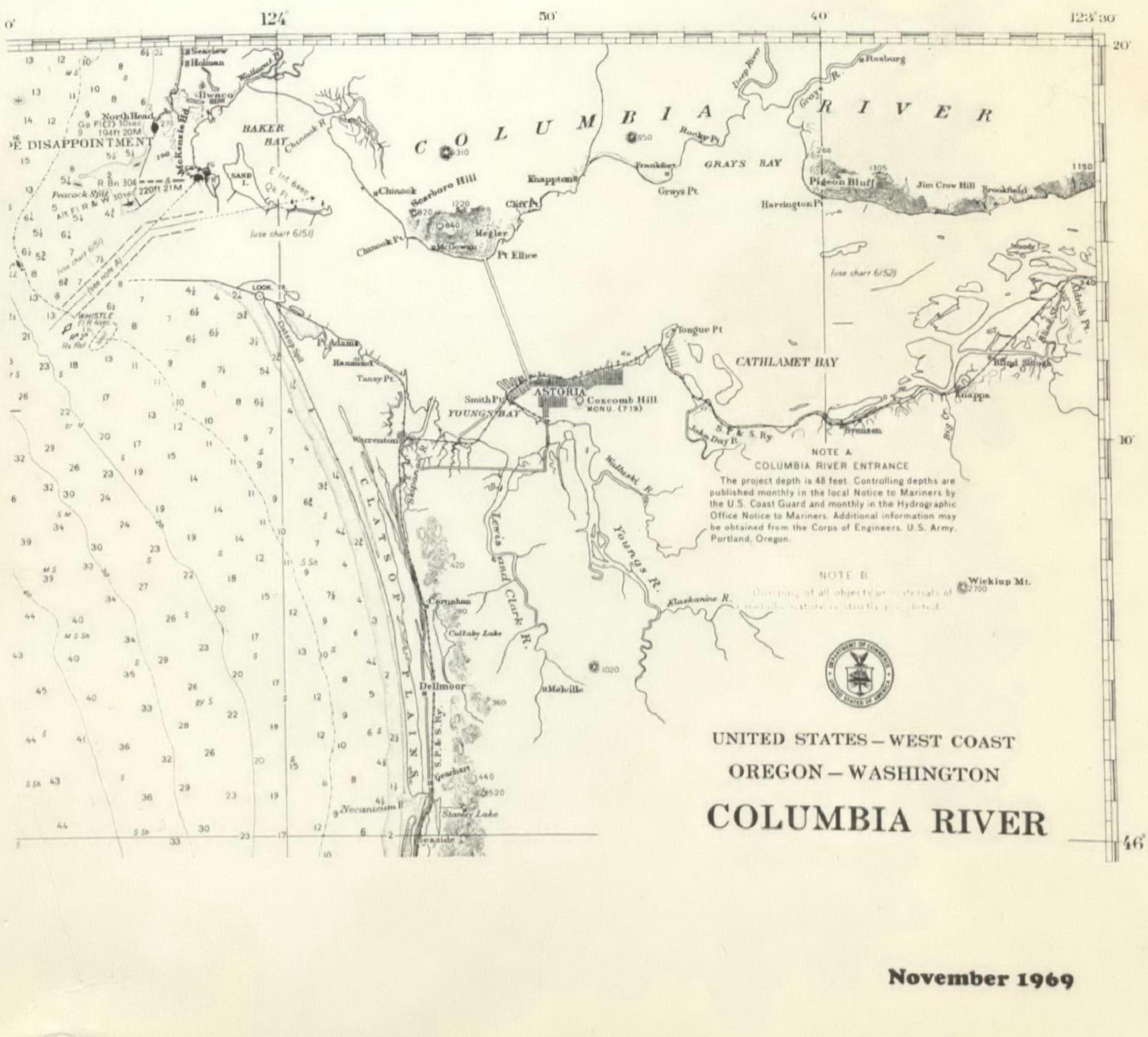
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

NORTHWEST REGION, PACIFIC NORTHWEST WATER LABORATORY

MATHEMATICAL MODEL OF THE COLUMBIA RIVER FROM THE PACIFIC OCEAN TO BONNEVILLE DAM

PART I



November 1969

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MATHEMATICAL MODEL OF THE COLUMBIA RIVER FROM THE PACIFIC OCEAN TO BONNEVILLE DAM

PART I

Theory, Program Notes and Programs

by

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ABSTRACT

The Columbia River from the Pacific Ocean to Bonneville Dam is treated as a series of two-dimensional finite elements in the formulation of a mathematical model of the system.

Currents and stages are simulated along the river via an explicit solution of the one-dimensional equations of motion and continuity; two-dimensional conditions in the horizontal are approached by means of a branched network of connecting channels and junctions. Computed net velocities and stages are used as inout to the advection-diffusion equation and solutions are obtained for any coupled (e.g., BOD-DO) or uncoupled, first order reaction, conservative and/or non-conservative substance.

Emphasis is placed on obtaining a solution for temperature as the dependent variable. Allowance is made for input of meteorological variables and a stepwise heat budget computation is made in order to predict temperature conditions on an hourly basis.

A discussion of some existing pollution models, numerical methods and error sources is given; computer programs and program notes are listed.

INTRODUCTION

This report is one result of a 1968 FWPCA decision to model the Columbia River system from the Canadian border to the Pacific Ocean for the purpose of evaluating existing and/or potential thermal pollution problems. Described here are the mathematical procedures, elementary theory, and documentation of computer programs employed in the lower Columbia study.

Part II of this report describes input procedures, provides a test program and gives examples of actual output. Verification procedures will also be given.

This work considers that portion of the Columbia from the Pacific Ocean to Bonneville Dam (Figure 1). The system above Bonneville has been treated as comprised of unstratified reservoirs (Morse, 1969) and stratified reservoirs (WRE, 1969).

At low flow, tidal effects in the form of a small diurnal tidal rise and fall are observable at the dam; by some definitions, the system up to the dam could be considered an estuary. However, the estuarine portion is usually restricted to that semi-enclosed part of the lower river where salt water is present. The fresh-water portion of the river, where ocean generated tidal effects occur, is called the tidal river.

In order to model the entire 146 miles of the Columbia to the dam, a rather large computational effort is required. Because

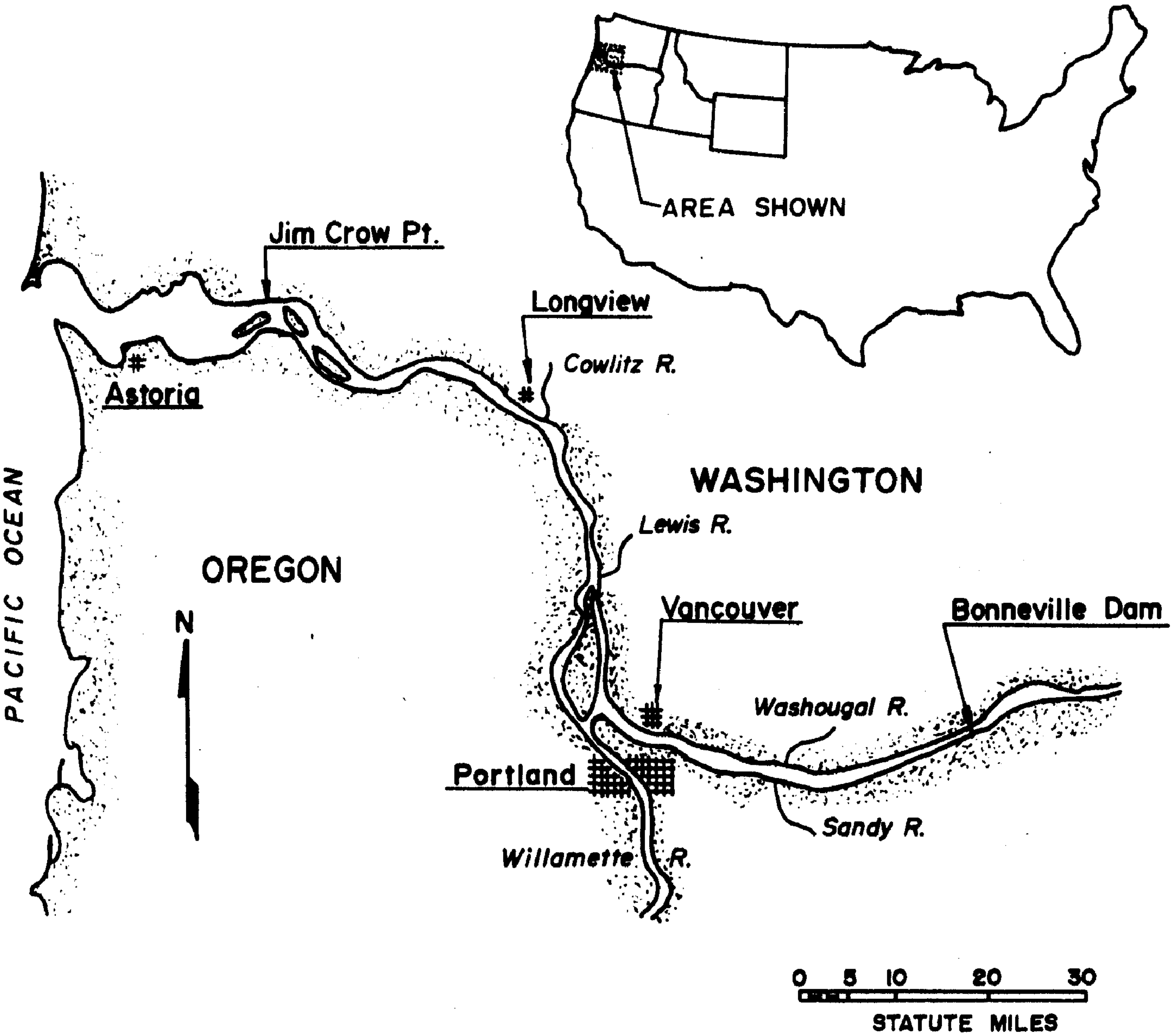

FIGURE 1. COLUMBIA RIVER - PACIFIC OCEAN TO BONNEVILLE DAM

the system includes estuarine to river-run circulation patterns, it was felt that a time record of longitudinal tidal flows and stage elevations would be required. Because there are many islands and tributaries on the main stream, it was also felt that these features should be incorporated in the model.

One method of solving this problem would have been to start from scratch and develop an in-house model of the system. However, the existence of a rather ingenious model developed by Water Resource Engineers of California (WRE) for the San Francisco Bay-Delta system tended to discourage this approach especially as the model had proved to be quite versatile in handling a number of situations. Foremost in these considerations was the ability of the model to approach two-dimensional (horizontally) conditions; not the least was the fact that several years of running experience were built into it.

Accordingly, copies of the program and decks were obtained from the Southwest Region of the FWPCA - the original contracting agency* - through the courtesy of Dr. Howard Harris and Mr. Ken Feigner**, who explained the basic workings of the programs, made suggestions on schematization and provided us with many helpful suggestions and comments.

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*Actually, Public Health Service before the creation of the FWPCA.

**Note added in press. Mr. Feigner is currently completing a documentation of FWPCA experience with the model in San Francisco and San Diego waters. It will serve as a valuable accompaniment to the present description.

The computer program developed by WRE did not treat temperature as such, hence, it was modified by us to accept temperature as a variable. Because of the general nature of the water quality portion of the program, i.e., its ability to handle conservative and non-conservative substances and to couple them if required, it was decided to retain those features rather than strip the model to handle only temperature. Thus, the description that follows emphasizes the methods employed in the temperature computations, but not at the exclusion of DO or BOD or any other substance.

It should be borne in mind that this is in actuality a one-dimensional model although provision is made to branch flows at junctions. Any substance discharged into a junction, is by the one-dimensional assumption, assumed to completely mix throughout the junction at each time step before being advected or diffused to another junction through a channel. Any numerical model will have similar artificialities; unfortunately, it is usually left to the user to uncover them for himself. Because the program received was undocumented, it was felt necessary to document it for those who might want to employ it for production runs. Rather than give only a description of card input requirements, a full documentation was developed because of the rather extensive knowledge required to understand the entire program. To mention a few of the subjects involved: open channel flow, diffusion and dispersion processes, numerical methods, sanitary engineering and heat budget methods in addition to estuarine flow processes. If the user is to be other than a knob turner, he should develop capability in these fields. If the program notes and literature cited are studied carefully, they should provide an independent start for getting on the estuary bandwagon complete with thermal pollution weaponry.

Models of Pollution Problems

Based on the premise that many marine pollution problems can be solved via computer methods, this section sets forth assumptions and limitations of some models currently in use. The "problem" is stipulated to be relatable to the physical environment, i.e., whether or not a bad situation will result is predictable on the basis of the pollutant's reaction rate and the hydrodynamic situation in the effluent discharge area. The condition is thus restricted to the prediction of the concentration of a specific pollutant at a given time and place given certain information on discharge rates, concentrations, and flow and diffusion in the estuary. How these predicted concentrations will affect the biota or whether or not they will lead to synergistic or antagonistic reactions is not discussed.

Deterministic (as opposed to stochastic) models of the environment are either steady-state or time varying. The steady-state assumption simply means that there is no concentration change of a substance or property with time. The effluent is discharged at a constant rate, and has been discharged for a long enough period to come into equilibrium with the receiving waters; any fresh water flow to the environment is constant, diffusion rates and other characteristics are also steady. The topography of the estuary can be modeled quite closely, i.e., any tide level, cross-sectional areas can be incorporated to show the irregular nature of the geographic setting. However, the effect of tidal height variations on cross-sectional areas (hence, water volume changes) and tidal current fluctuations cannot be modeled here except by repeated application of the steady-state case, in which case there would evolve a process of simulation. Simulation of various reaction rates, river flows, diffusion and reaeration rates is a logical extension of the steady-state assumption and perhaps the best justification for its use. For, by simulation, the expected range of concentration of a given pollutant can be easily explored by use of a steady-state digital model. Input information to a complex area can be obtained from existing hydrographic charts, flows can usually be extracted from federal or local government publications or files. The actual use of a developed steady-state model, as opposed to the judgement necessary to carry out a realistic simulation, is elementary. (Interpretation of results is, as always, the ultimate hangup; however, this does not relate to the present discussion.) The steady-state model, then, is useful in a situation where a rapid, first-cut approximation to a situation will suffice. In a highly complex industrialized setting such as the Delaware Estuary, the steady-state case has been used as the foundation of a linear programming method of meeting certain water quality standards. For instance, if wastes of known volume, concentration, and reaction rates are discharged at various locations along some miles of an estuary and a dissolved oxygen standard of, say, 5 ppm is to be obtained, the linear programming concept can be used in conjunction with the steady-state case to ensure that this goal will be met most of the time and at the least expense to the parties involved. Various external constraints are, of course, involved here, but the tools are available for the exercise of logical and unarbitrary decision making. Progress in extending this concept to the dynamic situation is underway. It is safe to predict that toolmaking will precede the implementation of these devices. The reason for this will be obvious to any manager who is or has been involved with a decision that has crossed political boundaries not to mention intra- or interstate geographic boundaries.

While the steady-state model has its uses, it also has its drawbacks. The fact is steady-state situations in nature don't really exist; hence, the absolute verification of such a condition is impossible. Most such problems have escape hatches; with the environmental scientist or engineer, the size of the hatch opening depends on how loose a definition of steady-state he is willing to accept. The purist will not be satisfied that steady-state verification has, in fact, been accomplished; nagging doubts will remain until he has gained: 1) experience with such models, 2) judgement on how critical a condition of, say, flow variation with time really is, 3) the realization that one is not usually concerned with precision in, e.g., the second decimal of the D.O. concentration.

Thus far, mention has not been made of the dimensionality of the problem. Here is meant the variation of water quality conditions with depth across stream and along the axis of the stream. The first stream model, proposed by Streeter and Phelps (1925), dealt with a freshwater condition and no variation of density was assumed with depth. Lateral (cross-stream) variations were also neglected, hence, the only gradient in concentration allowed was longitudinal (along the stream axis). Vertical variations in density occur in fresh water bodies, but unless the stream is deep, turbulent mixing ensures that such gradients are minimized. Obvious exceptions occur in the entrance of a stream to the headwaters of a reservoir. The reservoir may be markedly stratified during summer; use of a one-dimensional model obviously doesn't make sense in such a case although it could be implemented to grind out neat rows of numbers.

Proceeding from the freshwater to the seawater environment also usually means leaving the quasi-one-dimensional state and entering at least a periodically stratified water body. In the salt water portion of an estuary, one-dimensionality has in the past been inferred from a vertical profile of salinity showing little or no variation. The steady-state velocity distribution was also assumed to be invariant from top to bottom. Recent theoretical investigations (Hansen and Rattray, 1965) have shown that the vertical current profile need not be exactly related to the salinity distribution, although one's intuition would probably argue otherwise.

Other (Large Scale) Models

Presented here is a brief discussion of the basic philosophy and assumptions underlying models such as used by Thomann, O'Connor, and others on the East Coast and the modified Water Resources Engineers model used here. Then a description of the general flow diagram of the entire system is given in order that the functional interrelationships of the different parts of the system become familiar before discussing them in detail individually.

It is noted that the primary difference between the WRE model and that of Thomann (1963) is that the former representation of estuarine flow computes intratidal velocities, while the latter doesn't. There is, then a difference in viewpoint on how big a time average one is justified in taking. The original Thomann model used a time average of one day (numerical step size is smaller). One reason for this large time average is a matter of philosophy, namely that pollution control measures (measures that the model output indicates should be taken) on the order of a day are feasible, but those on a scale of hours generally are not. A recent paper by O'Connor, et al., (1968), indicates that the "...flux due to the tidal velocity, however, is too complex to be explicitly included in the mass balance." O'Connor's model integrates from slack tide to slack tide "...when the tidal velocity is zero."

One may argue that Thomann's original model took too large a time bite; but it must be remembered that his verification period consisted in simulating the dissolved oxygen profile at various points in the Delaware for one year. Shorter time periods, on the order of the WRE model, could have been included but the input-output problems would have been horrendous, to put it mildly. Accepting the idea that control measures in the Delaware need not be instantaneous, then it is doubtful that much would have really been gained by reducing the time step significantly, <u>if</u> it is assumed that the short time hydraulic effects do not affect the overall waste distribution computed. In any event, the time average employed is quite an important consideration and must be carefully spelled out.

The hydrography of the Columbia River is quite different from the Delaware. Discharge at the mouth is some 40 to 100 times as great; saltwater penetration is at most 25 miles upstream (Hansen, 1965), while in the Delaware, it is about three to four times that; tides are mixed, etc. The Columbia contains many islands and several channels may cut through small areas of the river. Tidal current reversal in the Columbia occurs some 75 to 100 miles upstream during low flow, although tide effects (vertical motion) can be seen at Bonneville Dam (Mile 146).

The steady-state assumption is an attractive one if for no other reason than that programming and computational effort necessary to achieve it is slight compared to the transient cases.

The use of a one-dimensional model is another questionable assumption, even though the model discussed is a "quasi" two-dimensional system. Obviously, in a stream as large as the Columbia, cross-channel velocity variations will be quite large; simulating a point source outfall on one bank of the river and then insisting that the effluent will be immediately and completely mixed in that particular cross-section is asking even the most devout simulation enthusiast to swallow a bit much. This is particularly true in the light of recent evidence that Taylor-type mixing probably won't occur for some distance (large diffusion time) downstream of a point source (Fischer, 1968). It is also true that the downstream distribution of waste discharged close to a bank in a large river system (width/depth ratio >>1) will usually be constrained to remain near that bank for some distance downstream. The utility of the model being used, then, is not in the simulation of small scale events, but as an indicator of the meteorological effects on a very large system. It is not unlikely that a small-scale model of waste heat discharge to the Columbia will encompass a single junction of the large model.

Recent work by Leendertse (1967) and W. Hansen (1966) on two-dimensional modeling will certainly provide a major step forward in solving pollution problems in embayments and coastal regions.

In treating the nonsteady dispersion equation, a great deal of computational effort is devoted to computing velocities in a (finite-grid) network of channels. If one were able to specify the velocities functionally then the largest part of the problem would be solved since the dispersion equation could be solved directly. In addition, if the diffusion coefficients were known functionally or could be assumed constant, another saving in labor could be effected. Such is not the case, unfortunately, and resort must be made to a scheme which will solve the momentum and continuity equations in such a fashion that 1) the tide wave amplitude and phase are verified with distance from the input wave and 2) flows and direction of flows are in reasonable agreement with known input lateral and mainstream flows. The constitution of a "reasonable" agreement between observed and computed flow is not easy to discern since there will always be discrepancies in, among other things, input conditions assumed and those actually occurring. This is, then, a problem of verification, which is discussed in Part II.

General Model Features

Several widely scattered papers have been published on the water quality aspects of the WRE model, for instance, Shubinski et al. (1965), and Orlob et al. (1967). A recent paper by Orlob (1968) discusses the various processes involved in modifying concentrations, particular their relation to the model's channels and junctions (or nodes).

In the model, physical characteristics of a real setting (Figure 2) are represented by junctions which occur at physical branches or at somewhat arbitrary spacings between branches in a network of channels and junctions.

Junctions connect short straight segments of regular cross-section; these segments are termed channels. Inflow-outflow occurs at the junctions which are characterized by a volume,

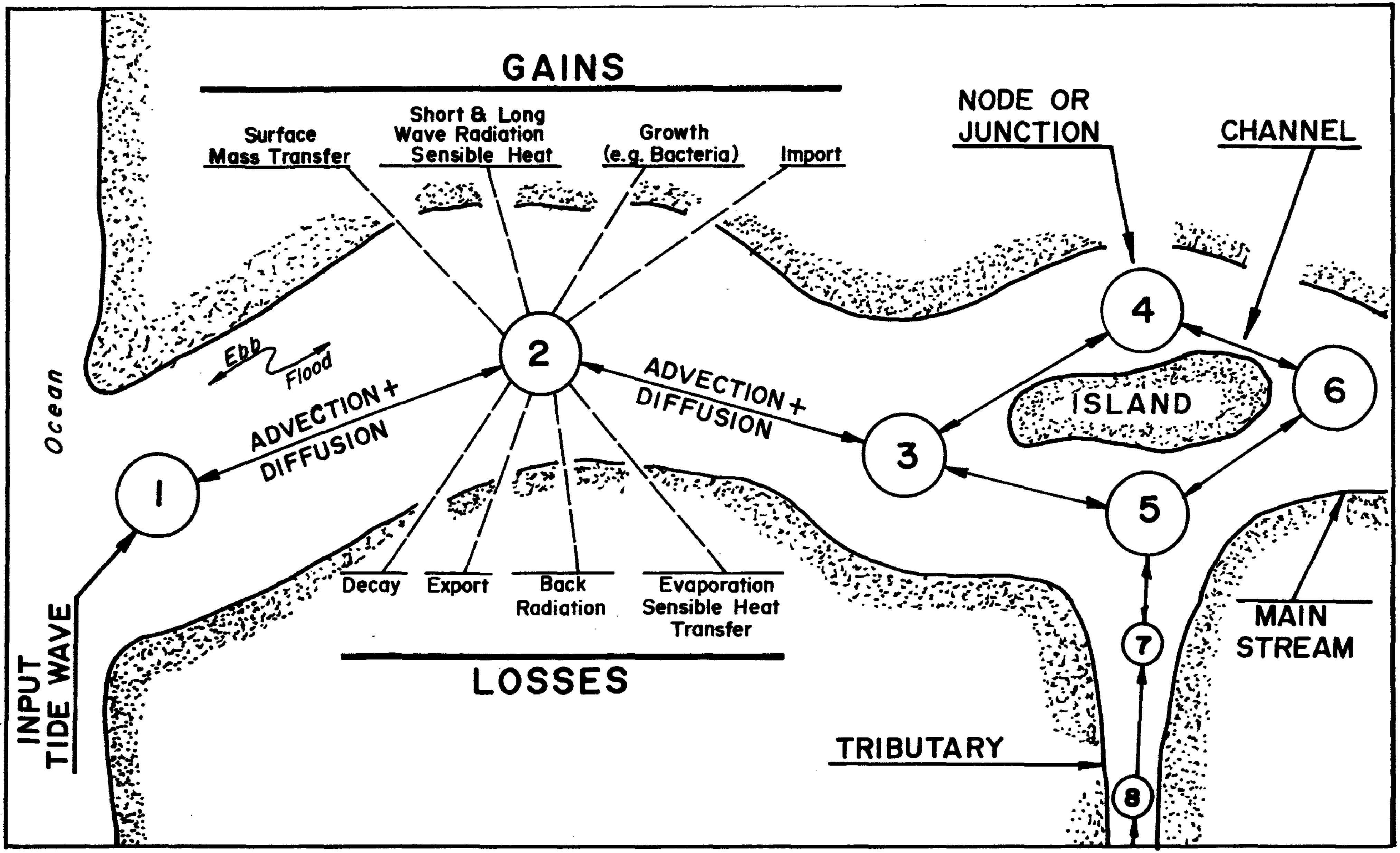

FIGURE 2. SCHEMATIC OF JUNCTION-CHANNEL NETWORK
AND
POSSIBLE TRANSFER PROCESSES

surface area, and head; in addition, constituent mass, decay, and growth rates are junction properties.

A channel is characterized by length, width, cross-sectional area, and hydraulic radius; in addition, net flows, velocities and friction are channel properties.

In essence, storage is provided at the junctions as well as potential and input-output; the channels provide conveyance between junctions.

Figure 2 summarizes the processes occuring in a schematic junction of a channel network.

At Junction 2, net change in heat or mass, ΔM, during a time step is brought about by the following:

$$
\begin{aligned}
\Delta M = \;& \text{Advection} \pm \text{Diffusion} \pm \text{Heat transfer process} \\
& + \text{Surface mass transfer} + \text{Growth} + \text{Import} \\
& - \text{Evaporation} - \text{Decay} - \text{Export.}
\end{aligned}
$$

Of course, change may only occur by processes of advection and diffusion or in combination with the remaining terms. If only temperature is being considered then only the first three terms on the right are used, since evaporation is computed separately.

