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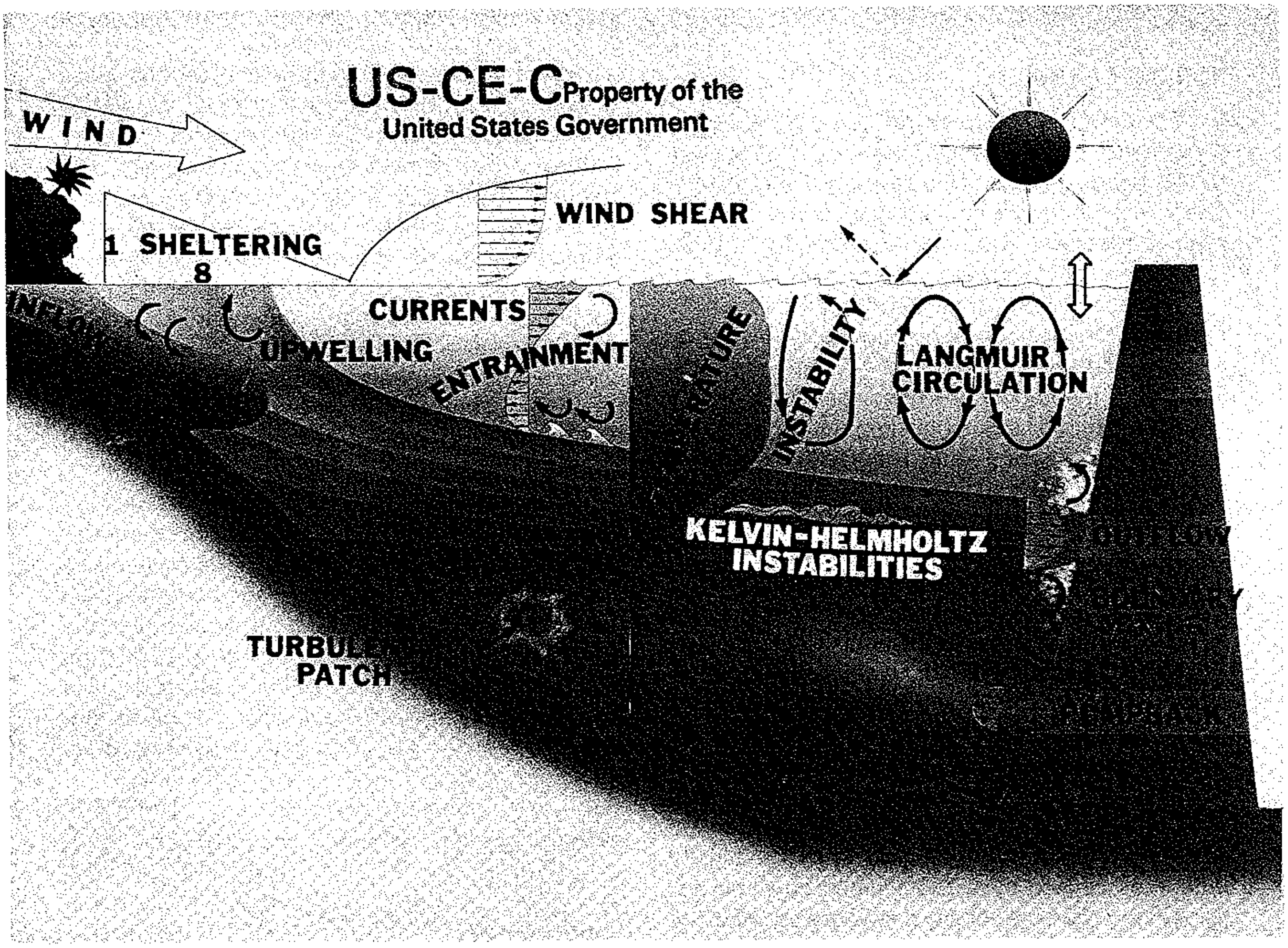

The objective of the Environmental and Water Quality Operations Studies (EWQOS) Work Unit IA, Reservoir Hydrodynamics, is to develop, improve, and verify methods for describing and predicting the hydrodynamics of reservoirs to provide a basis for improved understanding of water quality and ecological processes affecting environmental quality objectives.