The above is an expression of the advection-diffusion equation with source and sink terms and is solved numerically in the water quality program using the hydraulic program input in the advection term. If the solution is in terms of temperature (as a constituent) then it is an expression of the energy equation.

General Flow Diagram

In summary, the programs solve for current velocity and tide stage in one program; net velocities and heads are averaged over a suitable time period in a subroutine which is used as input to a stepwise solution of the dispersion equation.

Referring to Figure 3, the following step-by-step description of the general computer program can be used to define what is happening from the initial step of obtaining depth information to the final one of printing out predicted temperature or concentrations. As indicated above, most of the work occurs in step 2 (diffusion coefficients are introduced in step 7).

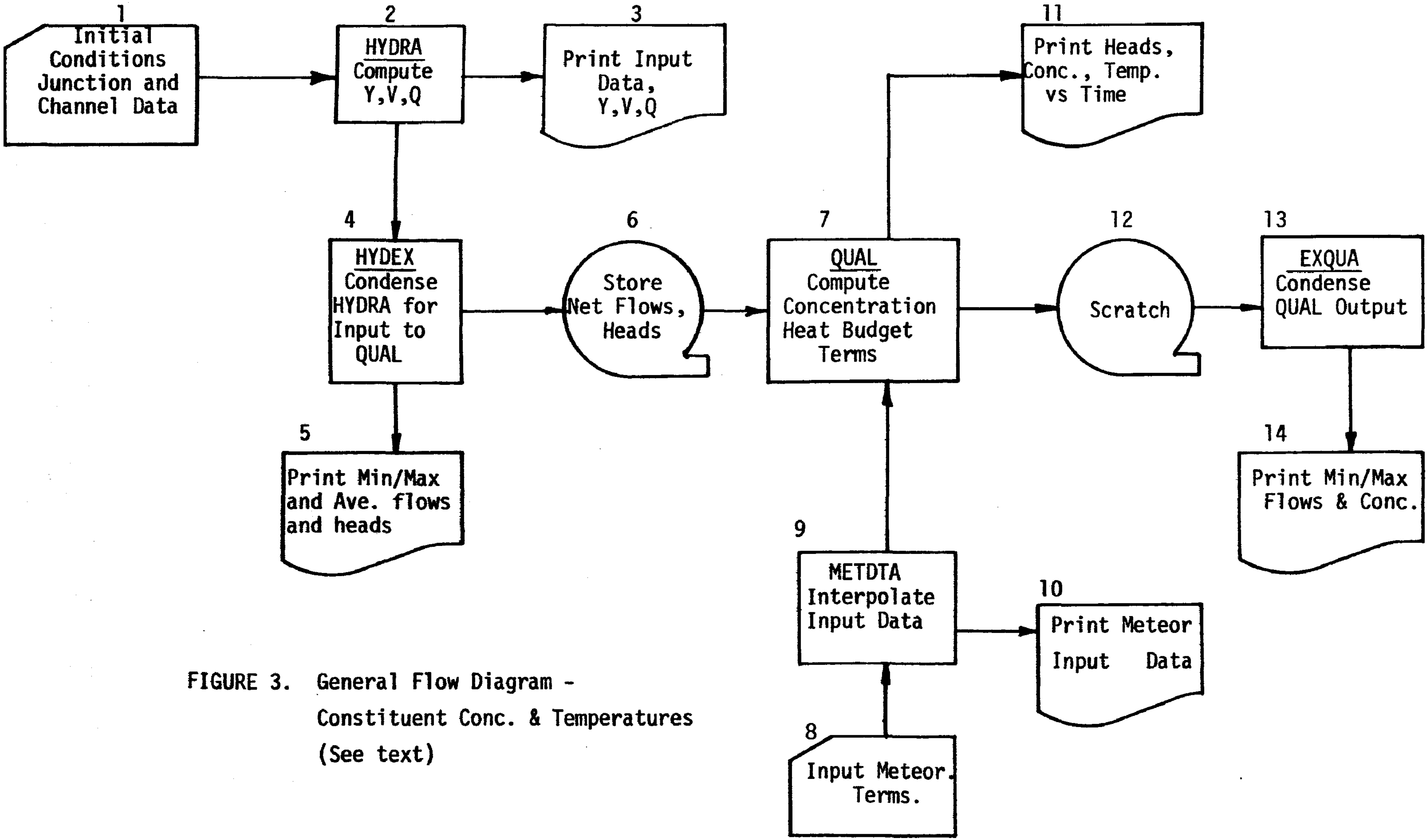

FIGURE 3. General Flow Diagram - Constituent Conc. & Temperatures (See text)

General Flow Diagram
For Use with Figure 3

1. Initial and boundary conditions, junction and channel data, such as cross-sectional areas and channel lengths, are read into Program HYDRA.

2. HYDRA computes heads at each junction and velocities and flows in each channel. These data are printed versus time (3) and/or summarized in subroutine HYDEX (4). Program will terminate after (3) if HYDEX is not called.

3. Print routine can be scheduled to list all or portions of the output.

4. HYDEX averages the data over certain time intervals (e.g., 15-30 minutes) for input to binary tape (6) and/or averages heads, flows and velocities for tidal cycles, days, etc., for printout.

5. Printout from HYDEX; execution will terminate here if QUAL is not used.

6. Net flows computed in HYDEX are stored in binary for use by QUAL.

7. Program QUAL needs average net channel flows calculated in HYDEX to run. From input initial and boundary conditions, QUAL computes concentrations of substances released at any network junction, allows for diversions and return flows, etc.

8. Local climatological data (net radiation - computed or observed, air temperature, cloud cover, wind speed, etc.) are read into subroutine METDTA if temperature is a constituent (9).

9. METDTA interpolates incoming radiation and other terms to conform to the selected quality time step.

10. Printout of meteorological data.

11. Printout of temperature and/or concentrations (up to five constituents are allowed) occurs here. Program may terminate here or pass to 13.

12. If subroutine EXQUA is called, data is stored on binary for execution by EXQUA. (Subroutine EXQUA is not discussed in this report but will be made available on request.)

13. EXQUA can be reprogrammed to summarize data in a manner similar to HYDEX (4).

14. Printout of a computation using EXQUA would be the final step.

MATHEMATICAL METHODS

Differential Equations - Terminology and Assumptions

The programs discussed present numerical solutions to one-dimensional linear or nonlinear partial differential equations that are coupled or uncoupled for substances that are conservative or nonconservative. The foregoing jargon is helpful in seeing through the bramble bush of the leapfrog solutions and other manipulations which are conceptually simple, but sometimes hard to follow. When all is said and done, we are faced with solving the "fundamental equation of linear sanitary engineering" which, in operational form in one-dimension, is:

$$1)\quad \left[\frac{\partial}{\partial t} - \frac{\partial}{\partial x}\left(D_L \frac{\partial}{\partial x}\right) + u \frac{\partial}{\partial x}\right](L, C, T, \ldots) = \Sigma S,$$

where BOD (L), D.O. (C), Temperature (T), etc., can be expressed as a sum of sources and sinks (ΣS).

Expressing equation (1) in the simplest form for all three variables:

$$2)\quad \frac{\partial L}{\partial t} - D_L \frac{\partial^2 L}{\partial x^2} + u \frac{\partial L}{\partial x} = -K_1 L$$

$$3)\quad \frac{\partial C}{\partial t} - D_L \frac{\partial^2 C}{\partial x^2} + u \frac{\partial C}{\partial x} = -K_1 L + K_2 (C_s - C)$$

$$4)\quad \frac{\partial T}{\partial t} - D_L \frac{\partial^2 T}{\partial x^2} + u \frac{\partial T}{\partial x} = K_3 (T_e - T)$$

L = BOD concentration

C = DO concentration

C_s = DO saturation concentration

D_L = Coefficient of long. dispersion

K_1 = Decay rate

K_2 = Reaeration rate

K_3 = A thermal exchange rate

T = Water temperature

T_e = Equilibrium temperature

u = Mean velocity.

The equations differ only in the source and sink terms which are peculiar to the particular substance. If there were no reaction terms ($K_1 = K_2 = K_3 = 0$), then the solution for one substance would be a simple multiple of another if, and only if, the diffusion rate, D_L, for each were equal and constant or varied alike with distance. (Such a condition is known as the Reynolds analogy, i.e., assuming that turbulent transfer rate of, say, heat is the same as that of oxygen.)

It can be seen that (2) must be solved for L before (3) can be computed (if the reaction rates are nonzero). The two equations are thus said to be coupled through L. If the reaction rates are nonzero, the substance (e.g., BOD) is said to be nonconservative; salinity is an example of a conservative substance.

The one-dimensional assumption is inherent in equation (1) as change is allowed only in the x (longitudinal) direction. Equation (1) is the simplified form of the local time change. In full bloom, the operator is written as:

$$\left[\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z} - \frac{\partial}{\partial x}\left(D_x\frac{\partial}{\partial x}\right) - \frac{\partial}{\partial y}\left(D_y\frac{\partial}{\partial y}\right) - \frac{\partial}{\partial z}\left(D_z\frac{\partial}{\partial z}\right)\right],$$

where the y, z diffusion terms are allowed to vary. This equation is merely a statement; it says nothing about what processes are affecting the distribution (see Sverdrup, et al., Chapter V, 1942, for an excellent discussion of the distribution of variables). Sometimes the longitudinal and/or vertical terms are neglected because the velocities involved are assumed to be very small. It may be that that is so, but it can also be true that the y and z gradients are very large so that the products ($v\frac{\partial}{\partial y}$, $w\frac{\partial}{\partial z}$) may not be negligible. If the cross-stream and vertical advection terms are to be neglected then they must either effectively cancel each other or be very small. When calling on the one-dimensional assumption, the gradients involved must be assumed to be negligible; this is the condition that obtains when an estuary is "well-mixed."

The remaining terms to be discussed concern linearity. The so-called non-linear terms, if not neglected, cause dreadfuls to occur. If a system of equations is linear, and a certain solution is found for the system, then additional solutions can be obtained by multiplying the answers (which might be the longitudinal BOD concentrations) by any given number. This number might correspond to, say, an increase or decrease in waste treatment. At any rate, the solutions are said to be superposable. If the system is nonlinear, then multiplying by a number in one position will not necessarily give a proportional output as the answer somewhere else. As a result, many, many analytical solutions may be required to determine the output in a nonlinear system, where a single solution may suffice in a linear one.

In dealing with the hydraulic equation (for a complete discussion, see Dronkers (1964), Baltzer and Lai (1968), and Leendertse (1967)), retention of the nonlinear term ($u \frac{du}{dx} = \frac{1}{2} \frac{du^2}{dx}$)* is usually required since it may be at least equal in magnitude to the linear terms. A tide wave becomes distorted with distance upstream because of changes in channel configuration and roughness through this nonlinear term and the nonlinear frictional term (ku^2). This is implied from the characteristic of linear systems by noting that the output generated by a sinusoidal input is also strictly sinusoidal even though the phase may be shifted

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*Also called the convective-inertial term or the advection of momentum term or the Bernoulli acceleration term.

and its amplitude modified. A problem in the prediction of water height in estuaries and tidal rivers concerns the nonlinearity of the system as the wave is distorted with its passage upstream. A wave describable by a single harmonic (for a short period) at the estuary mouth may require many harmonics for its description further upstream.

There are some problems in the practical use of equations 1, 2 in estuaries. First of all, there are irregular boundaries; u as used here is the net freshwater velocity (Q/A) and we really should consider $u = Q/A + u_t \cos(\omega t)$, where u_t is a tidal term and $\omega = 2\pi/T$, where T is a tidal period. In practice, the cosine term can be replaced by a Fourier series to represent any degree of tide complexity required. The one-dimensional pitfalls are fairly obvious, but one should bear in mind that this implies a uniform velocity from top to bottom and side to side (no shear). If there isn't any shear, then the primary turbulence generating mechanism is lost. We can overcome this (ignore it) by simply assigning a certain value to the diffusion term. (D_L in this case.) The surprising thing about all this, considering the assumptions, etc., is that with a finite difference model it can all be made to work, i.e., serve as a pollution planning and management tool.

We'll need to know, or might want to calculate, the velocity at any time at any point in a system in order to make use of (1).

This varies from strictly seaward directed river flow in the upper reaches (with a bit of a sine wave thrown in) to a diurnally reversing current in the estuary as shown in Figure 4 for the Columbia.

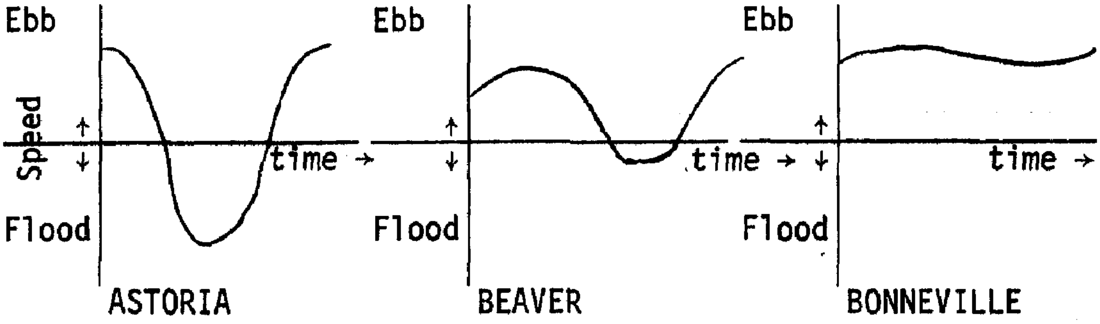

FIGURE 4. Schematic of Currents, Columbia River

Current velocity is obtained by solving the equations of motion (5) and continuity (6):

5) $$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x} + k|u|u = 0$$

6) $$\frac{\partial h}{\partial t} + \frac{1}{b}\frac{\partial q}{\partial x} = 0, \; q = Au.$$

Suffice it to say that equations 5, 6 are written in finite difference form, the estuary is schematized, i.e., depths, areas (A), widths (b), roughness coefficients (k), are determined, initial conditions are specified and u (and h) are solved for by the "leapfrog" method which is employed in solving the coupled momentum and continuity equations. In the leapfrog method, the initial conditions of velocity and stage are read into the computer along with the boundary conditions. Velocity and flow are computed from the momentum equation; the computed flow is substituted into the continuity equation to obtain a new stage elevation which is then used in place of the initial condition to obtain new velocity and flow values. The new flow obtained is again substituted into the continuity equation and the process leapfrogs until the cycle is complete.

Finite Differences and Explicit Solutions

In dealing with non-analytical solutions to differential equations, it is necessary to express derivatives in a form that the computer can handle, namely, finite difference approximations of infinitesimal quantities. What one really wants is to make the infinitesimally small derivative as big (finite) as possible while still satisfying the equation of motion or any other equation.

The usual drill is to start with the Taylor series expansion about x of a function, say u(x), which doesn't contain any sudden jumps in it:

7) $$u(x+\Delta x) = u(x) + \frac{\Delta x}{1!}\frac{du(x)}{dx} + \frac{\Delta x^2}{2!}\frac{d^2u(x)}{dx^2} + \frac{\Delta x^3}{3!}\frac{d^3u(x)}{dx^3} + \ldots$$

and

$$8) \quad u(x-\Delta x) = u(x) - \frac{\Delta x}{1!}\frac{du(x)}{dx} + \frac{\Delta x^2}{2!}\frac{d^2u(x)}{dx^2} - \frac{\Delta x^3}{3!}\frac{d^3u(x)}{dx^3} + \ldots$$

Equation (7) could be used to predict the value of u(x) a distance Δx ahead of it if the function and its derivatives were known at x. How good the approximation is will depend on how large h is.

Difference approximations are classified as either forward, backward, or central. A particular computing scheme may make use of one or more of these approximations, and the proper formulation must be employed to ensure a stable and convergent solution.

Referring to Figure 5, it can be seen that the first derivative of u(x) centered about the point P can be written by inspection as:

$$9) \quad u'(x) = \frac{du(x)}{dx} = \frac{1}{2\Delta x}\left\{u(x+\Delta x) - u(x-\Delta x)\right\},$$ where the chord AB is tangent to u(x) at P.

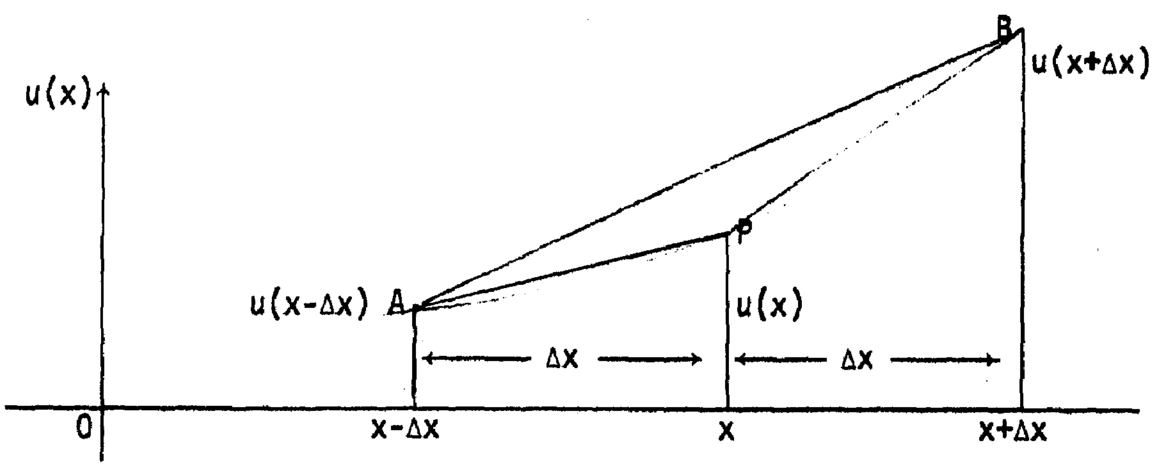

FIGURE 5. Definition sketch for difference equations

The same expression can be obtained by subtracting equation (8) from (7) and neglecting terms greater than or equal to Δx^3. The error is then said to be of order 3, is written as $O(\Delta x^3)$, and is the result of chopping off (truncating) the higher order terms. Truncation error is inevitable, but can be made insignificant.

The second derivative of u(x) at P can be written by adding equations (7) and (8) and neglecting terms of $O(\Delta x^4)$ and higher:

$$u(x+\Delta x) + u(x-\Delta x) = 2u(x) + \Delta x^2 \frac{d^2u(x)}{dx^2} + O(\Delta x^4)$$

or

$$\frac{d^2u(x)}{dx^2} = \frac{1}{\Delta x^2}\left\{u(x+\Delta x) + u(x-\Delta x) - 2u(x)\right\}.$$

The forward difference approximation of the slope at P $(\frac{du(x)}{dx})$ is:

$$10) \quad u'(x) = \frac{1}{\Delta x}\left\{u(x+\Delta x) - u(x)\right\},$$

hence, values only at P and forward of it are used. Similarly, the backward difference is:

$$11) \quad u'(x) = \frac{1}{\Delta x}\left\{u(x) - u(x-\Delta x)\right\}.$$

Since nonsteady-state problems must be dealt with, provision must be made to move the solutions ahead in time as well as along the axis of the estuary.

It is often desirable to solve a class of problems in such a manner that recomputing needn't be done every time there is a change in scale of a particular geometric or physical property, i.e., it shouldn't be required to compute the temperature distribution in a rod for every length of rod imaginable. Such a process occurs when the equations are expressed in terms of nondimensional variables. For instance, the parabolic heat equation describing the transient temperature distribution* in a rod can be written as:

12) $$\frac{\partial U}{\partial T} = c \frac{\partial^2 U}{\partial X^2} ,$$

where c is a constant; U is temperature; X is the distance from one end of the (thin, uniform) rod; and T is time. By making suitable transformations, this equation can be expressed in non-dimensional form as:

13) $$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2}$$

A finite difference grid can be used for the numerical solution of this equation. The "explicit" method is illustrated because it is used herein to solve the hydraulic and dispersion equations. Advantages and disadvantages of the explicit scheme are discussed later.

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*This is also one form of the Fick diffusion equation which is discussed in another section.

The Explicit Solution of $\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2}$

The finite difference form of the nondimensional heat equation is:

14) $$\frac{u_{i,j+1} - u_{i,j}}{\Delta t} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{(\Delta x)^2}$$

A forward difference is used for the time step and a central difference is used for the second (space) derivative; the subscripts are shown in Figure 6.

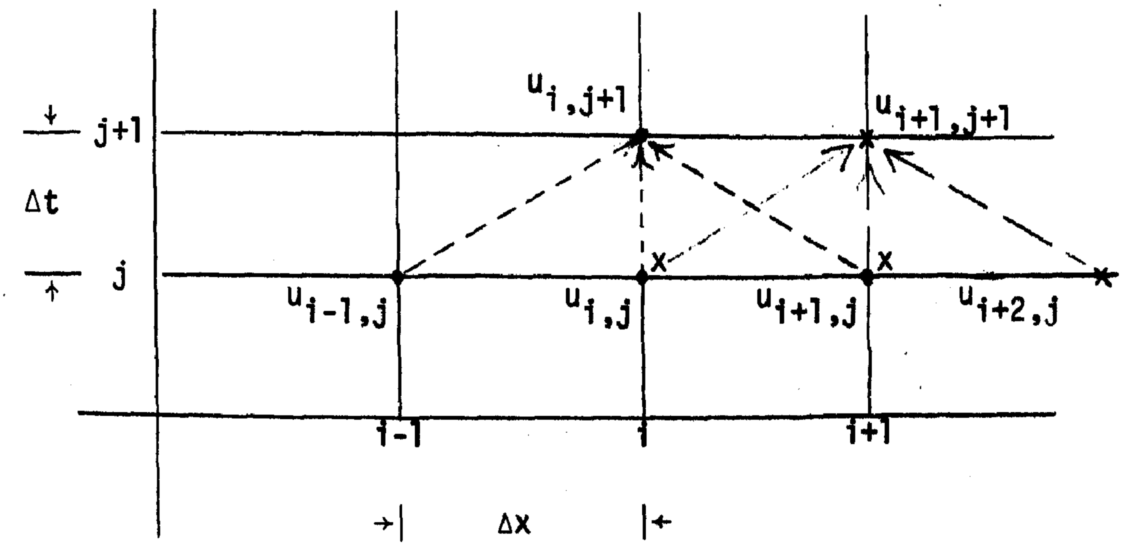


FIGURE 6. Explicit Integration Scheme

Rearranging equation (14) for the value of u(x,t) after one time step:

15) $$u_{i,j+1} = u_{i,j} + \frac{\Delta t}{(\Delta x)^2}(u_{i-1,j} - 2u_{i,j} + u_{i+1,j}).$$

The value of $u_{i+1,j+1}$ (located at the j+1 row by an x) can next be computed from the values $u_{i,j}$, $u_{i+1,j}$, and $u_{i+2,j}$. The whole scheme can be repeated until values are known for row j+1; these can then be used to obtain new (i.e., j+2) values at the next time step. This explicit formulation requires that the initial and boundary conditions be given.

Of critical importance in the numerical solution of the parabolic heat equation is that the ratio of time step, Δt, to the square of the space step, $(\Delta x)^2$, must lie between 0 and 1/2. This relates to the "stability" of the solution, a subject which will be treated later on in the treatment of the wave equation which has a somewhat different stability criterion. The use of a central difference formulation can create problems; these are also discussed in the section on stability.

It is possible to solve the system of equations simultaneously by matrix inversion or some other "implicit" method which has the advantage of being unconditionally stable for large time steps. Even here, however, short time steps may be required to obtain the necessary accuracy and to minimize numerical violations of water mass and constituent concentration conservation. It is not clear if an implicit solution for the Columbia would have justified the considerable reprogramming effort that would have had to be undertaken.

Runge-Kutta Solution of Hydraulic Equations

Although any method of forward integration could be used, a two (rather than the usual four) step Runge-Kutta (R-K) procedure is employed in the solution of the equations of motion and continuity. Other methods are known to be more efficient but have not yet been considered. The principal advantages in using R-K methods lies in their independence of past computing stages, i.e., the method is self-starting. The R-K method is also stable when grid spacings are uneven or change during computation. It is difficult, however, to estimate the truncation error at a given point in the computation although estimates can be obtained (see, e.g., Hildebrand, p. 238, 1956).

For a channel with constant width and employing a slightly different notation than before, the continuity equation is:

16) $$\frac{\partial}{\partial x}(VA) + B\frac{\partial H}{\partial t} = 0 ,$$

where

V = Average channel velocity during a time step (Δt)

A = Cross-sectional area of channel

H = Height of water surface above (arbitrary) horizontal datum

B = Channel width.

The equation of motion in the x-direction is:

17) $$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial H}{\partial x} + K|V|V = 0 ,$$

where

g = Acceleration due to gravity

K = Friction coefficient

and the absolute value of V ensures the proper direction of the frictional force, namely opposite to the direction of V.

The assumptions on which 16 and 17 are based are as follows:

1. Acceleration and momentum transfer normal to the x-axis is negligible. Thus, tributary inflows contribute to a change in junction head, but impart no momentum during the contribution.

2. Wave length is at least twice channel depth. If not, the shallow water assumption utilized here (in which wave celerity = $\sqrt{gh}$) would not hold. The "wave" referred to here is of tidal period, not a wind wave.

3. Coriolis and wind forces are negligible.

4. Each channel is straight (hence, no centrifugal effects) and the cross-sectional area does not vary over its length.

The steps outlined below are contained in sequence numbers 147 - 207 in the listing for program HYDRA.

Following the notation of Shubinski and Sheffey (1966), and Shubinski, et al. (1965, 1967) equations can be written for channel i, at equilibrium, as:

18) $$\frac{\Delta V_i}{\Delta t} = - V_i \frac{\Delta V_n}{\Delta x_n} - K_i |V_i| V_i - g \frac{\Delta H}{L_i}$$

where

V_i = ith channel velocity

Δt = time step (for R-K integration)

$\frac{\Delta V_n}{\Delta x_n}$ = velocity gradient evaluated as suggested by Lai (1966) as follows:

equation 16 is rewritten as

$$\frac{\partial V}{\partial x} = - \frac{B}{A}\frac{\partial H}{\partial t} - \frac{V}{A}\frac{\partial A}{\partial x} ,$$

expressed in finite difference form and substituted as

$\frac{\Delta V_n}{\Delta x_n}$

K_i = frictional resistance coefficient

g = gravitational acceleration

ΔH = head (potential) difference between junctions at ends of channel

L_i = channel length.

Similarly, the continuity equation is

19) $\frac{\Delta H_j}{\Delta t} = \frac{Q_j}{A_j}$, where j is now a junction index and

Q_j = net flow at j during a time step, Δt

A_j = junction surface area (constant)

ΔH_j = head of junction j.

The solution of 18 and 19 using a two-step R-K (leapfrog) procedure is as follows:

1. Initial and boundary conditions are specified so that the system state is known at time t. Predictions are required at time $(t + \Delta t)$ and multiples thereof. Superscripts t, t+1/4, t+1/2, t+1, imply values at time t, $t+\frac{\Delta t}{4}$, $t+\frac{\Delta t}{2}$, $t+\Delta t$, respectively. The superscript t+1/4 indicates a term using mixed time steps.

2. Compute half-interval velocities and "quarter"-interval channel flow

$$V_i^{t+1/2} = V_i^t + \frac{\Delta t}{2} \left(V_i^t \frac{\Delta V_n^t}{\Delta x_n} - K_i^t |V_i^t| V_i^t - g \frac{\Delta H^t}{L_i}\right)$$

$$Q_i^{t+1/4} = V_i^{t+1/2} A_i^t$$

3. Compute half-interval heads and quarter-interval channel areas

$$H_j^{t+1/2} = H_j^t + \frac{\Delta t}{2} \left(\frac{Q_j^t}{A_j}\right)$$

$$A_i^{t+1/4} = A_i^t + \frac{B_i}{2} \left(\Delta H_j^{t+1/2} - \Delta H_j^t\right)$$

4. Compute full-interval velocities and three-quarter interval channel flow

$$V_i^{t+1} = V_i^{t+1/2} + \Delta t \left(V_i^{t+1/2} \frac{\Delta V_n^{t+1/2}}{\Delta x_n} - K_i^{t+1/2} |V_i^{t+1/2}| V_i^{t+1/2} - g \frac{\Delta H^{t+1/2}}{L_i}\right)$$

$$Q_i^{t+3/4} = V_i^{t+1} A_i^{t+1/2}$$

5. Compute full-interval heads and three quarter interval areas

$$H_j^{t+1} = H_j^{t+1/2} + \Delta t\left(\frac{Q_j^{t+1/2}}{A_j}\right)$$

$$A_i^{t+3/4} = A_i^{t+1/2} + \frac{B_i}{2}\left(\Delta H_j^{t+1} - \Delta H_j^{t+1/2}\right)$$

6. Upgrade system parameters, K, Q, A, which can be computed from geometric considerations,etc.

7. Continue at step 2 until cycle is complete.

Diffusion and Dispersion

The spreading out of material from a point source is easy to visualize in terms of an instantaneous release, but real life effluent discharges are more likely to be continuous or periodic. A continuous release, however, can be synthesized analytically from a sum of instantaneous releases so that a discussion of the longitudinal diffusion of material properly starts with instantaneous releases. (See Okubo and Karweit, 1969, for a discussion of the above as well as on the effect of shear on diffusion.)

Estuarine pollution models derive from the advection-diffusion equation (as does a river model) which can be written as:

20)

$$\frac{\partial c}{\partial t} + u\,\frac{\partial c}{\partial x} + v\,\frac{\partial c}{\partial y} + w\,\frac{\partial c}{\partial z} - \left[\frac{\partial}{\partial x}\left(D_x\,\frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\,\frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\,\frac{\partial c}{\partial z}\right)\right] = \Sigma S\,.$$

By comparison with equation (1), it can be seen that the cross-stream and vertical terms were neglected in getting to the one-dimensional equation.

Confusion as to the meaning of dispersion as opposed to diffusion is easily rectified if equation (20) is referred to as the "dispersion equation." Dispersion will then include the advective transport of material as well as its diffusion due to turbulent flux.

If a one-dimensional coordinate system moves with the center of mass of material, equation (20) degenerates into the Fick equation originally developed to describe molecular scale phenomena in which local concentration changes are due to diffusion only (and diffusion is constant):

$$21)\quad \frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} .$$

In large scale problems, the eddy diffusion analog to the Fick Equation is often used.

The instantaneous point source solution of (21) is:

$$22)\quad C = \frac{M}{(4\pi Dt)^{1/2}} \quad e^{-x^2/4Dt}$$

which describes a Gaussian distribution curve about x=0, and where $M = \int_{-\infty}^{\infty} Cdx$. Since the Fick Equation is statistical in nature, it contains no force terms to "move" particles from regions of high to low concentrations. It can be seen from (22) that as time increases, the normal curve will flatten; the area under the curve remains finite and equal to the total mass of marked particles released at the source. It should be recognized that the solution for predicting the concentration of a diffusing substance is also a probabilistic equation, i.e., the mean concentration of marked particles at x is directly proportional to the probability of finding marked particles at that point. This idea is reinforced by noting that a so-called Monte Carlo simulation of diffusion can be obtained quite easily with a table of random numbers. The longitudinal distribution of a substance introduced into a pipe can be obtained by this method without employing the diffusion equation at all (See Crank, 1955, p. 216, for an example).

Because of the feeling of uneasiness generated in scaling up molecular analogs of diffusion to geophysical size, considerable research has been devoted to more satisfactory descriptions. Employed in the quality program is a form of the Kolmogoroff hypothesis (Orlob, 1959) for computing the diffusion coefficient:

23) $D_d = \mathfrak{C} \cdot E^{1/3} \cdot \ell^{4/3}$, where

$\mathfrak{C}$ = Empirical constant (dimensionless)

$E = V_i \cdot g \cdot \frac{\Delta H}{L_i}$, an energy dissipation term*

*Note that for E constant the dispersion term becomes the "4/3 law," $D_d = \mathfrak{C} \cdot \ell^{4/3}$

V_i = Channel velocity

g = Gravitational constant

$\Delta H/L_i$ = Potential (head) difference at ends of channel i

ℓ = Scale of phenomenon; written in terms of the hydraulic radius, R.

The dimensions (M, L, T) of the energy dissipation term are:

$$E = \left\{(LT^{-1})(LT^{-2})\right\}^{1/3} = L^{2/3}T^{-1}$$

and of the scale terms are

$$\ell = \{L\}^{4/3}, \text{ so that}$$

$$D_d = L^{2/3}T^{-1} \cdot L^{4/3} = L^2T^{-1}$$

and $\mathfrak{C}$ is dimensionless.

The diffusion of mass per time step is then

$$\text{Diff}/\Delta t = \mathfrak{C}|Q|R\,\frac{\Delta c_d}{L_i}$$

with dimension

$$MT^{-1} = (\cdot)(L^3T^{-1})(L)(ML^{-3})(L^{-1})$$

and where $\frac{\Delta c_d}{L_i}$ is mass concentration gradient and Q is flow.

As stated elsewhere, numerical errors can contribute to the spreading out of material. When this is not accounted for, the errors will be hidden in D_d leading to erroneous conclusions as to the relative magnitude of the advection and diffusion terms. When tidally-averaged formulations are employed, the "velocity" term in the one-dimensional equation is river flow ÷ cross-sectional area. Diurnal tidal variations are then not implicit, but are in reality responsible for producing the spread of material with time such that peak concentrations occur both up-stream and downstream of the source. This tidal displacement has to be accounted for even in the tidally-averaged equation and is generally dumped into some form of the diffusion coefficient. This coefficient is not a pure turbulent diffusion term, but is, rather, a catch-all.

Stability, Numerical Mixing and Other Errors

A finite difference representation of differential equations means that one will obtain solutions at discrete points at certain time steps. Because of this and the fact that computing machines carry only a finite number of decimal places, problems of truncation, roundoff error, convergence and stability will always arise. Certain of these concepts are stated concisely by O'Brien, et al. (1951):

"Let D represent the exact solution of the partial differential equation, Δ represent the exact solution of the partial difference equation, and N represent the numerical solution of the partial difference equation. We call $(D - \Delta)$ the truncation error; it arises because of the finite distance between points of the difference mesh. To find the conditions under which $\Delta \rightarrow D$ is the problem of convergence. We call $(\Delta - N)$ the numerical error. If a faultless computer working to an infinite number of decimal places were employed, the numerical error would be zero. Although $(\Delta - N)$ may consist of several kinds of errors, we usually consider it limited to round-off errors. To find the conditions under which $(\Delta - N)$ is small throughout the entire region of the integration is the problem of stability.

"The principal problem in the numerical solution of partial differential equations is to determine N such that $(D - N)$ is smaller than some preassigned allowable error throughout the whole region considered. We can assert that

$$(D - N) \equiv (D - \Delta) + (\Delta - N)$$

is small for a numerical calculation over a fine mesh using a stable, convergent difference scheme."

It should be noted that other definitions exist for truncation and convergence. If a Taylor series expansion is used to approximate derivatives, only a few terms are carried; the higher ordered terms are dropped and the series is said to be truncated. Likewise, a particular computing scheme may converge to a proper solution at a relatively fast or slow rate depending on the scheme employed and the choice of initial conditions.

Hydraulic Equations

Two types of errors can occur in the programs under discussion aside from truncation and roundoff. In the hydraulic program (HYDRA), stability is generally inferred from the so-called "Courant Condition" for explicit finite representations of the hydraulic (open-channel) equations. The Courant criterion can be written as:

$$24)\quad L_i \geqslant |V_i \sqrt{gH_{max}}\ |\Delta t\ ,$$

where

H_{max} = Maximum channel depth

Δt = Integration step

The term $\sqrt{gH_{max}}$ is the speed of a shallow water wave and holds where the wave length is greater than twice the channel depth. The approximation $L_i \geqslant \sqrt{gH}\ \Delta t$ usually suffices in schematization as is discussed later. "Wave length" refers to the length of a tidal wave with a period that is on the order of 12.4 hours.

It has been found (See, e.g., Perkins, 1968) that even though the Courant Condition is met, instability may occur and that this instability is due to the presence of the non-linear frictional resistance term, $K_i|V_i|V_i$, in the equation of motion. This term is written:

$$25)\quad K_i|V_i|V_i = \left[\frac{n^2|V_i|}{(1.49)^2\ R_i^{4/3}}\right]V_i = K_i'V_i\ ,$$

where

n = Manning coefficient

R_i = Hydraulic radius of ith channel

$K_i = ((n/1.49)^2 R_i^{-4/3})$

The modified Courant Condition is then written:

26) $L_i \geq |V_i \pm \sqrt{gH_{max}} - g \cdot K'|\Delta t$,

which says that for a given integration step and channel depth, the channel length must be at least of a certain length if stability is to be maintained.

During the process of verifying current and stage, the Manning coefficient can be adjusted in various reaches. This may result in instabilities if n becomes too large, however, and a shorter time step may become necessary or the schematization reexamined.

Checks are available in the program to determine the seriousness of violation of water mass conservation resulting from numerical procedures. These are discussed in part II.

Dispersion Equation

Two types of instability occur in the quality program. Recently, attention has been directed to these aspects by various authors (Orlob, et al., 1967; Bella and Dobbins, 1968; Prych, 1969).

Briefly, the problem occurs in the form of numerical errors in the convective transport calculation in that mass concentration is not conserved and a pseudo-dispersion of substance occurs. If diffusion is included in the dispersion equation, the error is masked as a longitudinal spreading of material in a manner that appears to be a turbulent diffusion of the substance. If the diffusion term is not included in the equation, then an initial load distributed evenly throughout a given channel should move as a self-contained parcel, i.e., it should not spread out with time.

Because the channel lengths and integration time steps are fixed (in the analysis under discussion), the velocity in a given channel times the time step (with resultant dimension as length) may not exactly equal the particular channel length. If it were exactly equal, there would be no problem, hence, a condition similar to the Courant Conditions for maximum stability would hold. In essence, then, more material may be transported into a junction than the junction can hold or more may be withdrawn than actually exists. Program statements are written to prevent negative concentrations or this type of supersaturation for dissolved oxygen concentrations. For other substances the statements are an indication of instability and a determination of the seriousness of the condition must be made.

The transport term ΔM_{ps} due to the "pseudo-dispersion" phenomenon can be expressed as follows:

$$\Delta M_{ps} = K_{ps} \; A_i \; \frac{\Delta C}{L_i} \; \Delta t,$$

where

K_{ps} = Pseudo-dispersion coefficient (L^2T^{-1})

A_i = Channel cross-section area (L^2)

$\Delta C/L_i$ = Concentration gradient (ML^{-4})

Δt = Time step (T).

The term K_{ps} will depend on the particular difference scheme employed and (Bella, 1969) can be roughly computed from:

27) $$K_{ps} = \frac{V_i}{2} [(1 - 2\gamma)L_i - V_i\Delta t]$$

γ = 0 for a backward difference solution

= .25 for a quarter-point difference solution

= 0.5 for a central difference solution

= 1.0 for a forward difference solution.

While some choices of γ will minimize ΔM_{ps}, they may prove to contribue to instability in the form of oscillations about the solution points.

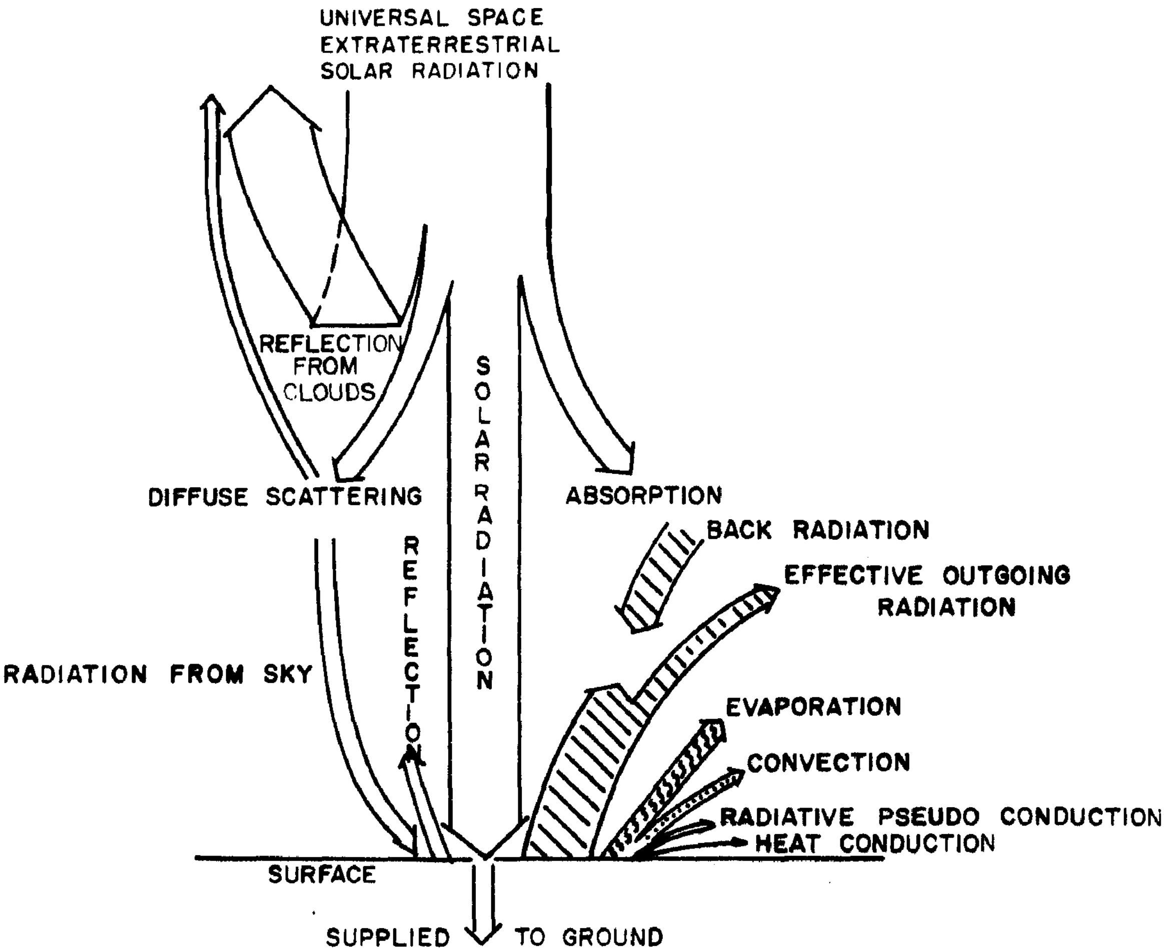
The pseudo-dispersion transport term is minimized in the quality program by employing the quarter-point method which yields "reasonably" accurate and stable solutions. Further testing of the model with the diffusion term omitted and various difference approximations is anticipated for branched junction schematizations.

HEAT BUDGET TERMS

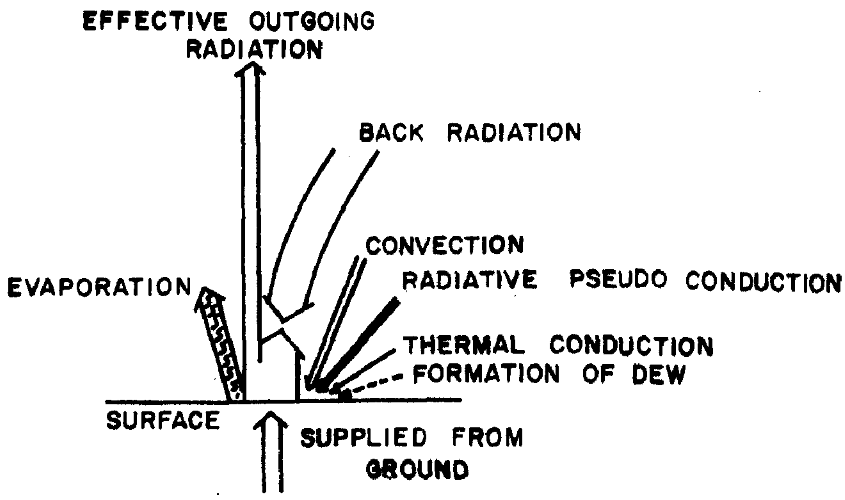
Only a brief discussion of heat budgetry will be given here since a certain familiarity with the subject is assumed and there are any number of excellent texts and papers readily available.

Figure 7 illustrates the heat exchange processes at an earth boundary during the day and at night. Similar magnitudes of energy transfer components hold for water surfaces, except for the evaporation term which may be relatively larger. It can be seen that some processes considerably outweigh others; in the heat budget formulation used here, this is reflected in the neglect of radiation pseudo-convection and heat conduction. Also neglected are terms for conduction of heat through the earth-water interface and advection by rain.

In any given time period, the temperature at a fixed point (Eulerian analysis) will be raised or lowered or remain constant depending on the heat balance of the heat budget terms and the advection and diffusion rates during that time period. The time period used in this discussion corresponds to the time step employed in the temperature simulation (program QUALTEMP). The net rate can be computed from empirical formulas; the formula summary prepared by TVA (1967) was used in the following resume as a basic reference. The system of units employed are: length in meters (M), mass in kilograms (KG), time in seconds (SEC), pressure in millibars (MB), temperatures in degrees centigrade (^{o}C) and degrees Kelvin (^{o}K) and heat in kilocalories (KCAL).



Energy balance at noon on a sunny day. The width of the arrows is proportional to the amount of energy transferred.



Energy balance at night drawn to the same scale as above.

FIGURE 7. Energy Balance Terms (From R. Gieger, "The Climate near the Ground," pp. 7, Harvard University Press, Cambridge, Mass. 1957)

Heat Flux Through the Water Surface, q_H, (KCAL $M^{-2}SEC^{-1}$)

28) $q_H = q_{sn} + q_{atn} + q_w + q_e + q_c$, where

q_{sn} = Net solar radiation flux, +:incoming

q_{atn} = Net atmospheric radiation flux, +:incoming

q_w = Water surface radiation flux, -:outgoing

q_e = Evaporative heat flux, -:outgoing

q_c = Convective heat flux, ±:either way, depending on the difference in air and water temperature (+, if $T_a > T_s$).

The first two terms on the right of (28) are discussed only briefly. They are quite complicated functions, but easily computable. It is assumed that the available meteorological programs have been made use of to obtain $q_{sn} + q_{atn}$ for specific times and geographic locations under discussion, or that direct measurements are available. These two terms are independent of the water surface temperature (unlike q_e, q_w, q_c) and can be computed by an external program not necessarily linked to that under discussion. Since a one-dimensional model is employed, all net incoming radiation is absorbed at the surface; it is distributed evenly throughout the water column via the one-dimensional assumption.

The temperature dependent heat budget terms are computed at each time step. The initial, or most recent, value of temperature is used in the formulas for q_e, q_w, q_c, to obtain new values which are in turn summed with the independent terms to compute a new net flux.

Temperature Dependent Terms, - Computation

The dependence of the surface temperature is direct for q_w and q_c and somewhat indirect for q_e as can be seen in the following approximations:

29) $q_w = a\cdot(T_s + 273.16)^4$

30) $q_c = b\cdot(T_s - T_a)$

31) $q_e = c\cdot(e_s - e_a)$,

where

T_s = Surface water temperature (^oC)

T_a = Air temperature (^oC)

e_s = Pressure of saturated water vapor at temperature T_s

e_a = Pressure of water vapor in ambient air

a,b,c = Empirical coefficients.

Back Radiation, q_w, (KCAL $M^{-2}SEC^{-1}$)

All bodies emit radiation at a rate proportional to the fourth power of the absolute temperature (T_o) of their surface. The heat budget term accommodates this phenomenon through the back radiation term, q_w. The surface radiation formula is:

32) $q_w = \varepsilon \cdot \sigma \cdot T_0^4$, where

ε = 0.97, the emissivity

$\sigma = 1.36 \times 10^{-11}$ KCAL $M^{-2}SEC^{-1}$ $^{O}K^{-4}$, the Stefan-Boltzman constant.

<u>Evaporation Heat Exchange, q_e, (KCAL $M^{-2}SEC^{-1}$)</u>

Heat loss by the vaporization of water is expressed by:

33) $q_e = \rho_w \cdot E \cdot HV$, where

E = Rate of water loss due to evaporation, M SEC^{-1}

HV = Latent heat of vaporization, KCAL KG^{-1}

ρ_w = Water density, 1000 KG M^{-3}.

E is computed by means of the formula:

34) $E = N \cdot U \cdot (e_s - e_a)$, where

N = Empirical constant, MB^{-1}

U = Wind speed, M SEC^{-1}. (If the reported wind speed is <0.05, it is set = 0.05 in the program.)

Provision is made in the program to write N*U as

N*U = (A + BB*U)

to accommodate usage of the many existing empirical evaporation formulas and where A, BB are empirical coefficients.

The heat vaporization term (KCAL KG^{-1}) is written:

$$HV = 597. - 0.57 \cdot T_s.$$

The vapor pressure terms (MB's) are computed through exponential approximation formulae first employed by Lamoreaux (1962) through the Clausius-Clapeyron equation. The coefficients used are taken from a WRE report (1969):

$$e_s = 2.1718 \times 10^8 \exp(-4157.0/(239.09 + T_s))$$

$$e_a = 2.1718 \times 10^8 \exp(-4157.0/(239.09 + T_{wb}))$$
$$-AP(T_a - T_{wb})(6.6 \times 10^{-4} + 7.59 \times 10^{-7} (T_{wb})),$$

where

T_{wb} = Wet bulb temperature (^oC)

AP = Air pressure (MB).

Convection Heat Exchange, q_c, (KCAL $M^{-2}SEC^{-1}$)

Convective exchanges, as sensible heat transfer, far outweigh conduction heat exchanges (which are neglected).

Although direct measurements of both q_e and q_c are possible, their measurement is quite complex due in part to instrumentation difficulties and the necessity to somehow measure turbulent flux terms (which are masked in transfer coefficients).

The method used here is to employ the Bowen ratio:

$$BR = q_c/q_e;$$

since q_e is easily computed (but not necessarily an accurate estimate) q_c can be evaluated through:

35) $q_c = BR \cdot q_e$.

The Bowen ratio is computed as follows:

$$BR = 6.1 \times 10^{-4} \cdot AP \cdot \left(\frac{T_a - T_s}{e_s - e_a} \right) .$$

Summary of Heat Budget Step

Initial conditions are used to compute the dependent heat budget terms; these are summed algebraically and added to the independent terms. The net flux (q_H, which will be zero, positive or negative, depending on the relative magnitude of the terms) during a computation step (1 hour, here) is multiplied by the time step (Δt) divided by density, depth (d) and specific heat (C_p) and added to the most recent temperature term:

36) $T_{new} = T_{old} + \dfrac{q_H \cdot t}{\rho_w \cdot C_p \cdot d}$.

During the next computational interval, T_{new} becomes T_{old}; advection and diffusion steps and time changes in depth are applied in the program just prior to the net heat flux step.

Equilibrium Temperature, T_e, ^oC

For a check on the temperature as computed above or as a substitute, temperature can be computed by using the "equilibrium temperature" approach. The most recent work on this subject has been conducted by Edinger, Geyer and associates whose publications (1965, 1967, 1968, e.g.) should be examined for a complete description of the subject. Briefly, the equilibrium temperature method is a shortened approximation to the net heat transfer method outlined above in that linear approximations to the vapor pressure and back radiation terms are employed. Temperature estimates can be made rather rapidly using a desk calculator if single water parcels (Lagrangian analysis) are dealt with.