Reservoir mixing results from the cumulative effects of internal energy inputs and project operation as shown in the above illustration. The research described in the following article addresses the mixing processes, which must be accurately represented to predict the impact of management alternatives on reservoir and release water quality.

RESERVOIR MIXING PROCESS

Dennis E. Ford*

A thorough understanding of reservoir hydrodynamics and mixing processes is important because:

- Tributary inflows are usually the major source of nutrients as well as suspended and dissolved material that impact reservoir water quality.
- Vertical mixing and the resultant thermal regime probably influence the reservoir environment more than any other factor.

Without an accurate representation of reservoir mixing processes, it is difficult to predict the impact of management alternatives on reservoir and release water quality.

INFLOW MIXING

Predictive techniques for describing inflow placement, plunge point location, propagation speed, and mixing are being developed in Task IA.1. These techniques are necessary to understand and predict reservoir water quality and to operate reservoirs to achieve water quality objectives.

Since the inflow density usually differs from the density of the reservoir water surface, inflows enter and move through reservoirs as density currents. Bell (1942) defined a density current as "a gravity flow of a liquid or a gas through, under, or over a fluid of approximately equal density." Density flows differ from normal fluid flows because the buoyancy of the surrounding fluid reduces the gravity force by the normalized density difference, $\Delta\rho/\rho$; i.e., reduced gravity force=$\Delta\rho/\rho(g)$. Vertical movements such as waves are therefore exaggerated at the density interface compared to the air-water interface.

Density differences can be caused by temperature, dissolved solids, and suspended solids. In most reservoirs, however, density differences are predominantly caused by temperature differences. For example, at 25°C, it takes approximately 330 mg/ℓ of dissolved solids or 420 mg/ℓ of suspended solids (specific gravity = 2.65) to equal the density difference caused by a 1°C temperature change. Depending upon the density difference between the inflow and reservoir, density currents can enter the epilimnion, metalimnion, or hypolimnion as overflow, interflow, or underflow, respectively (Figure 1).

When the inflow density is less than the water surface density, the inflow will float on the water surface (i.e., overflow). The following factors complicate the analysis of overflows:

1. Since the motive force is the excess hydrostatic pressure, the current will spread in all directions not obstructed by boundaries and three-dimensional effects should be considered.
2. The temperature (density) difference is quickly dissipated by heat transfer at the air-water interface.
3. Wind shear can direct the overflow into a cove or prevent it from moving down-reservoir. Horizontal dispersion will also be enhanced from wind shear.
4. Vertical mixing resulting from wind shear and/or convective cooling can distribute the density current through the water column.

If the inflow density is greater than the water surface density, the inflow will plunge. The plunge point is sometimes visible because of turbidity or floating debris, indicating a stagnation point. The location of the plunge point is determined by a balance of the stream momentum, the pressure gradient across the interface separating the river and reservoir waters, and the resisting shear forces. Some mixing occurs at the plunge point, but it is difficult to separate this mixing from entrance mixing, which includes the cumulative effects of all mixing processes acting on a density current from the time it first enters the reservoir until it plunges (Ford and Johnson, 1980).

After the inflow plunges, it follows the old river channel (thalweg) as an underflow. The speed and thickness of the underflow can be determined by assuming a two-layered system and a flow balance between the shear forces and the acceleration due to gravity (i.e., gradually varying flow theory). The momentum equation used in the two-layered flow analysis is similar to the open-channel flow formulation except for the additional buoyancy force.

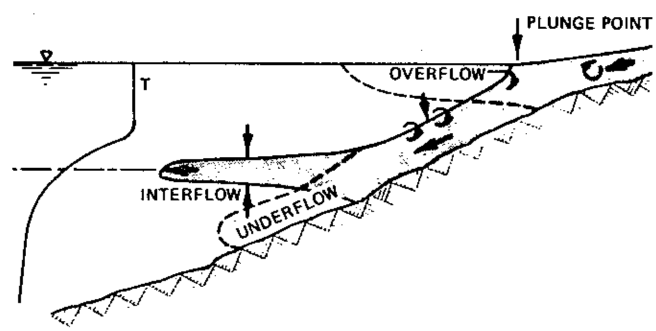

Figure 1. Schematic representation of density inflows to impoundments

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Entrainment in an underflow results from turbulence generated by bottom roughness. Changes in the current density from entrainment must be quantified before density interflow or intrusion can be analyzed, or the vertical placement of an interflow will be incorrect.

A density interflow or intrusion occurs when a density current leaves the river bottom and propagates horizontally into a stratified body of water. Intrusions differ from overflows and underflows because the densities of intrusion and reservoir are similar. Intrusions require a continuous inflow and/or outflow for movement, or they stall and collapse. Entrainment can usually be neglected in an intrusion because the density gradient in the metalimnion creates strong buoyancy forces which inhibit mixing.

Numerous simplified techniques have been proposed in the literature to predict the characteristics of density currents. Verification of these techniques under various hydrometeorological conditions has been lacking due to limited field data. Field investigations of density currents were undertaken in conjunction with the Reservoir Field Studies to evaluate these predictive techniques. Observations included overflows, interflows, and underflows during both base and elevated storm flow conditions (Table 1). Fluorescent dye or natural tracers such as turbidity, calcium, and specific conductance were used to trace the inflows through the impoundments. Initial evaluation of the techniques showed complex topography, mixing, and project operation were complicating factors that violated most simplifying assumptions and thereby limited their usefulness (Ford and Johnson, 1980).

INTERNAL MIXING

The objective of Task IA.2 is to develop a mathematical algorithm that realistically represents all major mixing processes occurring within a reservoir. This algorithm, when verified, will be incorporated into the one-dimensional reservoir water quality model, CE-QUAL-R1, being developed in Task IC.1 (EQWOS Newsletter Vol E-80-2).

Mixing processes. Mixing in reservoirs results from the cumulative effects of internal energy inputs such as surface heat exchange, solar radiation absorption, wind, inflow, outflow, and project operation (see artist representation on cover).

For large reservoirs, with theoretical hydraulic residence times greater than several months, the wind is a major source of energy for mixing. When the wind blows over the water surface, the resulting drag force will depend on the wind speed, variability, and direction. Specific wind-generated mixing mechanisms include surface stirring and shear

TABLE 1. RESERVOIR INFLOW STUDIES

Date	Reservoir	Tracer	Plunge/Take-off Point Data: Type Flow	Plunge/Take-off Point Data: Peak Flow m^3/sec (Type)	Normalized Density Difference $\times 10^{-4}$	Reynolds Number $\times 10^5$	Densimetric Froude Number
8/31/76	DeGray	Turbidity	Interflow	6.9(storm)	7.6	1.1	0.66
10/24/76	DeGray	Turbidity	Underflow	200(storm)	8.5	6.1	0.49
3/03/77	DeGray	Turbidity	Overflow	530(storm)	1.5	7.6	0.96
6/16/77	DeGray	Turbidity	Interflow	370(storm)	20.0	10.0	0.55
11/14/78	DeGray	Turbidity Specific conductance	Interflow	500(storm)	3.5	5.6	0.54
3/25/79	DeGray	Dye	Overflow	15(base)	0.95	3.5	2.8
3/29/79	DeGray	Turbidity Specific conductance Calcium	Overflow	700(storm)	1.6	2.4	3.3
5/01/79	DeGray	Turbidity Specific conductance	Interflow	190(storm)	3.9	3.0	0.20
7/16/79	DeGray	Dye	Interflow	4.6(base)	5.5	5.4	0.20
8/11/79	Red Rock	Dye	Interflow	230(storm)	2.0	17.0	2.3
10/11/79	DeGray	Dye	Underflow	15(base)	3.9	0.15	0.17