An option is provided in the program to compute the exchange coefficient, equilibrium temperature, and the water parcel temperature according to the equation:

37) $T_s = T_e + (T_{old} - T_e) \exp(- \frac{K \cdot t}{\rho_w \cdot C_p \cdot d})$,

where

T_e = Equilibrium temperature, ^oC

K = Thermal exchange coefficient, KCAL $M^{-2} SEC^{-1}$ $^oC^{-1}$.

Equation 37 could be used in itself for an analysis where the coordinate system moved with the water parcel; it is known as the exponential temperature decay equation.

SCHEMATIZATION

General

Details of the schematization of the Columbia River under tidal influence are described in detail below to exhibit the geographic and hydrologic input data for the model. The total schematization (Figures 8 - 11) consists of 396 finite elements called "junctions," each of which is an arbitrarily-shaped area centered about a junction point; the junctions are connected by 432 "channels." The large scale work charts of the schematization shown in Figures 8 - 10 which include the numbering system and other detail are on file at our laboratory. Part II explains how to select boundary conditions such that only portions of the schematization need be used.

Base Charts and Data Sources

The schematization was prepared primarily from U.S. Coast and Geodetic Survey navigation charts numbers 6151, 6152, 6153, 6154, and 6156, scale 1:40,000. Coast and Geodetic Survey Chart number 6155, scale 1:20,000, and U.S. Army Corps of Engineers dredge sheets, scale approximately 1:5040, were also used to obtain geographic data for selected areas of the river system.

Flow data were obtained from records of the U. S. Army Corps of Engineers, Portland District, and summarized by FWPCA personnel in the Pacific Northwest Regional Office.

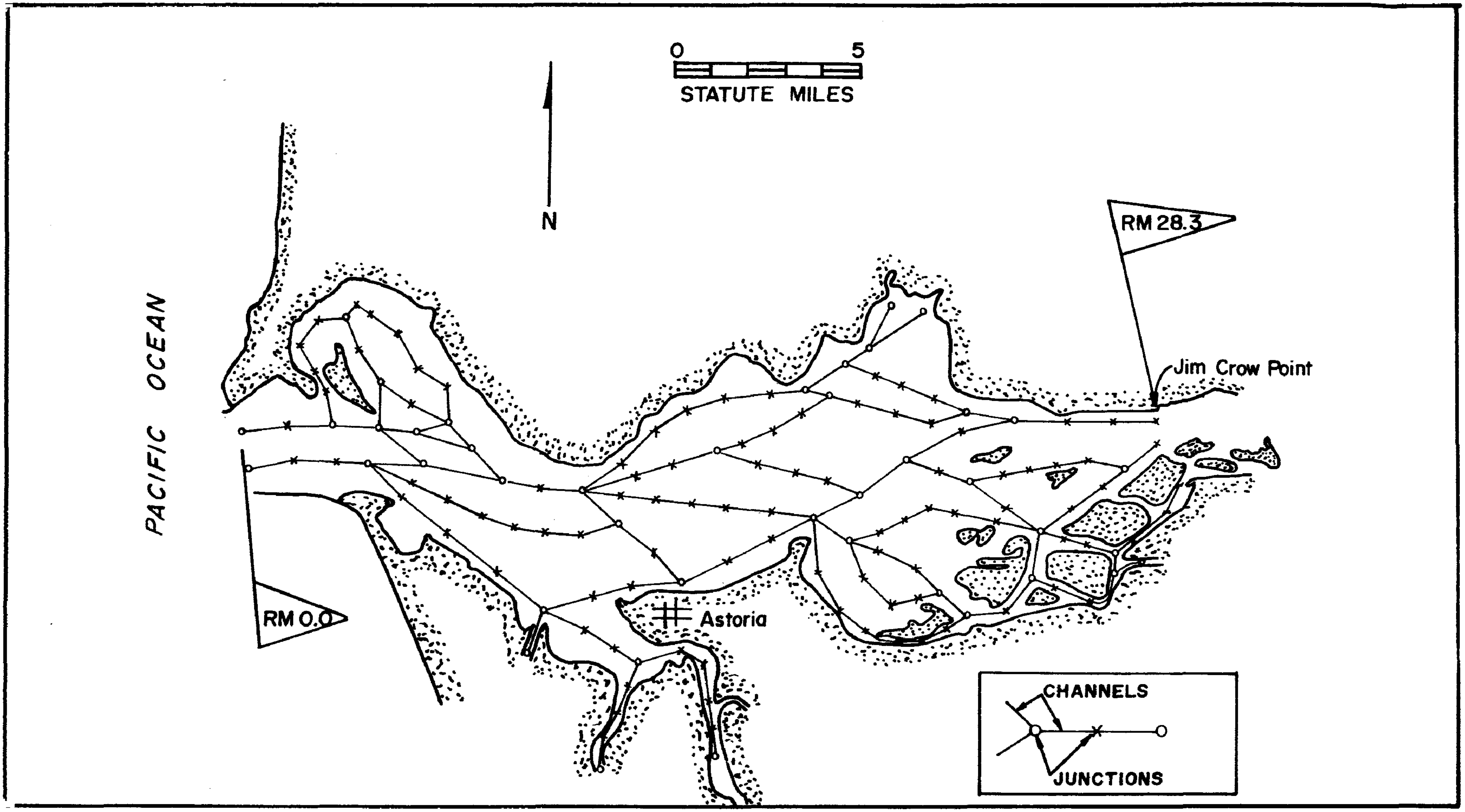


FIGURE 8. COLUMBIA RIVER SCHEMATIZATION
RIVER MILE 0.0 (PACIFIC OCEAN) TO
RIVER MILE 28.3 (JIM CROW POINT)

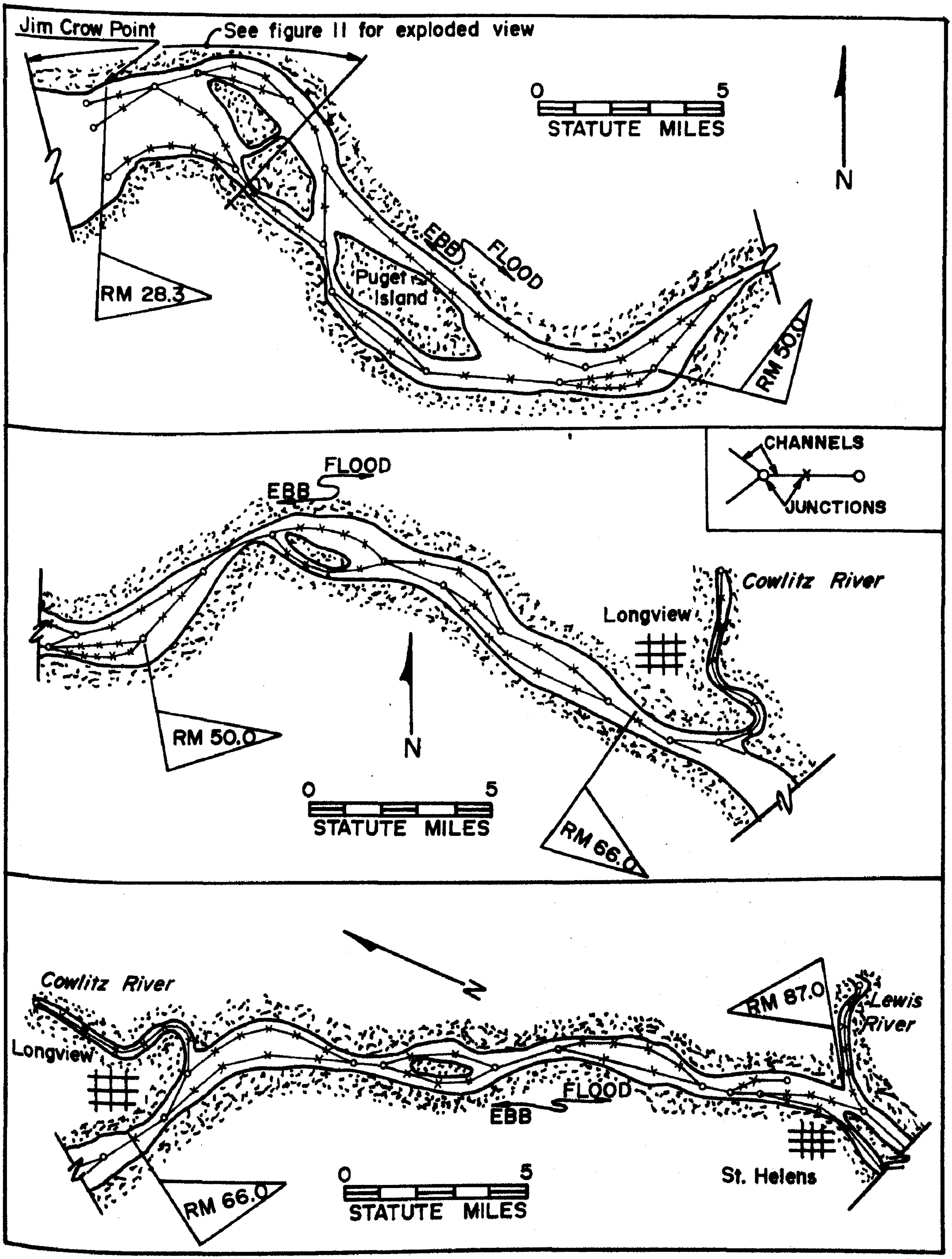


FIGURE 9. COLUMBIA RIVER SCHEMATIZATION RIVER MILE 28.3 (JIM CROW POINT) TO RIVER MILE 87.0 (LEWIS RIVER)

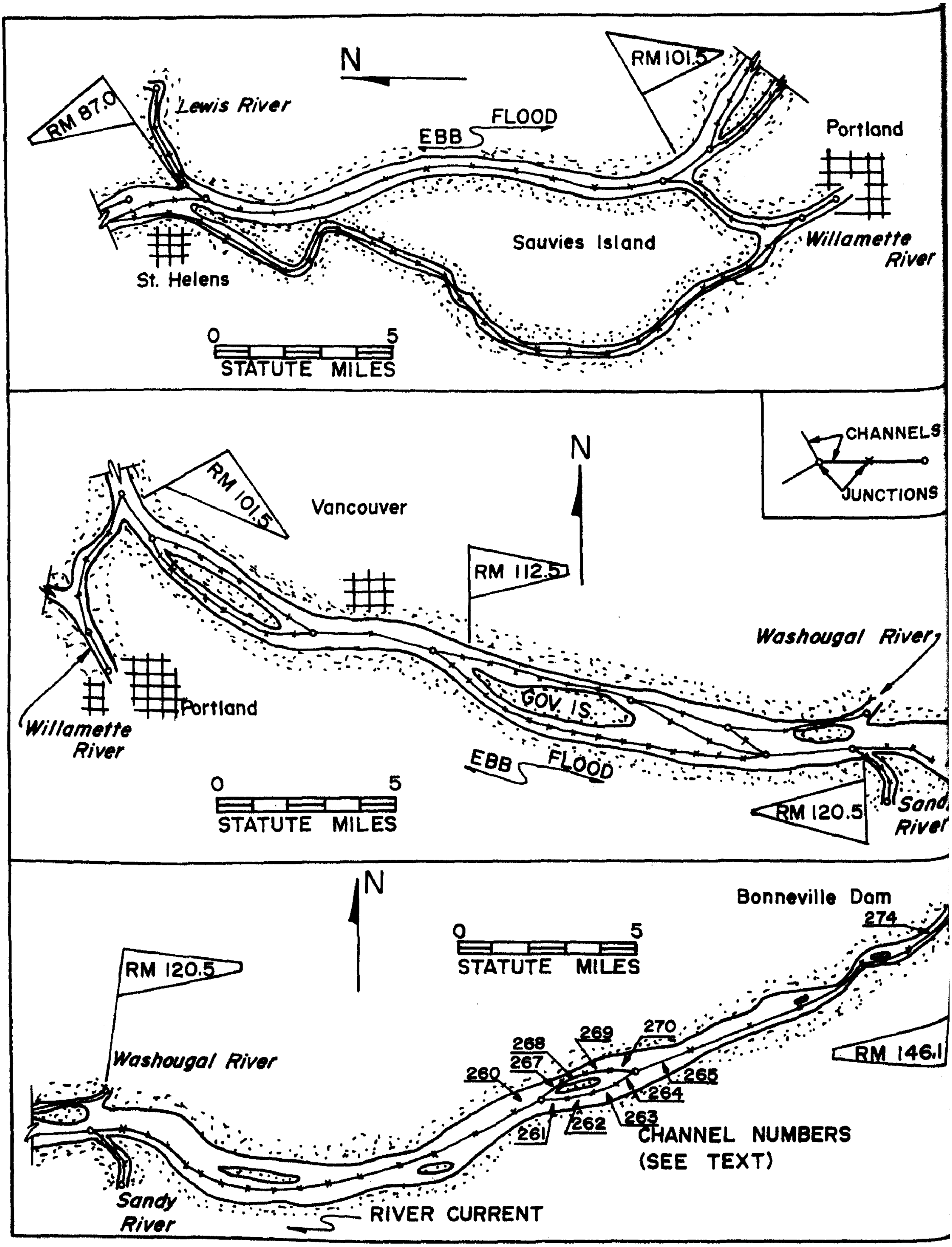


FIGURE 10 COLUMBIA RIVER SCHEMATIZATION
RIVER MILE 87.0 (LEWIS RIVER) TO
RIVER MILE 146.1 (BONNEVILLE DAM)

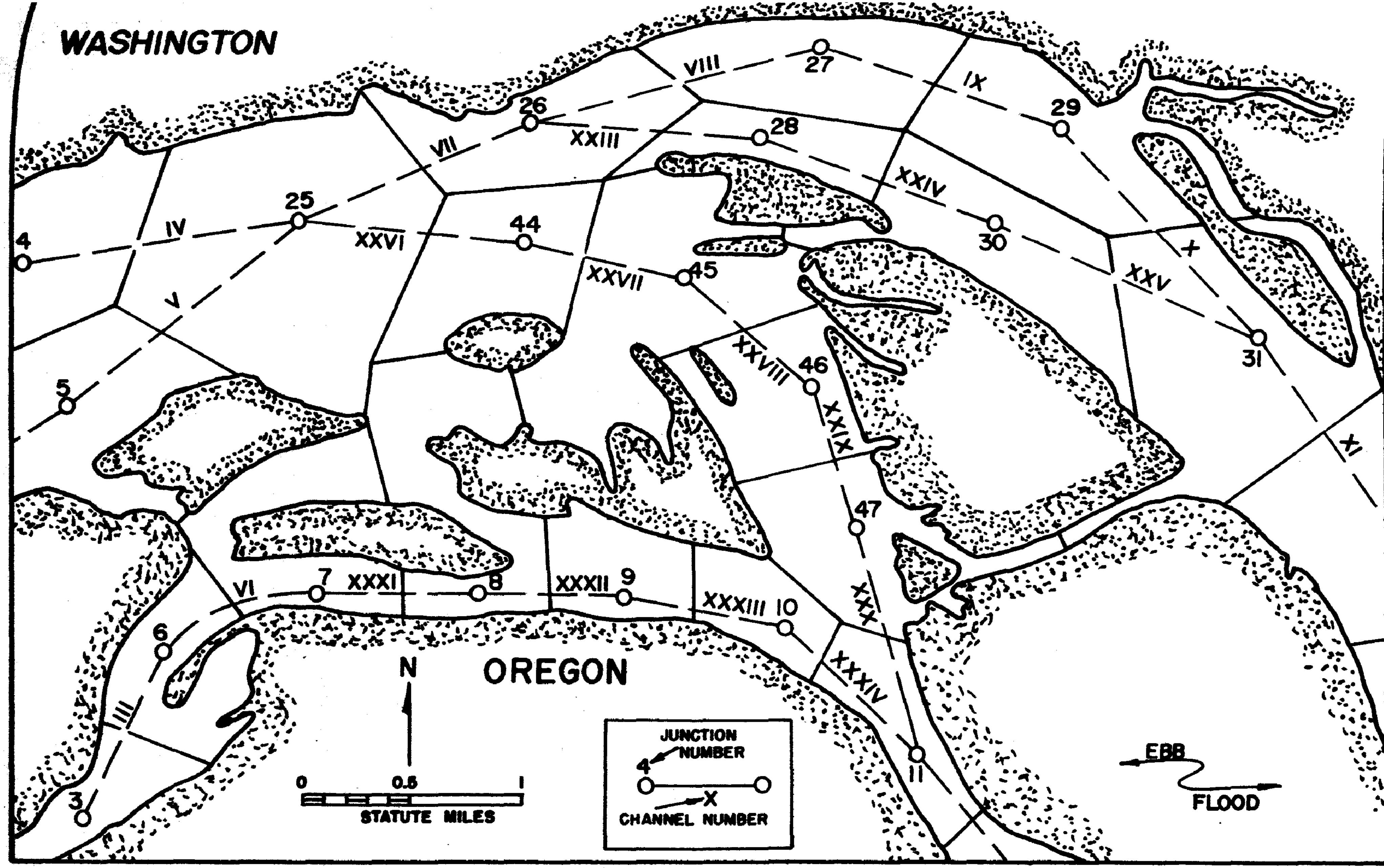


FIGURE 11. COLUMBIA RIVER OREGON-WASHINGTON SCHEMATIZATION RIVER MILE 28 TO RIVER MILE 35 (EXPLODED VIEW OF FIGURE 9 TOP)

Tidal information was taken from Coast and Geodetic Survey tide tables and navigation charts.

Datum Planes

Stream depths on the navigation charts are referenced to mean lower low water at lowest river stages, Columbia River Datum; mean sea level is used as the datum plane.

River Boundaries

Heavy black lines on the base charts mark the river bed boundaries. These lines were traced on overlay paper to provide an outline of the river. All islands, lower reaches of major tributaries, and major sloughs were outlined. Minor tributaries and sloughs were not included.

An exception to these boundaries is from river mile 125 to river mile 146. In this segment, the boundaries of the river were taken at the M.L.L.W. level; that is, the first dotted line within the riverbed proper. On the charts, these lines separate inter-tidal areas (green colored) from the water (blue colored). The decision to use this line as a boundary in this reach of the river was based on the assumption that tidal influence was minimal in this reach and that the primary use of the model would be to simulate low river flow conditions.

Junction Point Layout

The overlay was placed on the base chart and the apparent main flow routes sketched. The depth and width of the riverbed, islands, etc. were considered in this preliminary sketch. After it was felt the flow pattern was reasonably represented, the junction points were plotted on the overlay. Establishing these points (as well as sketching in the flow) is somewhat of an art; however, certain criteria must be met. These are discussed in the following section.

Boundaries were then established around the junction points. That part of a boundary between junction points connected by a channel was drawn across the channel, near its midpoint, to the edge of the estuary schematization or to the boundary separating unconnected junction points. Nominally these bounds are perpendicular to the channels. In the narrower parts of the schematization and in those areas where junction points lie near the side of the schematization, the schematization boundary forms part of the junction boundary. In the wider parts of the schematization bounds between unconnected junction points were somewhat arbitrary and generally were drawn along intertidal areas and shoal areas.

Criteria for Selecting Junction Points

The selection of junction points and the distance between points is based upon an initial choice of integration period and an "average" channel depth between junctions. As stated earlier the maximum average depth, H_{max}, determines the speed of a shallow water wave according to $\sqrt{gH_{max}}$. For a given integration time, Δt, the channel length, L_i, is limited according to the quantity[1/]

$$L_i \geq \Delta t \sqrt{gH_{max}} .$$

As mentioned before, the first "free hand" schematization is based on a pre-selected Δt. The actual channel depths, the areas of interest, the divergency and convergence of channels, and the detail one wishes to go into enter into the selection of junction points. Once this first selection has been made, it is possible to compute the required topographic information from a knowledge of the mean depths in each junction and the surface areas of the junctions.

Data Obtained from the Schematization

Upon completion of the schematization, pertinent input data for the model program were obtained from each junction and each channel.

Each junction has as input data: a number, from one to five channels connected to it, a surface area and an initial head. In

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[1/] The relation is more complicated as was discussed earlier; however, this simple formula was used to estimate the successive channel length in the actual schematization.

addition, those junctions located where a tributary enters the river has as input data the flow of that tributary.

Each channel has as input data: a number, two junctions connected to it, a width, a depth, an initial streamflow velocity, and a Manning coefficient.

Derivation of these data from the schematization and other pertinent records are discussed in the following sections.

Junction Data

Junction Numbers

There are 396 junctions or junction points in the entire scheme numbered from 1 through 396 inclusive. The schematization was prepared in two sections. Section I extends from river mile 28.3 (Jim Crow Point) to river mile 146.1 (Bonneville Dam) and the junctions are numbered consecutively from 1 though 260.

Section II of the scheme extends from river mile 0 (Pacific Ocean) to river mile 28.3. To facilitate the location of starting points in this part of the scheme, the two junctions at the seaward end were numbered 1 and 2, respectively. Those junctions near river mile 28.3 which had been numbered 1, 2, and 3 in Section I were renumbered 261, 262, and 263, respectively.*

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*It would have been easier to rewrite the program to handle any numbering system at the ocean end. This has been done by D. Fitzgerald (Northeast FWPCA Regional Office) for Boston Harbor; unfortunately we didn't think of it in time.

Additionally, junctions in Section II were renumbered 1 through 142 inclusive in order that Section II of the scheme could be operated independently of Section I.

Junction Surface Area

The surface area of each junction, at mean tide level datum, was measured with a planimeter and recorded in square feet.

Those junctions which have major sloughs entering them have included in their surface area the surface area of those sloughs.

Initial Head

The initial heads for each junction (the approximate height of the water surface at a flow of 147,200 C.F.S. at Bonneville Dam) were obtained from Corps of Engineers records. A graph of the heads at selected river mile intervals was prepared and the appropriate datum taken from the graph for each junction. Initial heads could have been taken as 0.0 throughout at the expense of a delay in convergence in the iteration.

Number of Channels at a Junction

From one to five channels may enter each junction. The number of each channel entering is listed as input data. The lowest numbered channel entering is listed first, the highest numbered channel last. More than five channels may be accommodated by appropriate increases in the program dimension statements.

Junction Depths

After the schematization was prepared, the mean depth of each junction was determined.* The technique for doing this is described below:

A transparent grid overlay consisting of 225-600 foot square squares, scale 1:40,000, was prepared. The steps given below outline the procedure for finding the depth of a junction.

1. The grid was placed over a junction outline on the base chart.

2. The depth at the center of each 600-foot square was read and recorded. A detailed explanation of this procedure is given in the paragraphs following these steps.

3. The square was marked with a grease pencil and counted.

4. In each junction, there were always some grid squares that fell on the junction boundaries, putting only parts of the grid squares within the junction boundary. These parts of grid squares were summed mentally to make a whole grid square and the depth estimated and recorded.

5. The sum of the squares read for each junction divided into the sum of the depths gave the mean depth for the junction.

---

*The depths thus calculated are not used directly in the program but were made to provide an independent deck of depths computed in the program from junction volumes and surface areas.

The procedure and the data entered on each card are described below.

1. The junction number was read and entered on the punch card in columns 1-3.

2. The card number was entered in column 4. Most of the junctions required that more than one card be used to record all the depth readings. The cards required for each junction were numbered sequentially from 1 through the number required.

3. The size of the grid squares being used was entered in columns 5-7.

4. The stage correction was entered in columns 8-10. The stage correction was applied to depths obtained from the chart, referenced to mean lower low water to obtain a depth referenced to mean tide level. The stage correction varied for different reaches of the river. Near the seaward end, it was 4 feet; in the reach immediately below Bonneville Dam, it was taken as 0. The stage correction was made to the nearest whole foot (Table 1, Stage correction vs River Miles).

TABLE 1

STAGE CORRECTIONS VS. RIVER MILES

Stage Correction	River Miles
4 feet	0 - 28
3 feet	28 - 50
2 feet	50 - 76
1 foot	76 - 122
No correction	122 - 146

5. The number of channels entering a junction was entered in column 11.

6. All of the data in columns 1-11 were entered on each card being used for a particular junction.

7. Depth data, read directly from the base charts, for each grid square was entered in columns 12 through 80. Three columns were used for each reading.

8. As noted in 4 above, all depths read directly from the chart were referenced to mean lower low water. This situation caused intertidal areas, shown in green on the charts, to be above the datum from which depths were read. In order to accommodate these areas, a negative depth, corresponding to the stage

correction applicable to that particular junction, was read by the reader when such an area occurred under a grid square. The depth was entered on the card with a 90 preceding it. For example, the intertidal area of a junction in that reach of the river having a stage correction of 3 feet would be entered on the card as 903.

9. After all the grid squares had been read and accounted for, a 999 was entered on the card to indicate the end of data for that junction.

10. Frequently, the reader and the keypunch operator would change roles and the junctions would be read a second time.

11. The two independent mean depths were compared; if the difference between them was less than two feet, the mean of the two readings was taken as the junction depth. If the two depths varied by two feet or more, the junction was read one or more times to obtain a usable junction depth.

Tributary Stream Flows

Flow data for several tributaries which enter the Columbia River were available from Corps of Engineers records. These data were entered as input data for the junctions in which the tributaries joined the river.

Channel Data

Channel Numbers

Channels in Section I of the scheme were numbered from 1 through 276 inclusive.

In Section II of the scheme, the two channels near the seaward end of the scheme were numbered 1 and 2, respectively. Those channels near river mile 28.3, which had been numbered 1, 2, and 3, were renumbered 277, 278, and 279, respectively. Additionally, the channels in Section II were renumbered from 1 through 159 inclusive, in order that it could be operated independently of Section I.

Channel Length

The length of each channel between two connected junctions was measured in feet and ranged from about 2,000 feet to about 12,000 feet.

Channel Depths

The depth of each channel is taken as the mean of the two depths of the junctions which that channel connects. It was felt that the preliminary smoothing effected by this averaging would compensate for channels lying partly in deep water and partly in shallow water.

Channel Widths

The widths of each channel were measured along the junction boundary which crossed a channel near its midpoint. Widths were measured in feet. Widths were measured at both M.L.L.W. and M.T.L.