production. Surface stirring results from the direct production of turbulent kinetic energy at the air-water interface and sharpens the density gradient in the metalimnion by entrainment (a one-way process where the turbulent upper mixed layer grows with depth as the nonturbulent metalimnion is entrained into it). In contrast, shear production is a localized mixing process resulting from mean current motion. Its net effect is to diffuse and weaken the density gradient in the metalimnion.

Reservoirs exhibit diurnal temperature fluctuations due to daytime heating and nighttime cooling. As reservoirs cool at night, heat is removed from a thin layer at the water surface. This thin layer of cooler, heavier water is buoyantly unstable and sinks, generating thermal or convective currents. The turbulent kinetic energy associated with the convective currents can be used for stirring the mixed layer. This convective mixing is termed penetrative convection if it results in the entrainment of water from the metalimnion. Penetrative convection can also occur during the daytime when there is a net positive heat transport. Since all heat fluxes except solar radiation act only at the water surface, it is possible for a reservoir to lose heat at the water surface and gain heat at lower depths, thereby generating an unstable condition and resulting in convective mixing. Penetrative convection is an important mixing process dominating during periods of cooling such as late summer and fall.

In stably stratified reservoirs, vertical mixing in the metalimnion and hypolimnion is suppressed by the buoyancy forces of density stratification while, at the same time, horizontal mixing is enhanced. The turbulent kinetic energy derived from the wind is not sufficient to overcome the buoyancy forces. Patchy and intermittent mixing does occur in these reservoirs. In general, this mixing is greater during periods of strong winds, inflows, and outflows and decreases with increasing stratification.

Turbulent patches of mixing are generated by boundary mixing phenomena and internal wave instabilities. In boundary mixing, turbulence generated at the sediment-water interface (boundary) by seiche motion propagates into the interior of the lake in the form of gravitational intrusions. Internal waves generated indirectly by the wind can occur in any region of density gradient. When sufficient energy is concentrated in the waves, the waves become unstable and break, thereby generating turbulence (i.e., Kelvin-Helmholtz instabilities). Regardless of the mode of generation, the turbulent patches quickly elongate and collapse under the action of buoyancy forces, producing a steplike structure or microstructure.

Mathematical algorithm. Several internal mixing models or algorithms were reviewed with respect to their ability to realistically simulate reservoir mixing processes. These models included both eddy diffusivity models and integral energy or mixed layer models.

Eddy diffusivity models have been used by the CE and are based on an analogy with molecular diffusion. They solve the one-dimensional thermal energy equation and assume that vertical transport can be expressed by the gradient of the transported quantity multiplied by an eddy diffusion coefficient. Eddy diffusion models, therefore, incorporate all mixing processes into one empirical coefficient that is a complicated function of time, space, and local stability.

Some early eddy diffusivity models considered the vertical eddy diffusion coefficient to be constant with depth; others considered it to be dependent on the density structure. More recent models use a Richardson number formulation that considers the stabilizing influence of the density gradients and their interaction with wind shear (Sundaram and Rehm, 1973). All of the models, however, assume mixing to result from the local supply of energy and not from surface stirring and penetrative convection. In addition, since eddy diffusion models assume mixing is proportional to and in the direction of the gradient of the transported constituent, they fail when gradients vanish or when coupled fluxes of two conservative quantities cause one of them to be transported against its own gradient. This will occur when the concentration of coupled constituents have opposing and unequal gradients.