Cross-sectional Area

In Section I, cross-section areas were constructed along each junction boundary crossing a channel, planimetered, and reported in square feet.

Cross-sectional areas in Section II were obtained by multiplying the M.T.L. width of a channel by its mean depth referenced to the appropriate datum.

Channel Flow

Streamflow in each channel was used to calculate initial velocities. Arbitrary initial velocities could also have been used; the extra work involved here was felt worthwhile in order to reduce the possibility of instability due to a bad choice of initial conditions which might have been difficult to correct.

The total flow in the river (at the mouth) was taken as the sum of the flow at Bonneville Dam plus the flow from tributaries, for which data were available, during the modeling period.

Flow in each channel was derived from the flow in the channel immediately upstream from it plus any flow entering from a tributary.

For example, in channel number 274, immediately below Bonneville Dam (see Figure 10), the flow is 147,200 C.F.S. (measured at Bonneville).

The flow remains constant for all channels downstream through number 265. This channel branches into channel numbers 264 and 270, respectively.

To find the flow in each of these channels, a straight line partitioning was done in the following fashion.

The sum of the cross-sectional areas of channel numbers 264 and 270 was found and the percentage each channel contributed to this total was calculated. This percentage was then multiplied by the flow in channel number 265 (the branching channel) to give the flow in 264 and 270, respectively.

Flow in channel #265 = 147,200 ft^3/sec.

Cross-section area channel #270 = 21,714 ft^2 = 36% of total

Cross-section area channel #264 = 38,164 ft^2 = 64% of total

Total = 59,878 ft^2

Flow in channel #264 = (0.64)(147,200 ft^3/sec) = 93,800 ft^3/sec.

Flow in channel #264 = (0.36)(147,200 ft^3/sec) = 53,360 ft^3/sec.

The flow in channel numbers 267, 268, and 269 remain the same as the flow in channel 270. Similarly, flow in channel numbers 261, 262, and 263 remain the same as the flow in channel number 264.

The flow in channel number 260 is the sum of the flow in channel numbers 261 and 267.

Similar partitioning and summing of flows was done throughout the scheme; about four hours were required to complete the entire channel initialization.

Channel Velocity

The initial water velocity (owing to streamflow) in each channel was found by dividing the flow in that channel by its cross-sectional area. If a channel ended in a slough or in a tributary with no recorded flow data, the velocity was set to zero.

Computing the velocities in this manner resulted in what were to be unrealistic velocities in some channels, on the order of 10 feet per second. When such velocities occurred, the width or depth of the channel was arbitrarily reduced an appropriate amount to make the flow realistic. Such changes were made in channel numbers 69, 70, 71, 72, 85, 206, 222, 234, 235, 236, 237, 240, 241 and 250.

DISCUSSION

Deterministic pollution models of the environment usually involve analytical or numerical solutions of the dispersion (or advection-diffusion) equation. The numerical methods employed are likely to be identical regardless of the constituent involved, hence a generalized model should obviate the necessity of deriving a new model for different topographical settings and constituents. This being the case an existing model was modified to handle temperature; the solutions obtained are thus forms of the energy equation.

Where Coriolis terms are unimportant and stratification (either vertical or horizontal) is slight, the finite element representation of two-dimensional environments may be quite satisfactory. If the Coriolis force is not negligible, then the methods used will not suffice since the velocity term in the y-direction is required in a solution of the x-direction equation of motion.

Since many open estuarine areas consist of numerous scoured channels, the junction-channel representation of these areas may not be as forced as it may first appear. Certainly, the use of a one-dimensional approach to sections of a tidal river may be questioned, but it is also questionable if a fine grid model incorporating horizontal shear terms would add a great deal to our present state of knowledge. One reason for this is the very difficult verification procedure which would be required for such a model, especially under different wind, tide and runoff conditions. It is well known that the only real limitation we have in the complete solution of the Navier-Stokes equations is one of computer hardware. Doubtless we will have mind-bogglingly fast machines with almost unlimited storage capacity sometime in the near future, but the big question is likely to remain on how to handle and verify the rather simple models we have even now. Such problems will always face the model user; if the uses of modeling are to be well served, verification will go hand-in-hand with modeling use.

In flood routing problems and for high-accuracy displays of periodically exposed tidal flats, procedures must be employed to allow for time-varying channel widths. Where very accurate representations of tidal flow are required, it may not be enough to vary only the cross-section; in this model, however, rectilinear channels were assumed and cross-section variation occurs only by a change in stage elevation. The two-dimensional model employed by Leendertse (personal communication) on Jamaica Bay, New York, apparently accounts for tide flat exposure every five time steps. Such models are highly desirable if not absolute necessities in shallow estuaries such as Tillamook Bay and other areas where only a stream cuts through extensive tide flat areas at low water. But again, "absolute necessity" can be tempered to the purposes of the modeler or manager and perhaps less rigorous approaches may suffice for certain aspects of a particular pollution model. It should be noted that a model such as Leendertse's or the one described here requires several years of continuous development, and pollution agencies usually operate on far more demanding time scales.

In the matter of the heat budget calculations (where Part II provides examples) it is known that the heat exchange process at the surface is much more involved than would be implied by the equations employed. Air-sea interaction occupies a large area of research in the oceanographic and meteorological community and involves studies of the flux of heat and momentum to and from the atmosphere. Turbulent processes at the surface are still rather mysterious, so ultimate solutions of heat budget processes are not likely in the immediate future; the approximations employed, however, have given reasonably satisfactory answers where verification has been possible.

Of more concern in certain areas, particularly the stratified marine environment, is the role that vertical velocity and density variations play in the overall pollution dispersion problem. Here again, field studies with an end to verification are major undertakings. As an indication of the upper part of the scale, field programs conducted by the U. S. Army Corps of Engineers for the purpose of verifying their movable-bed hydraulic model cost approximately $250,000. Aside from the usually back-breaking process of field collection is the general inadequacy (in terms of ease of use and reliability) of water quality measuring devices. (If the data has to be collected over one or more tidal periods, it is usually a toss-up as to whether the electronic gear will give out before the field personnel do.)

Finally, if it is assumed that the well-planned survey goes off without a hitch and the measuring devices do not balk, data reduction and analysis will surely manage to contain unplanned for and/or uncorrectable situations.

So much for executing the faultless survey; what is one to do? Short of designating the problem of verification and field collection as someone else's business, it behooves the model user and builder to be aware of what goes into the various terms and coefficients in order that they may be properly sampled or estimated at the appropriate time. He should also be aware of the realities and limitations of field techniques and existing instrumentation, as well as being aware of possible alternative solutions such as hydraulic models or strictly analytical solutions.

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APPENDIX I

NOTES FOR PROGRAM HYDRA

"...free from bugs,...
if possible,
If you know any such."

Aristophanes. The Frogs.

APPENDIX I

NOTES FOR PROGRAM HYDRA

Logical unit (or data set reference) numbers:

A time sharing conversational computer system was used for much of the work on the programs done in connection with this paper. Several separate data files were created for different portions of the input data; the program then referenced each file with a different unit number.

Most operating systems have facilities for equating different unit numbers to the same source. If card input is used, units listed below as card image input should be equated to the card reader.

Unit Number	Use
5	Control and System Input (card images)
6	Standard Output (printer)
7	Junction Input (card images)
8	Channel Input (card images)
9	Restart Output (card images)
10	Output for HYDEX (binary tape images)

PROGRAM NOTES

Program HYDRA

Sequence No.	FORTRAN Name	Comments
Dimensioned variables		
	AREA AREAT V VT Y YT	In the Runge-Kutta integration scheme, the variable quantities head (Y), velocity (V), and cross-sectional area (AREA), are extrapolated forward a half-cycle. The extrapolated values are held in arrays YT (for Y temporary), VT, and AREAT. The temporary values are then used to compute the new values at the time one cycle forward. Heads are junction properties, velocities and areas are channel properties.
Dimensioned variables		
	AK	Constant used in obtaining frictional resistance term = (G*CN**2/2·21), see line 146.
	ALPHA	Alphanumeric information used to identify printout.
	AREAS	Surface area of junction determined by, e.g., planimetering.
	B	Channel width.
	CLEN	Channel length.
	CN	Friction coefficient.
	JPRT	Junction numbers where data will be printed.

Sequence No.	FORTRAN Name	Comments
	NCHAN	Channels (maximum of 5) connected to junction J., e. g., NCHAN (J,1) = channel number of first channel connected to Junction J, etc.
	NJUNC	Junctions (maximum of 2) attached to either end of channel N, e.g., ...NJUNC (N,1) = junction number at one end of channel N, etc.
	Q	Channel flow.
	QIN	Tributary inflow.
	R	Hydraulic radius (=AREA/B).
Variables in COMMON		
	DELT	Time increment (seconds) used as integration step.
	NC	Total number of channels.
	NCYC	Number of cycles hydraulic program will run.
	NCYCC	Used to hold the current cycle for use outside the main loop.
	NJ	Total number of junctions.
	NOPRT	Number of junctions for which data is to be printed.
	NPRT	Printing output interval, i.e., results are printed every NPRTth cycle.
	PERIOD	Period of input wave at ocean end, hours.

Sequence No.	FORTRAN Name	Comments
Variable names listed as they occur in the program:		
19-24		Read input information and write a general heading.
20	TZERO	Initial time of this run.
20	NETFLW	Switch to call HYDEX: ≠0,calls.
20	ISTART	If the run is a restart, this is the next cycle to be processed. (= to 1 + the cycle number written in the run to be restarted.)
20	INPSUP	If ≠0, suppresses printing junction and channel data.
23	IPRT	Start printing on cycle ___.
23	IWRTE	Write binary output on 10 beginning at cycle ___.
23	KPNCHI	The interval at which the restart records will be written.
25-30		Position tape 10 if this is a restart.
27	ISTOP	The number of the last cycle processed in the run to be restarted.
34-40		Read junction initial conditions; unless this is a restart, set YT=Y; determine if the input data cards are in the correct order.
41-44		Write junction input data unless INPSUP ≠0.

Sequence No.	FORTRAN Name	Comments
48-53		Read channel initial conditions, calculate channel cross-sectional area (see text), determine if the input data cards are in the correct order.
54-58		Write channel input data unless INPSUP $\neq$0.
62		Read the numbers of the junctions for which data will be printed.
63-64		Read and write the amplitude, phase and period of the input tide wave.
68	NEXIT	A flag which is non-zero if there is a compatibility or restart problem.
69-88		Determine that the junction and channels are connected to each other properly.
92-101		Output the control and system data to unit 10. If IWRTE is 0, (hydraulic output desired for every cycle) calculate channel flows and output initial head, speed and flow to unit 10.
105	DELT2	Half a time step.
106		Convert the initial time to seconds.
107		Convert the period in hours to seconds.
108	W	Used in the Fourier series representation of the tidal input; 2π/Period.

Sequence No.	FORTRAN Name	Comments
109-119		The restart provision has two purposes: if the program terminates abnormally, (over time estimate, system failure, etc.) a restart record can be used to start the program at some mid-point without wasting all the computer time used in getting to the point. A restart record is also made at normal termination, so that the run can be extended if desired. Writing the restart record itself uses extra time. If abnormal termination is not a problem, set KPNCHI=0, and the restart record will be made only at the end. To protect against abnormal termination, set KPNCHI≥200 or so. A restart record will be made every KPNCHIth cycle. To use the restart unit, equate it to units 7 and 8, and run the program using cards only for the unit 5 read statements, get TZERO from the last line of printed output saying, "TZERO FØR RESTARTING = ..." Set ISTART = 1 + last cycle for which restart "deck" was made.
120		If there has been a compatibility problem, or an error in KPNCHI, stop.
121	G	Gravitational constant.
125-131		Calculate the frictional constant in each channel; reorder the junction numbers if necessary.
132	T	Set time equal to the initial time.

Sequence No.	FORTRAN Name	Comments
140		Loop through sequence number 289 (statement 285) for each hydraulic cycle, through NCYC cycles.
140-143		Replace current values of NCYCC, T2 and T each time through the loop. See section on Runge-Kutta integration, explicit solution, leapfrog methods.
147-156		Compute channel speeds and flows.
150-151		Divide the frictional constant by the hydraulic radius raised to the 4/3 power after computing the current value of the hydraulic radius.
152-155	DVDX	Compute the velocity gradient (dv/dx) and channel velocity from initial or last computed values of velocity and head.
160		Compute the Fourier series representation of the input tide wave for as many junctions as are at the ocean.
161-170		Determine the sum of tributary and channel flows into each junction.
171		Find a new junction head based on the amount of water added to or subtracted from each junction.
175		Perform second step of Runge-Kutta integration substituting values previously calculated as the old values.

Sequence No.	FORTRAN Name	Comments
204-207		Compute new values of the cross-sectional area based on the increase or decrease of heads previously computed.
211-215		If this is a binary output cycle, write the cycle number, junction numbers, heads, the speeds, and flows in the channels on unit 10.
216-237		If this is a print cycle or the last cycle, enter the "selective print routine."
	Print Routine	
221-222		Convert time to hours and print a general heading.
223-237		For the junctions that are to be printed, print the junction heads. For each channel connected to said junctions, print the channel flows and speeds after determining the correct sign.
241-245		If the channel speeds during any cycle exceed a predetermined value print the cycle and channel number and EXIT.
250-258		If this is a restart record cycle or the last cycle, write on unit 9. These data can be used for initial conditions to another case or used to start up again in case the run was interrupted.

End main loop.

Sequence No.	FORTRAN Name	Comments
267-274		Make a copy of the restart information on the printer.
278		Call hydraulic extract program.

```
      PROGRAM HYDRA
C       *********************************************************
C       *              EXPLICIT SOLUTION FOR                    *
C       *       DYNAMIC FLOW IN A TWO-DIMENSIONAL SYSTEM        *
C       *        PACIFIC NORTHWEST WATER LABORATORY             *
C       *      FEDERAL WATER POLLUTION CONTROL ADMINISTRATION   *
C       *********************************************************
      DIMENSION ALPHA(72),Y(5),YT(5),AREAS(5),QIN(5),
     * NCHAN(5,5),CLEN(5),B(5),AREA(5),AREAT(5),
     * CN(5),V(5),VT(5),Q(5),R(5),AK(5),
     * NJUNC(5,2),JPRT(75),DEEP(5)
      COMMON ALPHA,Y,YT,AREA,Q,AREAS,QIN,V,B,CLEN,R,CN,DELT,
     *     NCHAN,NJUNC,JPRT,NJ,NC,NCYC,NPRT,NOPRT,PERIOD,NCYCC
      REWIND 10
      REWIND 9
C***********************************************************************
C*                    READ, PRINT, AND CHECK DATA                      *
C***********************************************************************
      READ(5,100)(ALPHA(I),I=1,36)
      READ(5,105)NJ,NC,NCYC,NPRT,NOPRT,DELT,TZERO,NETFLW,ISTART,INPSUP
      WRITE(6,110)(ALPHA(I),I=1,36)
      READ(5,530) IPRT,IWRTE,KPNCHI
      WRITE(6,115) NJ,NC,NCYC,NPRT,DELT,TZERO,IWRTE,NCYC,KPNCHI,IPRT
      IF(ISTART.EQ.0)GO TO 118
      READ(10)
      READ(10)
      ISTOP=ISTART-1
      IPRT=(ISTOP/NPRT+1)*NPRT
      DO 116 J=IWRTE,ISTOP
  116 READ(10)
C                          **********************
C                          *    JUNCTION DATA   *
C                          **********************
  118 DO 119 J=1,NJ
      READ(7,120)JJ,AREAS(J),(NCHAN(J,K),K=1,5),Y(J),QIN(J),YT(J)
      IF(ISTART.EQ.0)YT(J)=Y(J)
      IF(JJ.EQ.J)GO TO 119
      WRITE(6,117) JJ,J
      STOP
  119 CONTINUE
```

```
      IF(INPSUP.NE.0)GO TO 121
      WRITE(6,124)
      WRITE(6,125)(J,Y(J),AREAS(J),QIN(J),(NCHAN(J,K),K=1,5),
     *  J=1,NJ)
C                        ***********************
C                        *    CHANNEL DATA     *
C                        ***********************
  121 DO 129 N=1,NC
      READ(8,130)NN,CLEN(N),(NJUNC(N,K),K=1,2),R(N),CN(N),B(N),V(N)
      AREA(N)=R(N)*B(N)
      IF(NN.EQ.N)GO TO 129
      WRITE(6,127) NN,N
      STOP
  129 CONTINUE
      IF(INPSUP.NE.0)GO TO 131
      WRITE(6,128)
      WRITE(6,135)(N,CLEN(N),B(N),AREA(N),CN(N),V(N),R(N),
     *   (NJUNC(N,K),K=1,2),N=1,NC)
C                     ****************************
C                     *    MISCELLANEOUS DATA    *
C                     ****************************
  131 READ(5,137)(JPRT(I),I=1,NOPRT)
         READ(5,177)A1,A2,A3,PHI2,PHI3,PERIOD
      WRITE(6,179)A1,A2,A3,PHI2,PHI3,PERIOD
C                     ******************************
C                     *    COMPATIBILITY CHECK     *
C                     ******************************
      NEXIT = 0
          DO 150 N=1,NC
          DO 150 I=1,2
          J=NJUNC(N,I)
              DO 140 K=1,5
              IF(N.EQ.NCHAN(J,K))GO TO 150
  140         CONTINUE
          NEXIT=1
          WRITE(6,145) N,J
  150     CONTINUE
          DO 170 J=1,NJ
              DO 165 K=1,5
              IF(NCHAN(J,K))170,170,155
```

```
 155        N=NCHAN(J,K)
              DO 160 I=1,2
              IF(J.EQ.NJUNC(N,I))GO TO 165
 160          CONTINUE
            NEXIT=1
            WRITE(6,145) N,J
 165        CONTINUE
 170      CONTINUE
C ***********************************************************************
C *    WRITE INITIAL, GEOMETRIC, AND DESCRIPTIVE DATA ON UNIT 10        *
C ***********************************************************************
      IF(ISTART.NE.0)GO TO 301
      WRITE(10) (ALPHA(I),I=1,36),NJ,NC,DELT,(CN(N),R(N),B(N),
     *   CLEN(N),N=1,NC)
      WRITE(10) (Y(J),AREAS(J),QIN(J),(NCHAN(J,K),K=1,5),J=1,NJ),
     *   (AREA(N),V(N),(NJUNC(N,I),I=1,2),N=1,NC)
      IF(IWRTE.GT.0)GO TO 301
      DO 300 N=1,NC
          Q(N) = AREA(N) * V(N)
 300      CONTINUE
      WRITE(10)    IWRTE,(Y(J),J=1,NJ),(V(N),Q(N),N=1,NC)
C************************************************************************
C*                            INITIALIZATION                            *
C************************************************************************
 301 DELT2  = DELT/2.0
     TZERO  = TZERO*3600.
     PERIOD = PERIOD*3600.
     W      = 6.2832/PERIOD
     INK = 0
     IF(KPNCHI.EQ.0)GO TO 51
     KWRITE = NCYC - KPNCHI
     IF(KWRITE.LE.0)GO TO 51
  48 IF(KWRITE.LE.KPNCHI+ISTART)GO TO 52
     KWRITE = KWRITE - KPNCHI
     INK = INK + 1
     IF(INK.LT.10)GO TO 48
     WRITE(6,406)KPNCHI,NCYC
     NEXIT=1
  51 KWRITE = NCYC
  52 IF(NEXIT.NE.0)STOP
```

```
      G = 32.1739
C                   ***********************************
C                   *    COMPUTE CHANNEL CONSTANTS    *
C                   ***********************************
      DO 190 N=1,NC
          AK(N)  =  G * (CN(N)**2/2.208196)
          IF(NJUNC(N,1).LE.NJUNC(N,2))GO TO 190
          KEEP=NJUNC(N,1)
          NJUNC(N,1)=NJUNC(N,2)
          NJUNC(N,2)=KEEP
  190     CONTINUE
      T = TZERO
      IF(ISTART.EQ.0)ISTART=1
C************************************************************************
C*                                 MAIN LOOP                            *
C************************************************************************
C                            *******************
C                            *   COMPUTATION   *
C                            *******************
      DO 285 ICYC=ISTART,NCYC
          NCYCC = ICYC
          T2 = T + DELT2
          T  = T + DELT
C                  **************************************
C                  *    COMPUTE HALF CYCLE VELOCITIES   *
C                  **************************************
          DO 204 N=1,NC
              NL=NJUNC(N,1)
              NH=NJUNC(N,2)
              R(N) = AREA(N) / B(N)
              AKT = AK(N) / (R(N)**1.333333)
              DVDX = (1.0/R(N))*(((Y(NH)-YT(NH)+Y(NL)-YT(NL))/DELT)+
     *          (V(N)/CLEN(N))*(Y(NH)-Y(NL)))
              VT(N)=V(N)+DELT2*((V(N)*DVDX)-AKT   *V(N)*ABSF(V(N))
     *          -(G/CLEN(N))*(Y(NH)-Y(NL)))
  204         Q(N)=VT(N)*AREA(N)
C                   ***********************************
C                   *    COMPUTE HALF CYCLE HEADS     *
C                   ***********************************
          YT(1)=A1+A2*SIN(W*T2+PHI2)+A3*SIN(W*T2+PHI3)
```

```
      DO 225 J=2,NJ
         SUMQ=QIN(J)
         DO 220 K=1,5
            IF(NCHAN(J,K).EQ.0)GO TO 225
            N=NCHAN(J,K)
            IF(J.NE.NJUNC(N,1))GO TO 215
            SUMQ=SUMQ+Q(N)
            GO TO 220
  215       SUMQ=SUMQ-Q(N)
  220       CONTINUE
  225    YT(J) = Y(J) - ((DELT/AREAS(J))*0.5)*SUMQ
C    ************************************************************
C    *    COMPUTE HALF CYCLE AREAS, FULL CYCLE VELOCITIES       *
C    ************************************************************
      DO 230 N=1,NC
         NL=NJUNC(N,1)
         NH=NJUNC(N,2)
         AREAT(N)=AREA(N)+0.5*B(N)*(YT(NH)-Y(NH)+YT(NL)-Y(NL))
         R(N) = AREAT(N) / B(N)
         AKT2 = AK(N) / (R(N)**1.333333)
         DVDX = (1.0/R(N))*(((YT(NH)-Y(NH)+YT(NL)-Y(NL))/DELT) +
     *     (VT(N)/CLEN(N)) * (YT(NH)-YT(NL)))
         V(N)=V(N)+DELT*((VT(N)*DVDX) -AKT2 *VT(N)*ABSF(VT(N))
     *     -(G/CLEN(N)) * (YT(NH)-YT(NL)))
  230    Q(N)=V(N)*AREAT(N)
C           ********************************
C           *    COMPUTE FULL CYCLE HEADS  *
C           ********************************
      Y(1)=A1+A2*SIN(W*T+PHI2)+A3*SIN(W*T+PHI3)
      DO 255 J=1,NJ
         SUMQ=QIN(J)
         DO 250 K=1,5
            IF(NCHAN(J,K).EQ.0)GO TO 255
            N=NCHAN(J,K)
            IF(J.NE.NJUNC(N,1))GO TO 245
            SUMQ=SUMQ+Q(N)
            GO TO 250
  245       SUMQ=SUMQ-Q(N)
  250       CONTINUE
  255    Y(J) = Y(J) - (DELT/AREAS(J))*SUMQ
```

```
C                  **********************************
C                  *    COMPUTE FULL CYCLE AREAS    *
C                  **********************************
      DO 256 N=1,NC
          NL=NJUNC(N,1)
          NH=NJUNC(N,2)
  256     AREA(N) = AREAT(N)+0.5*B(N)*(Y(NH)-YT(NH)+Y(NL)-YT(NL))
C*****************************************************************************
C*                MAIN LOOP (CONTINUED)    OUTPUT                            *
C*****************************************************************************
      IF(ICYC.LT.IWRTE)GO TO 259
C                       ************************
C                       *   BINARY TAPE OUT    *
C                       ************************
      WRITE(10)   ICYC,(Y(J),J=1,NJ),(V(N),Q(N),N=1,NC)
  259 IF(ICYC.NE.IPRT.AND.ICYC.NE.NCYC)GO TO 263
C                         ********************
C                         *   PRINTER OUT    *
C                         ********************
      IPRT=IPRT+NPRT
      TIME = T/3600.0
      WRITE(6,302) ICYC,TIME
      DO 340 I=1,NOPRT
          J=JPRT(I)
          WRITE(6,305) J,Y(J)
          DO 335 K=1,5
              IF(NCHAN(J,K).EQ.0)GO TO 335
              N=NCHAN(J,K)
              IF(J.NE.NJUNC(N,1))GO TO 320
              VEL=V(N)
              FLOW=Q(N)
              GO TO 325
  320         VEL=-V(N)
              FLOW=-Q(N)
  325         WRITE(6,330) N,VEL,FLOW
  335         CONTINUE
  340     CONTINUE
C                ****************************************
C                *   CHECK FOR REASONABLE VELOCITIES    *
C                ****************************************
```

```
  263     DO 275 N=1,NC
              IF(ABSF(V(N)).LT.20.)GO TO 275
              WRITE(61,270) ICYC,N
              STOP
  275         CONTINUE
          IF(ICYC.NE.NCYC.AND.ICYC.LT.KWRITE)GO TO 285
C                    **************************
C                    *    MAKE RESTART TAPE   *
C                    **************************
          WRITE(9,120)(J,AREAS(J),(NCHAN(J,K),K=1,5),Y(J),QIN(J),
     *      YT(J),J=1,NJ)
          WRITE(9,130)(N,CLEN(N),(NJUNC(N,K),K=1,2),R(N),CN(N),B(N),
     *      V(N),N=1,NC)
      KWRITE=KWRITE+KPNCHI
          ENDFILE 9
          REWIND 9
      TZERO2=T/3600.
          WRITE(6,281) ICYC,TZERO2
  285     CONTINUE
C**********************************************************************
C*                              END MAIN LOOP                        *
C**********************************************************************
      ENDFILE 10
C                   **************************
C                   *    PRINT RESTART INFO  *
C                   **************************
      WRITE(6,432)
      WRITE(6,402)
      WRITE(6,404)  (J,Y(J),AREAS(J),QIN(J),(NCHAN(J,K),K=1,5),J=1,NJ)
      WRITE(6,410)
      WRITE(6,412)            (N,CLEN(N),B(N),AREA(N),CN(N),V(N),R(N),
     *(NJUNC(N,K),K=1,2),N=1,NC)
      WRITE(6,299) IWRTE,NCYCC
      WRITE(6,422) NCYCC
C              ***************************************
C              *    CALL HYDRAULIC EXTRACT PROGRAM   *
C              ***************************************
      IF(NETFLW.NE.0)CALL HYDEX
      STOP
C                    **************************
```

```
C                   *    END MAIN PROGRAM     *
C                   ***************************
  100 FORMAT(18A4)
  105 FORMAT(5I5,2F10.0,3I5)
  110 FORMAT (1H1///
     *        1H 18A4,5X,47H FEDERAL WATER POLLUTION CONTROL ADMINISTRAT
     *ION/
     *       1H 18A4,5X,35H PACIFIC NORTHWEST WATER LABORATORY////)
  115 FORMAT(132H JUNCTIONS   CHANNELS   CYCLES   OUTPUT INTERVAL   TIME
     * INTERVAL   INITIAL TIME   WRITE BINARY TAPE   RESTART INTERVAL
     *START PRINT//
     * 1H I6,3I11,7H CYCLES,F11.0,5H SEC.,F12.3,14H HRS.  CYCLES I4,4H T
     *O I4,I8,19H CYCLES         CYCLE I4////)
  117 FORMAT(40HOJUNCTION DATA CARD OUT OF SEQUENCE. JJ= I4,4H,J= I4)
  120 FORMAT(I5,F10.0,5X,5I3,F10.5,F10.0,F10.5)
  124 FORMAT(1H ,25X,21H**  JUNCTION DATA  **///)
  125 FORMAT (86H JUNCTION   INITIAL HEAD   SURFACE AREA   INPUT:OUTPUT
     *     CHANNELS ENTERING JUNCTION//(1H ,I6,F15.4,F17.0,F11.2,I12,
     *     4I6))
  127 FORMAT(39HOCHANNEL DATA CARD OUT OF SEQUENCE. NN= I4,4H,N= I4)
  128 FORMAT(1H1///1H ,25X,20H**  CHANNEL DATA  **///)
  130 FORMAT(I5,F8.0,2I3,F6.1,F5.3,F5.0,5X,F10.3)
  135 FORMAT( 97H CHANNEL   LENGTH   WIDTH    AREA   MANNING   VELOCIT
     *Y   HYD RADIUS          JUNCTIONS AT ENDS//
     *(1H I5,F11.0,F8.0,F10.1,F9.3,F10.5,F13.1,I23,I6))
  137 FORMAT(14I5)
  145 FORMAT(30HOCOMPATIBILITY CHECK, CHANNEL I4,11H, JUNCTION I4)
  177 FORMAT(6F10.0)
  179 FORMAT(1H///
     *        1H,15X,32H**COEFFICIENTS FOR TIDAL INPUT**///
     *        6X,2HA1,8X,2HA2,8X,2HA3,8X,4HPHI2,8X,4HPHI3,8X,6HPERIOD//
     *        5F10.6,F10.2///
     *        6H WHERE//
     *         41H Y(1)= A1+A2*SIN(WT+PHI2)+A3*SIN(WT+PHI3))
  270 FORMAT(34HOVELOCITY EXCEEDS 20 FPS IN CYCLE I3,10H, CHANNEL I3,
     *23H, EXECUTION TERMINATED.)
  281 FORMAT(48HORESTART DECK TAPE WAS LAST WRITTEN AFTER CYCLE I4
     *,26H   TZERO FOR RESTARTING = F7.4)
  299 FORMAT(32HOTAPE 10 WAS WRITTEN FROM CYCLE I6,10H TO CYCLE I6//)
  302 FORMAT(1H1///
```

```
     *         27H SYSTEM STATUS AFTER CYCLE I4,F12.2,6H HOURS//
     *         54H JUNCTION        HEAD      CHANNEL     VELOCITY     FLOW/
     *         54H  NUMBER         (FT)       NUMBER        (FPS)       (CFS))
 305 FORMAT(1HOI5,F13.4)
 330 FORMAT (1H I28,F14.5,F12.1)
 402 FORMAT (1H1///
     *          32H  JUNCTION DATA FOR RESTART DECK///)
 404 FORMAT (86H JUNCTION   INITIAL HEAD   SURFACE AREA   INPUT-OUTPUT
     *      CHANNELS ENTERING JUNCTION//(1H ,I6,F15.4,F17.0,F11.2,I12,
     *      4I6))
 406 FORMAT(≠0WITH KPNCHI=≠,I6,≠ AND NCYC=≠,I6,
     *   ≠ RESTART RECORDS WILL BE MADE TOO MANY TIMES≠)
 410 FORMAT (1H1///
     *          31H  CHANNEL DATA FOR RESTART DECK///)
 412 FORMAT( 97H CHANNEL   LENGTH   WIDTH    AREA    MANNING   VELOCIT
     *Y   HYD RADIUS            JUNCTIONS AT ENDS//
     *(1H I5,F11.0,F8.0,F10.1,F9.3,F10.5,F13.2,      I23,I6))
 422 FORMAT(42HOEND OF TWO-DIMENSIONAL EXPLICIT PROGRAM. I4,8H CYCLES.)
 432 FORMAT(36HOEND OF FILE WAS WRITTEN ON TAPE 10.)
 530 FORMAT(3I5)
     END
```

APPENDIX II

NOTES FOR SUBROUTINE HYDEX

APPENDIX II

NOTES FOR SUBROUTINE HYDEX

Unit	Use
3	Output to QUALTEMP (binary records)
5	Control and System Input (card images)
6	Standard Output (printer)
10	Input from HYDRA (binary records)

PROGRAM NOTES

Subroutine HYDEX

Sequence No.	FORTRAN Name	Comments
Dimensioned variables in addition to those discussed in HYDRA.		
7-13	ARMIN, ARMAX	Minimum and maximum channel cross-sectional areas over the entire run.
	NMIN, NMAX	Cycle when the minimum and maximum head occurred.
	QEXMIN, QEXMAX	Minimum and maximum quality cycle average flows over the entire run; i.e., minimum and maximum QEXT's.
	QEXT	Accumulates channel flows over a quality cycle; becomes the average over the cycle.
	QNET	Accumulates channel flows over the entire run; becomes the average over the run.
	RANGE	(YMAX-YMIN)
	VEXT	Accumulates channel velocities over quality cycle; becomes the average over the cycle.
	VMIN, VMAX	Minimum and maximum channel velocities over the entire run. (Note: entire run means hydraulic cycles used by HYDEX-NSTART to NSTOP)
	YAVE	Used to accumulate junction heads over the entire run; becomes an average for the entire run.

Sequence No.	FORTRAN Name	Comments
	YMIN, YMAX	Minimum and maximum junction heads over the entire run.
	YNEW	Updated value for junction head.

Variable names as they occur in the program.

Sequence No.	FORTRAN Name	Comments
19		Rewind unit 10 which contains information from HYDRA.
24		Read heading information to be printed later.
25	NODYN	Read the number of hydraulic cycles per dynamic (water quality) cycle. Example: If a water quality cycle of one hour is to be used and the integration period in HYDRA is DELT = 120·0, then NODYN = 3600/120 = 30.
26	FNODYN	Floating Point NODYN.
30-33		Read system information computed by HYDRA and stored on unit 10.
34	NSTOP	Set NSTOP equal to the total number of cycles in HYDRA (NCYCC is passed through COMMON.)
35	NSTART	Start HYDEX a specified number of tidal cycles from NSTOP.

Example:

PERIOD = 12 hours
       = 12*3600 seconds

DELT = 120 seconds

NCYCC = 961

$$NSTART = 961 - \frac{3600 \times 12}{120} = 601$$

Sequence No.	FORTRAN Name	Comments
		This allows convergence to be achieved in HYDRA before extracting in HYDEX. This (converged) cycle can then be run repeatedly in QUAL for any number of dynamic steady-state cycles.
36-39		Write the alphanumeric information from HYDRA with a general heading.
37	DELTQ	Find the quality cycle in hours.
38		Print information from the hydraulics program as well as starting, stopping and interval cycles used.
39	JRITE	The hydraulic cycle number when the next quality cycle begins.
43	ICYCTF	Read from unit 10. The hydraulic cycle number which is currently being processed.
43		Read and ignore the hydraulic output from HYDRA on unit 10 until the hydraulic cycle read is the same as the starting cycle in HYDEX.
45-58		When the starting hydraulic cycle is read from the tape, initialize several variables.
59-65		As each hydraulic cycle is read from the tape, update minima and maxima, and add to accumulator variables.
69		After initializing, branch to write initial conditions on unit 3 (line 133).

Sequence No.	FORTRAN Name	Comments
71-80		If the velocity in a channel is zero, compute area from junction heads; otherwise, from Q/V.
81-85		Initialize the area variables if this is the (NSTART + 1) hydraulic cycle (KFLAG = 1).
86-94		If this is the first hydraulic cycle in the next dynamic cycle, summarize.
95-105		When one quality cycle is through, complete averages over the cycle, update minima, maxima and add to accumulator variables for entire run.
110-116		Adjust the flow and velocity accumulators to include only 1/2 of the current hydraulic cycle.
117-122		If this is the first quality cycle (KFLAG2 = 1) initialize minima and maxima variables.
123-126		Otherwise, update maxima and minima.
127		Output the flow and velocity average to unit 3.
128-131		Reinitialize the flow and velocity accumulators.
132		Skip to the summary portion if this is the last cycle.
133		Output the cycle number, and the initial heads for the next quality cycle.

Sequence No.	FORTRAN Name	Comments
134		Update JRITE (hydraulic cycle number at beginning of next quality cycle).
	Summary Section	
142	FNSMNS	Floating point representation of (NSTOP-NSTART).
143-153		Compute average flow, area, and hydraulic radius, range, and average heads.
155-165		Output average flows, descriptive and geometric information on unit 3.
166-171		Print summary results.
174	K	Number of dynamic cycles processed.
176-180		Print a few values from the ocean end of the estuary for each quality cycle, to check the tape.

```
      SUBROUTINE HYDEX
C     ************************************************************
C     *                   NET FLOW PROGRAM                       *
C     *          PACIFIC NORTHWEST WATER LABORATORY              *
C     *     FEDERAL WATER POLLUTION CONTROL ADMINISTRATION       *
C     ************************************************************
      DIMENSION VMIN(5),VMAX(5),ARMIN(5),ARMAX(5),
     *  QEXMIN(5),QEXMAX(5),YMIN(5),YMAX(5),RANGE(5),
     *  ARAVE(5),NMIN(5),NMAX(5)
      DIMENSION ALPHA(72),Y(5),AREAS(5),QIN(5),NCHAN(5,5),
     *  V(5),Q(5),AREA(5),B(5),CLEN(5),R(5),
     *  CN(5),NJUNC(5,2),JPRT(75),YNEW(5),QNET(5),
     *  QEXT(5),VEXT(5),YT(5),YAVE(5)
      COMMON ALPHA,Y,YT,AREA,Q,AREAS,QIN,V,B,CLEN,R,CN,DELT,
     *     NCHAN,NJUNC,JPRT,NJ,NC,NCYC,NPRT,NOPRT,PERIOD,NCYCC
C**********************************************************************
C*                     INPUT AND INITIALIZATION                       *
C**********************************************************************
      REWIND 10
      REWIND 3
C                 ************************************
C                 *    CONTROL CARDS UNIQUE TO HYDEX *
C                 ************************************
      READ(5,103) (ALPHA(I),I=37,72)
      READ(5,80) NODYN
      FNODYN=FLOATF(NODYN)
C                ****************************************
C                *    SYSTEM INFORMATION FROM UNIT 10   *
C                ****************************************
      READ(10)        (ALPHA(I),I=1,36),NJ,NC,DELT,(CN(N),R(N),B(N),
     *    CLEN(N),N=1,NC)
      READ(10)        (Y(J),AREAS(J),QIN(J),(NCHAN(J,K),K=1,5),J=1,NJ),
     *    (AREA(N),V(N),(NJUNC(N,I),I=1,2),N=1,NC)
      NSTOP = NCYCC
      NSTART = NCYCC - (PERIOD / DELT)
      WRITE(6,105)(ALPHA(I),I=1,72)
      DELTQ=DELT*FNODYN/3600.0
      WRITE(6,351) NSTART,NSTOP,DELT,NODYN,DELTQ
      JRITE = NSTART
C**********************************************************************
```

```
C*                               MAIN LOOP                                  *
C****************************************************************************
  202 READ(10) ICYCTF,(YNEW(J),J=1,NJ),(V(N),Q(N),N=1,NC)
      IF(ICYCTF - NSTART)202,204,208
  204 DO 206 N=1,NC
C                    ************************************
C                    *    PROCESS FIRST HYDRAULIC CYCLE  *
C                    *     (FOR INITIALIZATION)          *
C                    ************************************
          QNET(N)  =  0.5*Q(N)
          QEXT(N)  =  0.5*Q(N)
          VEXT(N)  =  0.5*V(N)
          VMIN(N)  =  V(N)
          VMAX(N)  =  V(N)
          ARAVE(N)=0.
  206     CONTINUE
      KFLAG = 0
      KFLAG2 = 0
      DO 207 J=1,NJ
          YAVE(J)  =  0.0
          YMIN(J)  =  YNEW(J)
          NMIN(J)  =  ICYCTF
          YMAX(J)  =  YNEW(J)
          NMAX(J)  =  ICYCTF
  207     CONTINUE
C              *********************************************
C              *    PROCESS ALL BUT FIRST HYDRAULIC CYCLE   *
C              *********************************************
      GO TO 218
  208 KFLAG = KFLAG + 1
      DO 154 N=1,NC
          IF(V(N).NE.0.)GO TO 152
          NL = NJUNC(N,1)
          NH = NJUNC(N,2)
          AREA(N)=AREA(N)+((B(N)/2.)*(YNEW(NH)-Y(NH)+ YNEW(NL)-Y(NL)))
          ARAVE(N)  =  ARAVE(N)  +  AREA(N)
          GO TO 154
  152     AREA(N)  =  Q(N)  /  V(N)
          ARAVE(N)  =  ARAVE(N)  +  AREA(N)
  154     CONTINUE
```

```
      IF(KFLAG.NE.1)GO TO 157
      DO 156 N=1,NC
         ARMIN(N) = AREA(N)
         ARMAX(N) = AREA(N)
156      CONTINUE
157   DO 210 N=1,NC
         QNET(N) = QNET(N) + Q(N)
         QEXT(N) = QEXT(N) + Q(N)
         VEXT(N) = VEXT(N) + V(N)
         IF(V(N).GT.VMAX(N))VMAX(N)=V(N)
         IF(V(N).LT.VMIN(N))VMIN(N)=V(N)
         IF(AREA(N).GT.ARMAX(N))ARMAX(N)=AREA(N)
         IF(AREA(N).LT.ARMIN(N))ARMIN(N)=AREA(N)
210      CONTINUE
      DO 180 J=1,NJ
         Y(J) = YNEW(J)
         YAVE(J) = YAVE(J) + YNEW(J)
         IF(YNEW(J).LT.YMAX(J))GO TO 176
         YMAX(J) = YNEW(J)
         NMAX(J) = ICYCTF
         GO TO 180
176      IF(YNEW(J).GT.YMIN(J))GO TO 180
         YMIN(J) = YNEW(J)
         NMIN(J) = ICYCTF
180      CONTINUE
      IF(ICYCTF.NE.JRITE)GO TO 202
C                 ***********************************
C                 *    SUMMARIZE ONE QUALITY CYCLE  *
C                 ***********************************
      KFLAG2 = KFLAG2 + 1
      DO 214 N=1,NC
         QEXT(N) = QEXT(N) - 0.5*Q(N)
         QEXT(N) = QEXT(N)/FNODYN
         VEXT(N) = VEXT(N) - 0.5*V(N)
         VEXT(N) = VEXT(N)/FNODYN
214      CONTINUE
      IF(KFLAG2.NE.1)GO TO 183
      DO 181 N=1,NC
         QEXMIN(N) = QEXT(N)
         QEXMAX(N) = QEXT(N)
```

```
181       CONTINUE
      GO TO 188
183   DO 187 N=1,NC
          IF(QEXT(N).GT.QEXMAX(N))QEXMAX(N)=QEXT(N)
          IF(QEXT(N).LT.QEXMIN(N))QEXMIN(N)=QEXT(N)
187       CONTINUE
188   WRITE(3)  (QEXT(N),VEXT(N),N=1,NC)
      DO 216 N=1,NC
          QEXT(N)  =  0.5*Q(N)
          VEXT(N)  =  0.5*V(N)
216       CONTINUE
      IF(ICYCTF.GE.NSTOP)GO TO 220
218   WRITE(3)  ICYCTF,(YNEW(J),J=1,NJ)
      JRITE  =  JRITE  +  NODYN
      GO TO 202
C***********************************************************************
C*                           END MAIN LOOP                             *
C***********************************************************************
C                     *****************************
C                     *     SUMMARIZE ALL CYCLES  *
C                     *****************************
220   FNSMNS=FLOATF(NSTOP-NSTART)
      DO 222 N=1,NC
          QNET(N)  =  QNET(N)  -  0.5*Q(N)
          QNET(N)  =  QNET(N)/FNSMNS
          ARAVE(N)  =  ARAVE(N)  /FNSMNS
          R(N)  =  ARAVE(N)  /  B(N)
222       CONTINUE
      DO 260 J=1,NJ
          RANGE(J)  =  YMAX(J)  -  YMIN(J)
          YAVE(J)  =  YAVE(J)  /  FNSMNS
          Y(J)  =  0.0
260       CONTINUE
      REWIND 10
      WRITE(3)(QNET(N),N=1,NC)
      WRITE(3)(ALPHA(I),I=1,36),NJ,NC,DELT,(CN(N),R(N),B(N),
     *    CLEN(N),N=1,NC)
      DO 246 N=1,NC
          NL  =  NJUNC(N,1)
          NH  =  NJUNC(N,2)
```

```
      AREA(N)=AREA(N)+(B(N)/2.0)*((Y(J)-YNEW(NH))+(Y(J)-YNEW(NL)))
  246     CONTINUE
      WRITE (3)  (Y(J),AREAS(J),QIN(J),(NCHAN(J,K),K=1,5),J=1,NJ),
     *     (AREA(N),V(N),(NJUNC(N,I),I=1,2),N=1,NC)
      END FILE 3
      WRITE(6,224)(N,QNET(N),QEXMIN(N),QEXMAX(N),VMIN(N),
     *  VMAX(N),ARMIN(N),ARMAX(N),ARAVE(N),N=1,NC)
      REWIND 3
      WRITE(6,262)(J,YMIN(J),NMIN(J),YMAX(J),NMAX(J),YAVE(J),RANGE(J),
     *     J=1,NJ)
C                 ************************************
C                 *    CHECK DATA ON OUTPUT UNIT 3   *
C                 ************************************
      K=(NSTOP-NSTART)/NODYN
      WRITE(6,242)
      DO 234 I=1,K
          READ(3) ICYCTF,(YNEW(J),J=1,NJ)
          READ(3) (QEXT(N),VEXT(N),N=1,NC)
          WRITE(6,232) ICYCTF, YNEW(1),QEXT(1),QEXT(2)
  234     CONTINUE
      REWIND 3
      WRITE(6,240)
      RETURN
C                    ******************************
C                    *    END ENTIRE SUBROUTINE   *
C                    ******************************
   80 FORMAT(5I5)
  103 FORMAT(18A4)
  105 FORMAT (1H1///
     *         1H 18A4,5X,47H FEDERAL WATER POLLUTION CONTROL ADMINISTRAT
     *ION/
     *        1H 18A4,5X,37H PACIFIC NORTHWEST WATER LABORATORY  /
     *        1H 18A4/1H 18A4////)
  224 FORMAT(119H                              * * * * *  FLOW  * * * * *
     *   * *   VELOCITY  * *      * * *  CROSS-SECTIONAL AREA  * * */
     *        118H CHANNEL     NET FLOW          MIN.              MAX.
     *      MIN.           MAX.          MIN.          MAX.          AVE./
     *        119H NUMBER          (CFS)           (CFS)             (CFS)
     *      (CFS)          (CFS)         (SQ. FT)      (SQ. FT)    (SQ. FT)//
     *  (1H I5,F15.2,2F16.2,2F13.3,F16.1,F13.1,F12.1))
```

```
232 FORMAT(I7,5X,F10.2,6X,F11.2,F12.2)
240 FORMAT(25HOEND OF NET FLOW PROGRAM.)
242 FORMAT(1H1///
   *        53H **** OUTPUT FOR CHECKING DATA ON EXTRACTED TAPE ****///
   *        49H HYDRAULIC      HEAD AT         *FLOW IN CHANNEL*/
   *        49H   CYCLE     JUNCTION NO.1      NO.1          NO.2//)
262 FORMAT(1H1////
   * 98H JUNCTION    MINIMUM HEAD    OCCURS AT    MAXIMUM HEAD    OCCU
   *RS AT    AVERAGE HEAD    TIDAL RANGE/
   * 94H  NUMBER          (FT)          CYCLE           (FT)          CY
   *CLE          (FT)           (FT)//
   *  (1H I6,F15.2,I13,F16.2,I13,F16.2,F15.2))
351 FORMAT(88H ******** FROM HYDRAULICS PROGRAM ********     HYDRAULIC
   * CYCLES PER     TIME INTERVAL IN/
   *87H START CYCLE   STOP CYCLE    TIME INTERVAL         QUALITY CYCLE
   *          QUALITY PROGRAM//
   *1H I7,I14,F11.0,9H  SECONDS,10X,I6,12X,F9.2,7H  HOURS/////)
    END
```

APPENDIX III

NOTES FOR PROGRAM QUALTEMP

APPENDIX III

NOTES FOR PROGRAM QUALTEMP

Unit	Use
2	Control Input (except unit 11) (card images)
3	Input from HYDEX (binary records)
9	Restart output (card images)
10	Output for extracting program (binary records)
11	Waste flow input (card images)
16	Standard Output (printer)
61	Standard Output (printer or teletype)

PROGRAM NOTES

QUALTEMP

Sequence No.	FORTRAN Name	Comments

Dimensioned variables in addition to those discussed in HYDRA and HYDEX

7-18	ALPH	Intercept (millibars) used in temperature, vapor-pressure approximation.
	ASUR	Junction surface area.
	BETA	Proportionality coefficient (MB^{o} C^{-1}) used in the linear approximation of the temperature, vapor-pressure relation. (See Edinger, et al., 1965).
	C	Initial (or present) concentration at a junction.
	CIN	Concentration of the ocean input water. CIN(M,K), for example, is the concentration in the ocean for constituent M,K quality cycles into a tidal cycle.
	CLIMIT	Upper concentration limit for a constituent. If exceeded during computation, execution is terminated.
	CMASS	Mass of a constituent in a junction.
	CONST	Constant mass of pure constituent added to a diverted flow, which appears at the junction to which the diverted flow is returned.

Sequence No.	FORTRAN Name	Comments
	CSAT	Saturation concentration of a (dissolved gas) constituent. If the concentration ever exceeds this value, the concentration is forced to the saturation value and an error message printed.
	CSPEC	Concentration of a waste discharge. This differs from CONST in that it is in MG/L and dependent on the diverted flow rate.
	DECAY	Decay coefficient (K_1) in SEC^{-1} for BOD or other substance with a reaction rate. Base e.
	DIFFK	Diffusion coefficient, computed from CDIFFK and channel dimensions.
	EQTEM	The equilibrium temperature at a junction.
	FACTR	Multiplication factor applied to the concentrations to accelerate convergency. (See NJSTOP, for example)
	JDIV1	Junction number where a diversion is to occur.
	JDIV2	Junction number where a diversion is to occur.
	JRET1	Junction number to which the diversion from JDIV1 is returned.

Sequence No.	FORTRAN Name	Comments
	JRET2	Junction number to which the diversion from JDIV2 is returned. (There may be up to NUNITS of the JDIV1-JRET1, JDIV2-JRET2 pairs.)
	MARK	Contains the quality cycle numbers which bound a series of KOUNTT quality cycles; used in keeping track of the binary output for the quality extraction program.
	NCONDK	Contains the nonconservative numbers. For example, NCONDK(I) is the constituent number for the Ith nonconservative constituent; a decay rate is associated with each such constituent.
	NCONOX	Contains constituent numbers with an associated reoxygenation rate. The value of NCONOX(K) (≠0) is the constituent number which is paired with constituent number NCONDK(K).
	NGROUP	Number of groups of junctions for each constituent. For example, NGROUP (K) is the number of groups of junctions to which multiplication factors are applied for the Kth constituent. Each group consists of junctions in the series of
	NJSTRT	to
	NJSTOP	, inclusive. For example, suppose that for constituent number 3, a convergency factor of 1.5 is to be applied to junctions 1-4, and that a convergence factor of 2.5 is to be applied in junctions 7-8. Then,

Sequence No.	FORTRAN Name	Comments
		NGROUPS (3) = 2, NJSTRT (3,1) = 1, and NJSTOP (3,1) = 4, and FACTR (3,1) = 1.5. NJSTRT (3,2) = 7, and NJSTOP (3,2) = 8, and FACTR (3,1) = 2.5.
	ODECAY	1.0 - DECAY (SEC^{-1})
	QC	Convective heat exchange at a junction.
	QE	Evaporative heat exchange at a junction.
	QINWQ	The flow into a waste producing entity. There is a QINWQ for each junction. It is zero if no water is being removed from the junction, or if water is returned to the junction only after having been removed from another junction. If it is negative, waste is being added to the junction from an external source which obtained the water from outside the system. If it is positive, water is being removed from the junction, and may or may not be returned to another junction.
	QNET	The net channel flow during a quality cycle.
	QTOT	The total heat exchanged at a junction.
	QW	The back radiation from a junction.