An alternative approach to solving the one-dimensional thermal energy equation is to solve the total energy equation, which is the approach used in integral energy models. Integral energy models use the turbulent energy generated at or near the water surface by the wind (i.e., surface stirring) and by natural convection (i.e., penetrative convection) to work against gravity at the bottom of the mixed surface layer where denser water is entrained. Since integral energy models calculate the depth of the mixed surface layer, they are sometimes referred to as mixed-layer models. During periods of complete vertical mixing (e.g., spring and fall overturn), the depth of the mixed layer extends to the lake bottom.

In integral energy models, mixing in the metalimnion and hypolimnion must still be approximated by the eddy diffusion approach. This approximation is valid, however, because in these zones mixing results from internal processes such as seiching and internal wave instabilities. If it is assumed that the whole reservoir is in equilibrium with the external energy sources, then mixing in the hypolimnion can be approximated by a vertical eddy diffusivity, which is a function of external energy inputs such as wind, inflows, and outflows (Fischer el al., 1979).

Integral energy models, by inclusion of surface stirring, have several advantages over pure eddy diffusion models. First, according to Niiler and Kraus (1977), integral energy models are more realistic than eddy diffusion models because of the significance assigned to the vertical transport of turbulent kinetic energy generated at the air-water interface. Second, the onset of stratification is simulated more accurately (Ford et al., 1980). Third, calibration is simplified because each of the major mixing processes is considered separately and can be calibrated separately at the time it dominates. Finally, both shallow and deep reservoirs can be simulated.

It is essential that physically realistic mixing algorithms be used in water quality models. Thornton et al. (1979) found that a 10-percent change in the eddy diffusion coefficient had relatively little effect on the predicted thermal structure but had a significant effect on the prediction of phytoplankton blooms. If the onset of stratification cannot be accurately simulated, it is difficult to accurately predict water quality problems such as hypolimnetic dissolved oxygen depletion.

STATUS AND FUTURE WORK

Task IA.1, Inflow Mixing, is scheduled for completion in FY 80. Technical reports describing the field studies and recommended predictive techniques will be published in FY 81. Guidance will also be forwarded to the Office, Chief of Engineers, in FY 81 for distribution to field offices describing the use of fluorescent dyes to track inflows through reservoirs and recommending simplified techniques to describe density currents.

A technical report describing reservoir mixing processes (Task IA.2) is also scheduled for publication in FY 81. Future work in this task will investigate the interaction between turbulent mixing and various biological processes such as phytoplankton growth. Comprehensive field studies are being planned for FY 81 on Eau Galle Lake, Wisconsin. Results from these studies will be used to verify improved modeling techniques, which, in turn, will be incorporated in a one-dimensional reservoir model (Task IC.1).

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ENVIRONMENTAL ASSESSMENT TECHNIQUES

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Since the passage of the National Environmental Policy Act (NEPA) and the development of the Water Resource Council's Principles and Standards for Planning Water and Related Land Resources, the Corps has developed Engineer Regulations (ERs) to implement these mandates. In particular, the ER 1105-2-200 series provides general guidance on the environmental concerns to be addressed in Corps planning efforts. These regulations do not

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provide (nor were they intended to provide) specific techniques to address these concerns. The objectives of EWQOS Work Unit IVA are to identify specific techniques for environmental analysis that are compatible and consistent with the Corps environmental mission as defined in the ER 1105-2-200 series and to evaluate their potential for implementation by field offices.

JUDICIAL REVIEW UNDER NEPA

NEPA established the protection and enhancement of all aspects of the human environment as national policy. In addition to its policy requirements, NEPA contained procedural requirements for Federal agencies to prepare Environmental Impact Statements (EISs) documenting the effects of their actions on the environment. While the policy goals of NEPA of preservation and enhancement are easy to define, what is required of an agency to comply with this policy has often become a matter of controversy.

The implementation of the policy and procedural requirements of NEPA has been accompanied by considerable litigation concerning compliance with various aspects of the Act. The judicial interpretations and decisions concerning compliance to a large degree dictate the manner in which subsequent impact statements are prepared.