Sequence No.	FORTRAN Name	Comments
	REOXK	Reoxygenation rate (K_2) in SEC^{-1} for dissolved oxygen. Base e.
	RETRNF	Proportion of constituent that is returned to a junction after a diversion.
	VOL	Volume of a junction.
	VOLQIN	Volume of wastewater removed during a quality cycle (QINWQ() * DELTQ).

Undimensioned variable names in COMMON in addition to those discussed in HYDRA, HYDEX.

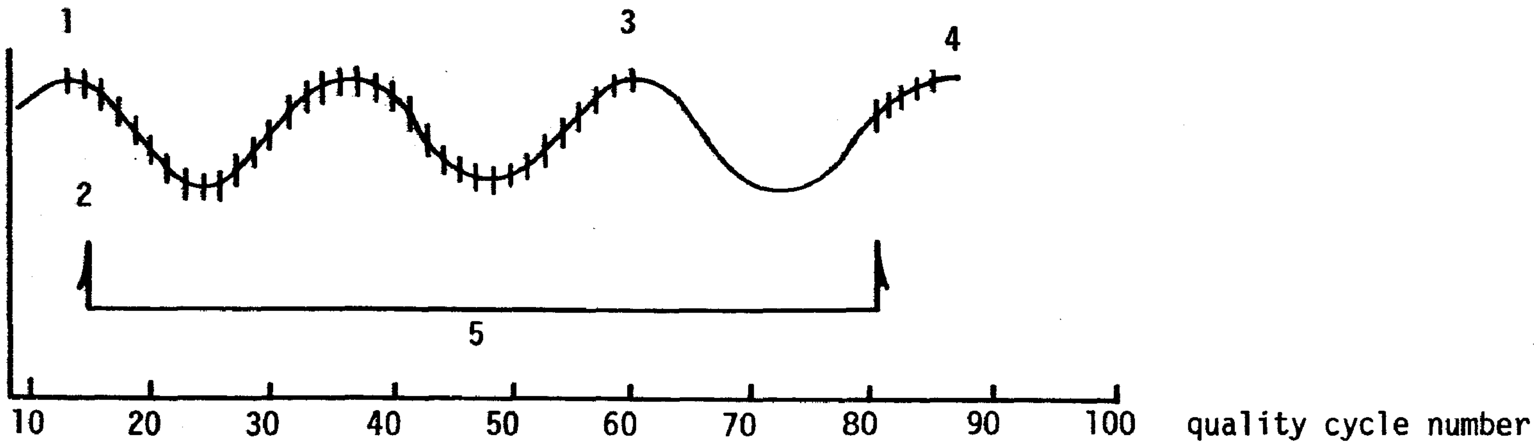
20-21	A	Coefficient in evaporation equation.
	AP	Air pressure, millibars. Interpolated as necessary in subroutine METDTA.
	BB	Coefficient in evaporation equation.
	QRNET	Net incoming radiation (KCAL $M^{-2}SEC^{-1}$) calculated for each cycle in subroutine METDTA.
	TA	Dry bulb temperature, ^{o}C, calculated in METDTA.

Variable names listed as they occur in the program.

36	NOJ	The number of junctions that are at the ocean end of the model. If NOJ is 2, then junctions 1 and 2 are assumed at the ocean end.

Sequence No.	FORTRAN Name	Comments
	ITEMP	The number of the constituent that is temperature; i.e., the ITEMPth constituent is temperature. (=0 if temperature is not a constituent).
	IEQTEM	Switch which, when non-zero, indicates that the equilibrium temperature should be computed.
37	NRSTRT	The first hydraulic cycle to be used from the extract type.
	INCYC	The first quality cycle which is to be processed by QUAL.
	NQCYC	The last quality cycle which is to be processed by QUAL.
	NOEXT	Switch which can be used to indicate that EXQUA should be called.
	CDIFFK	Constant used in computing the eddy diffusion coefficient.
	NTAG	Counter to indicate how many quality cycles have passed in one tidal cycle. Initially, it describes where in the tidal cycle the program will start. NTAG runs up to NSPEC, and is then reset to zero.
38	IPRT	Holds the next quality cycle which will generate printed output. (See Figure 12)
	NQPRT	Print output every NQPRTth cycle.
	NEXTPR	Output is printed every NQPRTth cycle for one tidal cycle. Then, several

Sequence No.	FORTRAN Name	Comments
	INTBIG	quality cycles are skipped, and output is then printed again at the NEXTPRth cycle, every NQPRTth cycle for one tidal cycle, etc. See Figure 12)
	IWRITE	Analagous to IPRT for the binary output.
	NEXTWR	Analagous to NEXTPR for the binary output.
	IWRINT	Analagous to INTBIG for the binary output.
39	NOJP1	Number of ocean junctions plus one.
40-53	K	The number of quality cycles on the extracted tape, usually a tidal cycle. Bypass all of the extracted hydraulic information on tape to obtain the net flow and system information from HYDEX.
54-55		Read additional alphameric information from cards, and print the aggregate alphameric information.
56	DELTQ	Length of a quality cycle, seconds.
57	DELTQ1	Length of a quality cycle, hours.
58	DELTQ2	Length of the printing interval, in hours.
59-61		Print constants, counters, flags, for the run.
62	NUMCON	The number of constituents in the run.



1. IPRT = 10. Begin printing at the 10th quality cycle.

2. NQPRT = 2. Print every 2nd cycle (thus, the 10th, 12th, 14th, etc.), until...

3. a tidal cycle has elapsed, then

4. start printing again at NEXTPR after

5. INTBIG cycles have elapsed since beginning of last print cycle.

FIGURE 12. Integer terms employed in scheduling print output in the water quality program

Sequence No.	FORTRAN Name	Comments
64-66	NALPHA	The number of alphameric variables to be read which depend on the number of constituents. Read and print a card descriptive of each constituent.
67	CLIMIT	Read the limiting concentrations for each constituent.
68-80		Read and print the reoxygenation and decay coefficients. If there are none (exit from loop with k=1) print a message.
84-94	NUNITS	Read the number of diversion return combinations. Then read and print the diversion-return information. If no diversion-return information, so print.
98-111		Input waste flow information. Since all of it won't fit on a card for five constituents, read two sets of cards if there are more than three constituents. Check each card for proper sequencing (JJ=J). If a sequence error is noted, stop.
98	NFIRST	Is used in reading the two sets of cards.
116		Print a "multiplication factor" heading. Then, for each constituent,
118		1) read a card containing the number of groups for that constituent.
119		2) if there are no groups for that constituent, go to the next one.

Sequence No.	FORTRAN Name	Comments
121		3) for each group, read information describing the group.
123-129		4) with that information, apply the return factors to the starting concentrations.
131		Print "no concentration factors applied" for constituents for which NGROUP is zero.
136-139		Print the wasteflows, and adjusted concentrations.
143	NSPEC	The number of times concentrations are input at the ocean end. There should be enough for one tidal cycle at the appropriate interval. For example, if the tidal cycle is 25 hours and the quality cycle is 20 minutes, NSPEC=75. Read cards containing NSPEC concentrations.
148	NOPRT	The number of junctions for which printout is desired.
149	JPRT	Contains the junction numbers of NOPRT junctions.
150-163		Print the channel and junction geometry.
164	METDTA	The entry point in the meteorological data subroutine which inputs the meteorological data.
168	NCOUNT	Counts the number of times data is printed in a tidal cycle, so that when the tidal cycle is over, NEXTPR may be used to skip several tidal cycles.

Sequence No.	FORTRAN Name	Comments
169	KOUNTT	Used in controlling the binary output notes in MARK.
170	NOB	The number of binary output tidal cycles elapsed.
171	NEOT	ICYCTF at end of extracted tape.
172-177		Reorder the junctions connected to a channel, if necessary.
181-194	KVOL	A flag to indicate that the loop following has been gone through twice. The junction volumes are computed twice. They are computed from CLEN, B, and R, where the first time, R is an average from all of the quality cycles. The volume thus calculated is an average volume.
196-198		The average volume, and other initial and descriptive parameters are output as initial information to the quality binary output tape.
200-210		A new R is computed, which will make the volume correct for a specific junction head, Y. The new junction volume is then computed from the R's when this is done, skip to 774.
211-214		The heads which started the hydraulics extract tape are input, and the volumes corrected for these heads.
218-222		Initial mass concentrations are computed from the initial volumes and concentrations.

Sequence No.	FORTRAN Name	Comments
226-227		Eddy diffusion constants are computed from channel geometry.
228-230		Waste water volumes which change during a quality cycle are computed.
231-239		If binary output is to be made from the first cycle, write the initial concentrations.
244	NQCYCC	Used to retain the value of ICYC when the main loop is complete.
248		Channel flows and volumes are obtained from the extracted information.
249		If all of the information from the hydraulics program has been read, rewind it, so that it can be read again to continue the quality computations for an indefinite time with the same basic hydraulic information.
250		Read junction heads from extracted information.
255	VOLFLW	The volume of flow during a quality cycle.
254-272	FACTOR	Depending on whether the channel is connected to the ocean, and the direction of flow in the channel, the quarter point solution technique is applied to the channel concentration gradient. For a discussion, see Orlob, et al. (1967).

Sequence No.	FORTRAN Name	Comments
273-274		Adjust the mass concentrations for advection and diffusion.
280-291		Adjust the mass concentrations for decay and reoxygenation. If NCONDK(I)=0, the Ith constituent is conservative, and no correction is made for that constituent. If it is non-zero, a correction is made, and NCONOX(K) checked. If non-zero, a reoxygenation correction is made based on the constituent.
295-296	NTAG	The ocean concentrations are input for one tidal cycle, at each quality cycle. If the tidal cycle is complete, reset NTAG, so that the ocean concentration information can be used again.
297-300		Set the concentrations at the ocean junctions to the ocean concentration.
305-310		Adjust for waste flows. If the waste flow is negative, an inflowing waste from outside the system is assumed, and the mass concentration at the junction is adjusted using the volume flow and CSPEC, the concentration of the waste.
311-314		If the waste flow is positive, an outflow is assumed, and the mass concentration is adjusted using the concentration at the junction.
318		If NUNITS is zero, bypass the loop for adjusting concentrations for diversion returns.

Sequence No.	FORTRAN Name	Comments
319-330		For each diversion, adjust the mass concentration of the receiving junction on the basis of the volume flow from the contributing junction, the original concentration in that junction, the return factor (RETRNF), and CONST, (which allow for pollutant which enters during the diversion.)
332		If temperature isn't being computed, skip the next loop.
335	FMD	The subroutine which Fetches the Meteorological Data according to ICYC.
336		DO for each junction where CIN isn't an input, i.e., where the concentration isn't fixed by the junction being in the ocean.
337	RHOW	Water density in KGM^{-3}.
338	TWC	Initialize surface temperature (or update it).
339	HV	Compute latent heat of vaporization.
340	ROXDR	The reciprocal of RHOW*DEPTH with a conversion factor for ft to meters.
341	EA	Saturation vapor pressure (MB) at the wet bulb temperature of the air.
343	ES	Saturation vapor pressure (MB) at the temperature of the water surface.

Sequence No.	FORTRAN Name	Comments
344	DELVAP	Difference of the above two.
345		Since evaporation can still go on at (reported) wind speeds of 0 $MSEC^{-1}$ wind is set to 0.05 $MSEC^{-1}$ even if it is a calm day.
346	T1	Temporary variable used in computing QE, QC.
349	DELTMP	Difference in air-water temperature.
350	BOWMOD	Modified Bowen ratio.
353	QDEP	Sum of the terms dependent on surface water temperature. KCAL $M^{-2}SEC^{-1}$.
354	QR	Atmospheric radiation terms (measured or computed) which are independent of surface temperature.
356		Computed temperature gain or loss since initial condition, or updated from the last computed value.
357		Bypass, if not interested in the equilibrium temperature.
358-359		The limits of the table used in computing EEKTEMP are 0-30°C.
360		Find out where the initial (or last computed) temperature lies within the table.
361, 362	T2, T3	Temporary variables, using ALPH, BETA to compute the heat exchange coefficient and the equilibrium temperature.

Sequence No.	FORTRAN Name	Comments
363	XCHCF	The exchange coefficient.
366	DTEM	Difference between last temperature and equilibrium temperature.
367	TEM2	Temperature calculated by the equilibrium temperature equation.
368-371		See if TEM2 (above) uses values of ALPH, BETA originally assumed. If not, use the newly computed value of temperature to obtain new values and go through the loop again.
376-381		Compute new junction volumes, and from them, new specific concentrations.
385-392		If negative concentrations occur, set the concentrations to zero. This condition can occur if the time step is too large. This is one form of instability and this corrective procedure doesn't really cure the instability, although it may be partly justified if the concentrations are low. If this is a print cycle, an error message is printed.
394-408		Two checks are made on the high side of concentration. If the constituent is nonconservative, a check is made that the paired constituent does not exceed its saturation value. If it does, it is set to the saturation value and a message is printed.

Sequence No.	FORTRAN Name	Comments
409-418		All constituents are checked against an upper limit (CLIMIT). If they are higher than that limit, execution is terminated.
419-438		Binary output is made for the quality extracting program according to a rather confusing sequence of counters and flags. Basically, these are arranged to give output every quality cycle for one tidal cycle, and then to skip several tidal cycles, and output again later in the program.
423	KOUNTT	Accumulates the number of times in a tidal cycle that output has occurred. When KOUNTT = NSPEC, the last output is written, and output is suppressed until NEXTWR, which is computed from when the last series of output began.
439-458		A restart card deck containing the non-constant variables is made if this is the last cycle. These could be used to continue the program if the values have not stabilized in the length of run selected initially. Because all of the information will not fit on a card, two loops are necessary if there are more than three constituents.
426-477		Printed output is now made according to a series of counters and flags described above.

Sequence No.	FORTRAN Name	Comments
478-489		If the equilibrium temperature is to be calculated, it is printed in addition to the heat budget terms which are listed in both KCAL/M^2-sec, and BTU/hour.
497-499		A subroutine to extract the quality data in a form somewhat similar to HYDEX has been used elsewhere. However, it is rather specific to a given locale and not particularly useful in the case of the Columbia River and is not described in this report.
620-END	Meteorological Data Subroutine	
629	INT	The interval, in seconds, between data points on input.
	NPTS	The number of data points input (should be enough for one day).
	NQCSM	Time, expressed as the number of quality cycles since midnight at the start of the quality program.
632	QRNETA()	An array of QRNET's (net radiation).
	UWINDA()	An array of UWIND's (wind speed).
	TAA()	An array of TA's (air temperature).
	TAW()	An array of TAW's (wet bulb temperature).
	APA()	An array of AP's (air pressure).
635	IDQ	The integer representation of the length of the quality cycle in seconds.

Sequence No.	FORTRAN Name	Comments
636	FINT	The floating representation of the interval in seconds between meteorological data points.
637	LOT	The length of the meteorological table in seconds.
639	FMD	"Fetch meteorological data." Called when the table is to be referenced at a particular time. The values are interpolated from the arrays, and stored in COMMON in variables QRNET, UWIND, TA, TAW, and AP.
646	ITIM	The seconds of elapsed time in the simulation since the start of the program.
647	ITIT	The seconds of elapsed time since the start of the last meteorological data set.
648	I	The entry in the meteorological table which immediately precedes the present time.
649	FACT	A factor for interpolating between the Ith and (I+1)th value.

```
      PROGRAM QUALTEMP
C*****************************************************************
C*                QUALITY PROGRAM QUARTER POINT VERSION           *
C*                PACIFIC NORTHWEST WATER LABORATORY              *
C*          FEDERAL WATER POLLUTION CONTROL ADMINISTRATION        *
C*****************************************************************
      DIMENSION DECAY(5),REOXK(5),NCONDK(5),NCONOX(5),CSAT(5),ODECAY(5)
      DIMENSION NGROUP(10),FACTR(5,10),NJSTRT(5,10),NJSTOP(5,10),
     *  MARK(10,2)
      DIMENSION JDIV1(20),JDIV2(20),JRET1(20),JRET2(20),RETRNF(20,5),
     *      CONST(20,5)
      DIMENSION YNEW(5),VOLQIN(5),C(5,5),CSPEC(5,5),
     *     CIN(5,100),VOL(5),ASUR(5),QINWQ(5),QNET( 5),
     * CMASS(5,5),DIFFK( 5),   ALPHA(198),CLIMIT(5)
      DIMENSION           Y(5),AREAS(5),QIN(5),NCHAN(5,5),
     *    V( 5),Q( 5),AREA( 5),B( 5),CLEN( 5),R( 5),
     *    CN( 5),NJUNC( 5,2),JPRT( 75),DEEP(5)
      DIMENSION QC(5),QW(5),QE(5),EQTEM(5),QTOT(5)
      COMMON ALPHA,C,CSPEC,VOL,QINWQ,NSPEC,DELTQ,NUMCON,NALPHA,NJ,ICYC,
     *         NODYN,NSTART,NSTOP,ASUR,MARK,NOB,ITEMP,IEQTEM,QRNET,
     *         UWIND,TA,TAW,AP,A,BB
      COMMON/DATA/ALPH(6),BETA(6)
      DATA(ALPH=5.7,4.0,.757,-5.41,-15.29,-30.43),
     *(BETA=0.62,0.842,1.107,1.459,1.898,2.449)
      EQUIVALENCE (AREAS,ASUR),(QIN,QINWQ),(CN,DIFFK),(VOLQIN,QNET)
     *,(CMASS,NCHAN),(YNEW,AREA)
      REWIND 3
      REWIND 10
      DO 38 NOB=1,10
      DO 36 K=1,2
   36 MARK(NOB,K) = 0
   38 CONTINUE
C                  ********************************
C                  *    INPUT CONTROL CONSTANTS   *
C                  ********************************
      READ(2,80) NJ,NC,NSTART,NSTOP,NODYN,NOJ,ITEMP,IEQTEM
      READ(2,84) NRSTRT,INCYC,NQCYC,NOEXT,CDIFFK,NTAG
      READ(2,80)   IPRT,NQPRT,NEXTPR,INTBIG,IWRITE,NEXTWR,IWRINT
```

```
      NOJP1=NOJ+1
C          ****************************************************
C          *    FIND SYSTEM INFORMATION FROM HYDEX UNIT   *
C          ****************************************************
      K = (NSTOP-NSTART)/NODYN
      DO 86 I = 1,K
      READ(3)
      READ(3)
   86 CONTINUE
      READ(3)     (QNET(N),N=1,NC)
      READ(3)(ALPHA(I),I=1,36),NJ,NC,DELT,(CN(N),R(N),B(N),
     *     CLEN(N),N=1,NC)
      READ(3)(Y(J),AREAS(J),QIN(J),(NCHAN(J,K),K=1,5),J=1,NJ),
     *     (AREA(N),V(N),(NJUNC(N,I),I=1,2),N=1,NC)
      REWIND 3
      READ(2,103)(ALPHA(I),I=37,72)
      WRITE(61,105) (ALPHA(I),I=1,72)
      DELTQ=DELT*FLOATF(NODYN)
      DELTQ1=DELTQ/3600.0
      DELTQ2=DELTQ1*FLOATF(NOPRT)
      WRITE(61,106) NSTART,NSTOP,DELT
      WRITE(16,107)NRSTRT,INCYC,NQCYC,INTBIG,DELTQ2,DELTQ1,CDIFFK
      WRITE(16,109) IPRT,IWRITE
      READ(2,112) NUMCON
      WRITE(16,120) NUMCON
      NALPHA = 108 + NUMCON * 18
      READ(2,103)  (ALPHA(I),I=109,NALPHA)
      WRITE(16,122)(ALPHA(I),I=109,NALPHA)
      READ(2,110)  (CLIMIT(K),K=1,NUMCON)
C     ************************************************************
C     *      INPUT/OUTPUT--REOXYGENATION AND DECAY COEFFICIENTS   *
C     ************************************************************
      READ(2,40)  (NCONDK(K),NCONOX(K),K=1,NUMCON)
      DO 44 K=1,NUMCON
      IF(NCONDK(K).EQ.0)GO TO 46
      READ(2,42) DECAY(K),REOXK(K),CSAT(K)
      ODECAY(K) = 1.0 - DECAY(K)
      IF(NCONOX(K).EQ.0)WRITE(16,58)NCONDK(K),DECAY(K)
      IF(NCONOX(K).NE.0)WRITE(16,56)NCONDK(K),DECAY(K),
     *  NCONOX(K),REOXK(K),CSAT(K)
   44 CONTINUE
   46 IF(K.EQ.1)WRITE(16,50)
```

```
C          ***************************************************
C          *   INPUT/OUTPUT--DIVERSION-RETURN FACTORS        *
C          ***************************************************
      READ(2,112) NUNITS
      IF(NUNITS.NE.0)GO TO 115
      WRITE(16,81)
      GO TO 118
  115 WRITE(16,198)
      DO 117 I=1,NUNITS
      READ(2,116)JDIV1(I),JDIV2(I),JRET1(I),JRET2(I),
     *   (RETRNF(I,M),CONST(I,M),M=1,NUMCON)
      WRITE(16,350) I,JDIV1(I),JDIV2(I),JRET1(I),JRET2(I),
     * (RETRNF(I,M),CONST(I,M),M=1,NUMCON)
  117 CONTINUE
C          ****************************************************
C          *    INPUT--WASTE FLOW CONCENTRATIONS AND AMOUNTS  *
C          ****************************************************
  118 NFIRST=3
      IF(NUMCON.LT.3)NFIRST=NUMCON
      DO 206 J=1,NJ
      READ(11,200) JJ,QINWQ(J),(C(J,K),CSPEC(J,K),K=1,NFIRST)
      IF(JJ.EQ.J)GO TO 206
  202 WRITE(16,204)JJ,J
      STOP
  206 CONTINUE
      IF(NUMCON.LE.3)GO TO 212
      NFIRST=NFIRST+1
      DO 210 J=1,NJ
      READ(11,200) JJ, (C(J,K),CSPEC(J,K),K=NFIRST,NUMCON)
      IF(JJ.NE.J)GO TO 202
  210 CONTINUE
C          ***************************************************
C          *    INPUT--MULTIPLICATION FACTORS TO BE APPLIED  *
C          *                  APPLY THEM                     *
C          ***************************************************
  212 WRITE(16,224)
      DO 222 I=1,NUMCON
      READ(2,112) NGROUP(I)
      IF(NGROUP(I).EQ.0)GO TO 222
      NG = NGROUP(I)
```

```
      READ(2,220) (FACTR(I,K),NJSTRT(I,K),NJSTOP(I,K),K=1,NG)
      WRITE(16,228)I,(K,FACTR(I,K),NJSTRT(I,K),NJSTOP(I,K),K=1,NG)
      DO 234 K=1,NG
      NJ1 = NJSTRT(I,K)
      NJ2 = NJSTOP(I,K)
      DO 234 J=NJ1,NJ2
      C(J,I) = C(J,I) * FACTR(I,K)
  234 CONTINUE
  222 CONTINUE
      DO 232 I=1,NUMCON
      IF(NGROUP(I).EQ.0)WRITE(16,216)I
  232 CONTINUE
C                ****************************************
C                *    OUTPUT--ADJUSTED CONCENTRATIONS   *
C                ****************************************
      WRITE(16,241)
      DO 283 J=1,NJ
      WRITE(16,282) J,QINWQ(J),(C(J,K),CSPEC(J,K),K=1,NUMCON)
  283 CONTINUE
C           ***************************************************
C           *  INPUT/OUTPUT--OCEAN JUNCTION CONCENTRATIONS    *
C           ***************************************************
      READ(2,112) NSPEC
      DO 186 M=1,NUMCON
      READ(11,184) (CIN(M,I),I=1,NSPEC)
      WRITE(61,188)M,(CIN(M,I),I=1,NSPEC)
  186 CONTINUE
      READ(2,112) NOPRT
      READ(2,192)(JPRT(I),I=1,NOPRT)
      IF(NJ.LE.NC)GO TO 72
      N1=NC
      N2 = NJ
      GO TO 74
   72 N1 = NJ
      N2 = NC
   74 WRITE(61,196)(N,CLEN(N),B(N),AREA(N),CN(N),QNET(N),
     * R(N),(NJUNC(N,K),K=1,2),N,Y(N),(NCHAN(N,I),I=1,5),N=1,N1)
      N1 = N1 + 1
      IF(NJ - NC)76,79,78
   78 WRITE(61,195)(J,Y(J),(NCHAN(J,K),K=1,5),J=N1,N2)
```

```
      GO TO 79
   76 WRITE(6I,194)(N,CLEN(N),B(N),AREA(N),CN(N),QNET(N),
     * R(N),(NJUNC(N,K),K=1,2),N=NI,N2)
   79 IF(ITEMP.NE.0)CALL METDTA
C***********************************************************************
C*                             INITIALIZATION                          *
C***********************************************************************
      NCOUNT = 0
      KOUNTT = 0
      NOB = 0
      NECT = NSTOP - NODYN
      DO 358 N=1,NC
      IF(NJUNC(N,1).LE.NJUNC(N,2))GO TO 358
      KEEP=NJUNC(N,1)
      NJUNC(N,1)=NJUNC(N,2)
      NJUNC(N,2)=KEEP
  358 CONTINUE
C                   **********************************
C                   *     COMPUTE JUNCTION VOLUMES   *
C                   **********************************
      KVOL = 0
  359 DO 373 J=1,NJ
      ASUM   = 0.0
      DSUM   = 0.0
      DO 371 K=1,5
      IF(NCHAN(J,K).EQ.0)GO TO 372
      N=NCHAN(J,K)
      ABAR = CLEN(N)*B(N)
      ASUM = ASUM + ABAR
      DSUM = DSUM + ABAR*R(N)
  371 CONTINUE
  372 DBAR = DSUM/ASUM
      VOL(J) = ASUR(J)*DBAR
  373 CONTINUE
      IF(KVOL.NE.0)GO TO 774
      WRITE(10)      (ALPHA(I),I=1,NALPHA)
      WRITE(10)      NJ,NODYN,NSPEC,DELTQ,(QINWQ(J),VOL(J),ASUR(J),
     *  (CSPEC(J,K),K=1,NUMCON),J=1,NJ)
      KVOL =  1
      DO 710 N=1,NC
```

```
      R(N) = AREA(N) / B(N)
  710 CONTINUE
      GO TO 359
C                *****************************************
C                *   CORRECT VOLUMES FOR STARTING HEADS  *
C                *****************************************
  774 READ(3)     ICYCTF,(YNEW(J),J=1,NJ)
      IF(ICYCTF.GE.NRSTRT)GO TO 776
      READ(3)     (Q(N),V(N),N=1,NC)
      GO TO 774
  776 DO 780 J=1,NJ
      VOL(J) = VOL(J) + ASUR(J)*(YNEW(J)-Y(J))
      Y(J)   = YNEW(J)
  780 CONTINUE
C                  ************************************
C                  *   COMPUTE CONTAMINANT VOLUMES    *
C                  ************************************
      DO 378 J=1,NJ
      DO 377 K=1,NUMCON
      CMASS(J,K)=C(J,K)*VOL(J)
  377 CONTINUE
  378 CONTINUE
C                *****************************************
C                *   COMPUTE EDDY DIFFUSION CONSTANTS    *
C                *****************************************
      DO 385 N=1,NC
  385 DIFFK(N)=CDIFFK*R(N)*DELTQ/CLEN(N)
      DO 388 J=NCJP1,NJ
      VOLQIN(J) = QINWQ(J) * DELTQ
  388 CONTINUE
      IF(IWRITE - (INCYC - 1))30,32,34
   30 IWRITE = INCYC
      GO TO 34
   32 WRITE(10)     IWRITE,((C(J,K),K=1,NUMCON),J=1,NJ)
      NOB = NOB + 1
      MARK(NOB,1) = IWRITE
      WRITE(61,493)NOB,IWRITE
      KOUNTT = KOUNTT + 1
```

```
   34 CONTINUE
C*********************************************************************
C*                                 MAIN LOOP                         *
C*********************************************************************
      DO 536 ICYC = INCYC,NQCYC
      NQCYCC = ICYC
C                   ***************************************
C                   *    INPUT HYDRAULICS INFORMATION     *
C                   ***************************************
      READ(3)       (Q(N),V(N),N=1,NC)
      IF(ICYCTF.GE.NEOT)REWIND 3
      READ(3)       ICYCTF,(YNEW(J),J=1,NJ)
C               ********************************************
C               *    ADJUST FOR ADVECTION AND DIFFUSION    *
C               ********************************************
      DO 416 N=1,NC
      VOLFLW = Q(N) * DELTQ
      NL = NJUNC(N,1)
      NH = NJUNC(N,2)
      IF(N.GT.NOJ) GO TO 406
      IF(Q(N).GE.0.)GO TO 404
      FACTOR=0.
      GO TO 412
  404 FACTOR = 1.00
      GO TO 412
  406 IF(Q(N).GE.0.)GO TO 410
      FACTOR = 0.25
      GO TO 412
  410 FACTOR = 0.75
  412 DO 414 K=1,NUMCON
      QGRAD = C(NL,K) - C(NH,K)
      CONC = C(NH,K) + FACTOR * QGRAD
      ADMASS = CONC * VOLFLW
      DIMASS = DIFFK(N) * ABSF(Q(N)) * QGRAD
      CMASS(NH,K) = CMASS(NH,K) + ADMASS + DIMASS
      CMASS(NL,K) = CMASS(NL,K) - ADMASS - DIMASS
  414 CONTINUE
  416 CONTINUE
C                        **************************
C                        *    ADJUST FOR DECAY    *
C                        **************************
      DO 422 K=1,NUMCON
```

```
      IF(NCONDK(K).LE.0)GO TO 424
      NCON = NCONDK(K)
      NCONO = NCONOX(K)
      DO 420 J=NOJP1,NJ
      CMASS(J,NCON)=CMASS(J,NCON) * DECAY(K)
      IF(NCONO.LE.0)GO TO 420
      CMASS(J,NCONO) = CMASS(J,NCONO) - C(J,NCON) * VOL(J) * ODECAY(K)
     *  + REOXK(K) * DELTQ * VOL(J) * (CSAT(K) - C(J,NCONO))
  420 CONTINUE
  422 CONTINUE
  424 CONTINUE
C             ***********************************************
C             *    SET CONCENTRATIONS AT OCEAN JUNCTIONS    *
C             ***********************************************
      NTAG = NTAG + 1
      IF(NTAG.GE.NSPEC)NTAG=0
      DO 429 K=1,NUMCON
      DO 429 J=1,NOJ
      C(J,K) = CIN(K,NTAG+1)
  429 CONTINUE
C     ************************************************************
C     *    ADJUST FOR WASTE OUTFLOWS, AND FOR WASTE INFLOWS      *
C     *    FROM EXTERNAL SOURCES                                 *
C     ************************************************************
      DO 434 J=NOJP1,NJ
      IF(QINWQ(J))430,434,432
  430 DO 431 K=1,NUMCON
      CMASS(J,K)=CMASS(J,K) - CSPEC(J,K) * VOLQIN(J)
  431 CONTINUE
      GO TO 434
  432 DO 433 K=1,NUMCON
      CMASS(J,K)=CMASS(J,K) - C(J,K) * VOLQIN(J)
  433 CONTINUE
  434 CONTINUE
C                 *************************************
C                 *    ADJUST FOR DIVERSION RETURNS   *
C                 *************************************
      IF(NUNITS.EQ.0)GO TO 442
      DO 440 I=1,NUNITS
      JDI = JDIV1(I)
```

```
      JD2 = JDIV2(I)
      JR1 = JRET1(I)
      JR2 = JRET2(I)
      DO 438 M=1,NUMCON
      CMASS(JR1,M)=CMASS(JR1,M)+(C(JD1,M)*VOLQIN(JD1)*RETRNF(I,M))+
     *   CONST(I,M)
      CMASS(JR2,M)=CMASS(JR2,M)+(C(JD2,M)*VOLQIN(JD2)*RETRNF(I,M))+
     *   CONST(I,M)
  438 CONTINUE
  440 CONTINUE
  442 IF(ITEMP.EQ.0)GO TO 443
C    ***************************************************************
C    *    ADJUST TEMPERATURE FOR NON-ADVECTIVE HEAT TRANSFERS       *
C    ***************************************************************
      CALL FMD
      DO 1500 J=NOJP1,NJ
      RHOW=1000.
      TWC = C(J,ITEMP)
      HV=597.-.57*TWC
      ROXDR=1.0/((VOL(J)*304.80061)/ASUR(J))
      EA=2.1718E8*EXP(-4157.0/(TAW+239.09))-AP*
     * (TA-TAW)*(6.6E-4+7.59E-7*TAW)
      ES=2.1718E8*EXP(-4157.0/(TWC+239.09))
      DELVAP=ES-EA
      IF(UWIND.LT.0.05)UWIND=0.05
      T1=RHOW*HV*(A+BB*UWIND)
      QE(J)=T1*DELVAP
      IF(DELVAP.LT.0.0)QE(J)=0.0
      DELTMP=TWC-TA
      BOWMOD=0.61*T1
      QC(J)=BOWMOD*DELTMP
      QW(J)=7.36E-2+1.17E-3*TWC
      QDEP=QE(J)+QW(J)+QC(J)
      QR=QRNET
      QTOT(J)=QR-QDEP
      CMASS(J,ITEMP)=CMASS(J,ITEMP)+QTOT(J)*DELTQ*ROXDR*VOL(J)
      IF(IEQTEM.EQ.0)GO TO 1500
    4 IF(TWC.GE.30.0)TWC=29.9
      IF(TWC.LT.0.0)TWC=0.0
      NN=IFIX(TWC)/5+1
```

```
      T2=BETA(NN)+6.1E-4*AP
      T3=ALPH(NN)-EA-6.1E-4*AP*TA
      XCHCF=1.17E-3+T1*T2
      DNUM=QR-7.36E-2-T1*T3
      EQTEM(J)=DNUM/XCHCF
      DTEM=TWC-EQTEM(J)
      TEM2=EQTEM(J)+DTEM*EXP(-((XCHCF*DELTQ)*ROXDR))
      II=IFIX(TEM2)/5+1
      IF(II.EQ.NN)GO TO 1500
      TWC=TEM2
      GO TO 4
 1500 CONTINUE
C *****************************************************************
C *    COMPUTE SPECIFIC CONCENTRATIONS FROM MASS CONCENTRATIONS   *
C *****************************************************************
  443 DO 446 J=NCJP1,NJ
      VOL(J) = VOL(J) + ASUR(J)*(YNEW(J)-Y(J))
      DO 444  K=1,NUMCON
      C(J,K)=CMASS(J,K)/VOL(J)
  444 CONTINUE
  446 CONTINUE
C                   *************************************
C                   *    CHECK NEGATIVE CONCENTRATIONS  *
C                   *************************************
      DO 466 J=1,NJ
      Y(J) = YNEW(J)
      DO 464 K=1,NUMCON
      IF(C(J,K).GE.0.)GO TO 464
      IF(ICYC+NSPEC+1.GE.NQCYC)WRITE(61,460)J,ICYC,K,C(J,K)
      C(J,K) = 0.0
      CMASS(J,K)= 0.0
  464 CONTINUE
  466 CONTINUE
      IF(NCONDK(1).EQ.0)GO TO 479
C                       ******************************
C                       *    CHECK SUPERSATURATION   *
C                       ******************************
      DO 476 K=1,NUMCON
      IF(NCONDK(K).EQ.0.OR.NCONOX(K).EQ.0)GO TO 476
      NCON=NCONOX(K)
```

```
      DO 475 J=1,NJ
      IF(C(J,NCON).LE.CSAT(K))GO TO 475
      WRITE(6I,474)NCON,J,ICYC,C(J,NCON)
      C(J,NCON) = CSAT(K)
      CMASS(J,NCON) = C(J,NCON) * VOL(J)
  475 CONTINUE
  476 CONTINUE
  479 CONTINUE
      DO 482 J=1,NJ
C                 **********************************
C                 *    CHECK OVER MAXIMUM LIMIT    *
C                 **********************************
      DO 480 K=1,NUMCON
      IF(C(J,K).LE.CLIMIT(K))GO TO 480
      WRITE(6I,478)K,CLIMIT(K),J,ICYC
      STOP
  480 CONTINUE
  482 CONTINUE
      IF((ICYC+NSPEC)-NQCYC)486,484,490
C          ************************************************
C          *    MAKE BINARY OUTPUT FOR EXTRACTING PROGRAM  *
C          ************************************************
  484 KOUNTT = 0
      GO TO 490
  486 IF(ICYC.LT.IWRITE)GO TO 500
  490 KOUNTT=KOUNTT+1
      IF(KOUNTT -1)492,492,494
  492 NOB = NOB +1
      MARK(NOB,1) = ICYC
      WRITE(16,493) NOB,ICYC
  494 IF(KOUNTT.LT.(NSPEC+1))GO TO 498
      MARK(NOB,2)=ICYC
      WRITE(16,497) NOB,ICYC
      KOUNTT=0
      IWRITE = NEXTWR
      NEXTWR = NEXTWR + IWRINT
  498 WRITE(10)     ICYC,((C(J,K),K=1,NUMCON),J=1,NJ)
  500 CONTINUE
      IF(ICYC.LT.NQCYC)GO TO 520
C                    **************************
C                    *    MAKE RESTART DECK   *
C                    **************************
```

```
      NFIRST=3
      IF(NUMCON.LT.3)NFIRST=NUMCON
      WRITE(9,103)(ALPHA(I),I=1,72)
      DO 556 J=1,NJ
      WRITE(9,555) J,QINWQ(J),(C(J,K),CSPEC(J,K),K=1,NFIRST)
  556 CONTINUE
      IF(NUMCON.LE.3)GO TO 517
      NFIRST = NFIRST + 1
      DO 558 J=1,NJ
      WRITE(9,557) J,(C(J,K),CSPEC(J,K),K=NFIRST,NUMCON)
  558 CONTINUE
  517 CONTINUE
      WRITE(16,518)ICYC,ICYCTF,NTAG
      END FILE 9
      REWIND 9
  520 CONTINUE
C                       ***************************
C                       *     OUTPUT TO PRINTER   *
C                       ***************************
      IF(ICYC+NSPEC+1.GE.NQCYC)GO TO 528
      IF(ICYC.LT.IPRT)GO TO 536
      IPRT = IPRT +NQPRT
      NCOUNT = NCOUNT + 1
      IF(NCOUNT.LT.NSPEC/NQPRT+2)GO TO 528
      NCOUNT = 0
      IPRT = NEXTPR
      NEXTPR = NEXTPR + INTBIG
  528 HOURS = DELTQ * FLOATF(ICYC) / 3600.0
      KDAYS = HOURS / 23.99999
      HOURS = HOURS - FLOATF(24 * KDAYS)
      WRITE(16,530) ICYC,KDAYS,HOURS
      DO 534 I=1,NOPRT
      J=JPRT(I)
      WRITE(61,532)J,Y(J),(C(J,K),K=1,NUMCON)
  534 CONTINUE
      IF(IEQTEM.EQ.0)GO TO 536
      BTU2=QR*1327.29
      WRITE(61,531)
```

```
      DO 535 I=1,NOPRT
      J=JPRT(I)
      BTU1=QTOT(J)*1327.29
      BTU3=QW(J)*1327.29
      BTU4=QE(J)*1327.29
      BTU5=QC(J)*1327.29
      WRITE(61,533)QTOT(J),BTU1,QR,BTU2,QW(J),BTU3,QE(J),BTU4,
     *  QC(J),BTU5,EQTEM(J)
  535 CONTINUE
  536 CONTINUE
C*****************************************************************************
C*                            END MAIN LOOP                                  *
C*****************************************************************************
      REWIND 3
      WRITE(61,540)((MARK(J,K),K=1,2),J=1,NOB)
      WRITE(61,542)  NQCYCC
C       ******************************************************
C       *    CALL TO QUALITY EXTRACTION PROGRAM GOES HERE   *
C       ******************************************************
      STOP
   40 FORMAT(10I5)
   42 FORMAT(3E10.0)
   50 FORMAT(1H0////
     *          53HOALL CONSTITUENTS TREATED AS CONSERVATIVE IN THIS RUN//)
   56 FORMAT(1H0////
     *          17HOCONSTITUENT NO. I1,59H IS TREATED AS A NON-CONSERVATIVE
     * WITH DECAY COEFFICIENT = F10.7,36H AND IS PAIRED WITH CONSTITUENT
     * NO. I1/34H WITH MASS TRANSFER COEFFICIENT = F15.9,32H AND SATURAT
     *ION CONCENTRATION = F10.2)
   58 FORMAT(1H0/
     *          17HOCONSTITUENT NO. I1,59H IS TREATED AS A NON-CONSERVATIVE
     * WITH DECAY COEFFICIENT = F10.7,45H BUT IS NOT PAIRED WITH ANY OTH
     *ER CONSTITUENT//)
   80 FORMAT(7I5)
   81 FORMAT(38HONO WASTE WATER RETURN FACTORS APPLIED//)
   84 FORMAT(4I5,F10.0,I5)
  103 FORMAT(18A4)
  105 FORMAT(1H1////
     *           1H 18A4,5X,47H FEDERAL WATER POLLUTION CONTROL ADMINISTRAT
     *ION/
```

```
     *       1H 18A4,5X,37H PACIFIC NORTHWEST WATER LABORATORY  /
     *       1H 18A4/1H 18A4////)
  106 FORMAT(42H ******** FROM HYDRAULICS PROGRAM ********/
     *       42H START CYCLE   STOP CYCLE    TIME INTERVAL//
     *       1H I7,I14,F12.0,9H  SECONDS/////)
  107 FORMAT(117H    STARTING CYCLE    INITIAL QUALITY  TOTAL QUALITY  *
     *** OUTPUT INTERVALS ***    TIME INTERVAL IN       CONSTANT FOR/
     *       122H ON HYD. EXTRACT TAPE      CYCLE           CYCLES
     * CYCLES       HOURS       QUALITY PROGRAM   DIFFUSION COEFFICIENT
     *5//
     *     I13,I18,I16,I13,F14.2,F17.3,6H HOURS,F17.3////)
  109 FORMAT(31H PRINTOUT IS TO BEGIN AT CYCLE I4//
     *     49H QUALITY TAPE FOR EXTRACTING IS TO BEGIN AT CYCLEI5////)
  110 FORMAT(5F10.0)
  112 FORMAT(I5)
  116 FORMAT(I3,3I4,5(F5.0,E8.2))
  120 FORMAT(1H0I5,42H CONSTITUENTS BEING CONSIDERED IN THIS RUN//)
  122 FORMAT(1H018A4)
  184 FORMAT(7F10.0)
  188 FORMAT(55H0SPECIFIED C-FACTORS AT JUNCTION 1 FOR CONSTITUENT NO. I
     *1//
     * (1H 7F12.2))
  192 FORMAT(14I5)
  194 FORMAT(I5,2F8.0,F9.0,F8.3,F12.2,F10.1,I9,I6)
  195 FORMAT(85X,I9,F8.2,I8,4I5)
  196 FORMAT(1H1////
     *     132H ****************************   CHANNEL DATA    ********
     *********************                    **********    JUNCTION DATA    *
     **********/
     *     132H CHAN.  LENGTH   WIDTH    AREA   MANNING  NET FLOW  HYD.
     *RADIUS  JUNC. AT ENDS                  JUNC.  HEAD    CHANNELS ENTERING
     * JUNCTION//
     * (I5,2F8.0,F9.0,F8.3,F12.2,F10.1,I9,I6,10X,I9,F8.2,I8,4I5))
  198 FORMAT(1H1////
     *     132H ******************************************    TABLE O
     *F WASTE WATER RETURN FACTORS       ****************************
     **********/
     *     37H       JUNCTIONS USED   JUNCTIONS USED/
     *     132H        FOR DIVERSIONS   FOR RET. FLOWS   1ST. CONSTITUENT
     *  2ND. CONSTITUENT   3RD. CONSTITUENT   4TH. CONSTITUENT   5TH. CO
```

```
     *NSTITUENT/
     *      132HUNIT   NO. 1  NO. 2     NO. 1  NO. 2    COEFF.    CONST.
     *  COEFF.   CONST.   COEFF.    CONST.   COEFF.    CONST.   COEFF.
     *   CONST.//)
 200 FORMAT(I5,7F10.0)
 204 FORMAT(31HODATA CARD OUT OF SEQUENCE, JJ= I4,3H,J= I4)
 216 FORMAT(52HONO MULTIPLICATION FACTOR APPLIED TO CONSTITUENT NO.I2/)
 220 FORMAT(F5.0,2I5,F5.0,2I5,F5.0,2I5,F5.0,2I5,F5.0,2I5)
 224 FORMAT(70H1*****MULTIPLICATION FACTORS APPLIED TO OBTAIN STARTING
     *CONCENTRATIONS//
     *         51H CONSTITUENT    GROUP    FACTOR    JUNCTION NUMBERS)
 228 FORMAT(1H //I8,I11,F11.2,I12,2H -,I4/
     *    (I19,F11.2,I12,2H -,I4))
 241 FORMAT(1H1////
     *      120H ***********************************************   WATER
     *QUALITY DATA    **********************************************/
     *      120H                  * FIRST CONSTITUENT * SECOND CONSTITUENT
     * * THIRD CONSTITUENT * FOURTH CONSTITUENT * FIFTH CONSTITUENT */
     *      118H                          INITIAL     INFLOW   INITIAL      INFLOW
     *   INITIAL    INFLOW   INITIAL       INFLOW   INITIAL      INFLOW/
     *     118H JUNC.  INFLOW       CONC.        CONC.     CONC.        CONC.
     *     CONC.       CONC.     CONC.       CONC.     CONC.      CONC.//)
 282 FORMAT(I4,F10.4,F12.1,2F10.1, F11.1,3F10.1,F11.1,2F10.1)
 350 FORMAT(I3,I8,I7,I10,I7,F9.2,E12.2,4(F7.2,E12.2))
 460 FORMAT(39H DEPLETION CORRECTION MADE AT JUNCTION I3,7H CYCLE I4,
     * 21H FOR CONSTITUENT NO. I1,12H. CONC. WAS F10.2)
 474 FORMAT(36H0SUPERSATURATION OF CONSTITUENT NO. I1,23H PREVENTED AT
     *JUNCTION I4,7H CYCLE I4,10H CONC. WAS F10.2//)
 478 FORMAT(34H0CONCENTRATION OF CONSTITUENT NO. I1,8H EXCEEDS,F7.1,
     * 13H IN JUNCTION I3,14H DURING CYCLE I5,25H.   EXECUTION TERMINATE
     *D.)
 493 FORMAT(///6H MARK(I2,5H,1) =I5///)
 497 FORMAT(///6H MARK(I2,5H,2) =I5///)
 518 FORMAT(1H1////46HRESTART DECK TAPE WAS LAST WRITTEN AFTER CYCLEI5/
     *        50H HYDRAULIC CYCLE ON EXTRACT TAPE FOR RESTARTING = I5/
     *     8H NTAG = I3///)
 530 FORMAT(1H1////
     *        35H SYSTEM STATUS AFTER QUALITY CYCLE I4,I12,6H DAYS,
     * F6.2,6H HOURS//
     *      109H                         ***************************
```

```
     *  CONCENTRATION FACTORS     ****************************/
     *       109H JUNCTION       HEAD            1ST. CONSTIT.    2ND. CONSTI
     *T.    3RD. CONSTIT.    4TH. CONSTIT.    5TH. CONSTIT./
     *       135H  NUMBER       (FT)                (MGL)              (MGL)
     *            (MGL)               (MGL)               (MGL)/)
  531 FORMAT(≠)      ****************  RADIATION TERMS AND EQUIL≠,
     *≠IBRIUM TEMPERATURES  ****************≠/
     *≠0(KCAL IMPLIES KILOGRAM-CALORIES PER SQUARE METER PER ≠,
     *≠SECOND. BTU IMPLIES BTU PER SQUARE FOOT PER HOUR)≠/
     *≠- NET RADIATION  INCOMING SOLAR   BACK RADIATION    EVAPORA≠,
     *≠TION     CONDUCTION   EQUIL TEMP≠/
     *1X,5(≠   KCAL    BTU  ≠),≠ CENTIGRADE≠)
  533 FORMAT(1H0,5(E9.2,F6.3,1X),F9.2)
  532 FORMAT(1H0I5,F12.2,F20.2,4F17.2)
  540 FORMAT(36H0QUALITY TAPE WAS WRITTEN FROM CYCLE,I6,9H TO CYCLE,I6/)
  542 FORMAT(20H-END OF QUALITY RUN.,I5,9H  CYCLES.)
  555 FORMAT(I5,F10.4,6F10.2)
  557 FORMAT(I5,6F10.2)
      END
      SUBROUTINE METDTA
C   ***************************************************************
C   *                SUBROUTINE TO INPUT METEOROLOGICAL DATA      *
C   *                   FOR QUALITY PROGRAM                       *
C   ***************************************************************
      DIMENSION QRNETA(24),UWINDA(24),TAA(24),TAWA(24),APA(24)
      COMMON ALPHA(198),C(5,5),CSPEC(5,5),VOL(5),QINWQ(5),NSPEC,DELTQ,
     *  NUMCON,NALPHA,NJ,ICYC,NODYN,NSTART,NSTOP,ASUR(5),MARK(10,2),
     *  NOR,ITEMP,IEQTEM,QRNET,UWIND,TA,TAW,AP,A,BB
      READ(2,10)INT,NPTS,NOCSM,A,BB
      WRITE(6,12)
      DO 100 I=1,NPTS
      READ(2,11)QRNETA(I),UWINDA(I),TAA(I),TAWA(I),APA(I)
      WRITE(6,13)QRNETA(I),UWINDA(I),TAA(I),TAWA(I),APA(I)
  100 CONTINUE
      IDQ=IFIX(DELTQ)
      FINT=FLOATF(INT)
      LOT=INT*NPTS
      RETURN
```

```
      ENTRY EMD
C*******************************************************************
C*               ENTRY POINT TO FETCH CURRENT (INTERPOLATED) VALUE   *
C*               OF METEOROLOGICAL VARIABLES            *
C*******************************************************************
      NOCSM=NOCSM+1
      ITIM=NOCSM*IDQ
      ITIT=ITIM-(ITIM/LOT)*LOT
      I=ITIT/INT
      FACT=FLOATF(ITIT-I*INT)/FINT
         I=I+1
      J=I+1
      IF(J.GT.NPTS)J=1
      QRNET=(QRNETA(J)-QRNETA(I))*FACT+QRNETA(I)
      UWIND=(UWINDA(J)-UWINDA(I))*FACT+UWINDA(I)
      TA=(TAA(J)-TAA(I))*FACT+TAA(I)
      TAW=(TAWA(J)-TAWA(I))*FACT+TAWA(I)
      AP=(APA(J)-APA(I))*FACT+APA(I)
      RETURN
   10 FORMAT(3I10,F5.2,E9.2)
   11 FORMAT(F4.4,3F3.1,F4)
   12 FORMAT(≠1     ***************************   TABLE OF METEORO≠,
     *   ≠LOGICAL DATA  *****************************≠/
     *≠0    NET                    DRY    WET≠/
     *≠ INCOMING      WIND      BULB   BULB  ATMOSPHERIC≠/
     *≠ RADIATION     SPEED     TEMP   TEMP     PRESSURE≠/
     *≠  (KC/M2/SEC) (M/SEC)     (C)     (C)        (MB)≠)
   13 FORMAT(1H0F10.3,F8.4,F7.2,F6.2,F10.1)
      END
```

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