As a part of Work Unit IVA, the Environmental Law Institute was contracted to review litigation cases concerning NEPA to provide judicial guidance on:

- Treatment of conflicting professional opinions in EISs.
- Documentation of the planning and decision-making process.
- Quantification of environmental impacts.
- Consideration of alternatives in EISs.
- Composition and operation of interdisciplinary teams conducting environmental assessments.

Results of this judicial review are summarized in Technical Report E-80-2, "Judicial Review Under NEPA—Lessons for Users of Various Approaches to Environmental Impact Assessment," published in January.

In addition to the review of litigation, existing Corps regulations for preparation of EISs were examined in the areas of the judicial holdings previously described. The ERs were found to be quite comprehensive including instructions (relevant to this review) to:

- Cite sources, make appropriate references, and indicate how documents summarized in the impact statement can be obtained.
- Avoid slighting or ignoring adverse effects in an effort to justify an action previously recommended or currently supported.
- Summarize accurately detailed appraisals of other agencies and concerned environmental groups and provide evaluation of these appraisals.
- Make every effort to obtain quantifiable values and describe the nature and extent of non-quantifiable tradeoffs.
- Provide qualitative descriptions of unquantifiable costs and benefits with assumptions or criteria on which judgments are based.
- Include and discuss irreconcilable opposing views.

The report contains numerous references and citations that may be of benefit to field offices.

EVALUATION AND SENSITIVITY ANALYSIS PROGRAM (ESAP)

As described in a previous issue of this bulletin (Volume E-80-1, February 1980), another Work Unit IVA effort concerns the development of sensitivity analysis procedures for the evaluation of water resource plans. The procedures have been developed through a contract with the Center for Research on Judgment and Policy, Institute of Behavioral Science, University of Colorado, Boulder, and have been field tested as part of the Whitewater River Basin Flood Control Study, Los Angeles District.

The procedures are in the form of a packaged computer program (ESAP) to be made available for field use. The ESAP has two purposes: to help program users incorporate both scientific/technical and value information into the evaluation of alternatives and to help users investigate the effects of uncertainty of either type of information on this evaluation. Although ESAP is directly applicable to alternative evaluation, it is also useful in alternative formulation and impact assessment.

In setting up an ESAP analysis, the user develops an in-depth description of the evaluation problem by identifying all of the general categories of variables to be taken into account during later analyses and then dividing and subdividing each general category into specific variables. This procedure was named TREE because the output resembles a tree: branches emerge from a common origin or root; each branch has stems; and at the end of the stems are leaves (Figure 1). As in all ESAP procedures, the

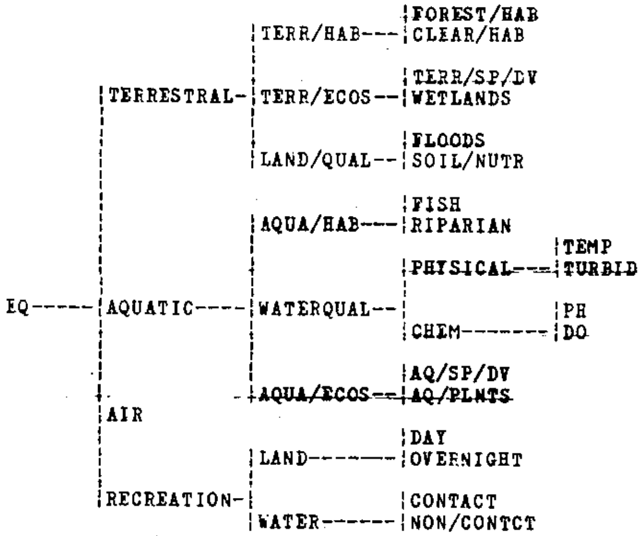

Figure 1. Output of TREE procedure: various resources defining environmental quality for a water resources evaluation problem

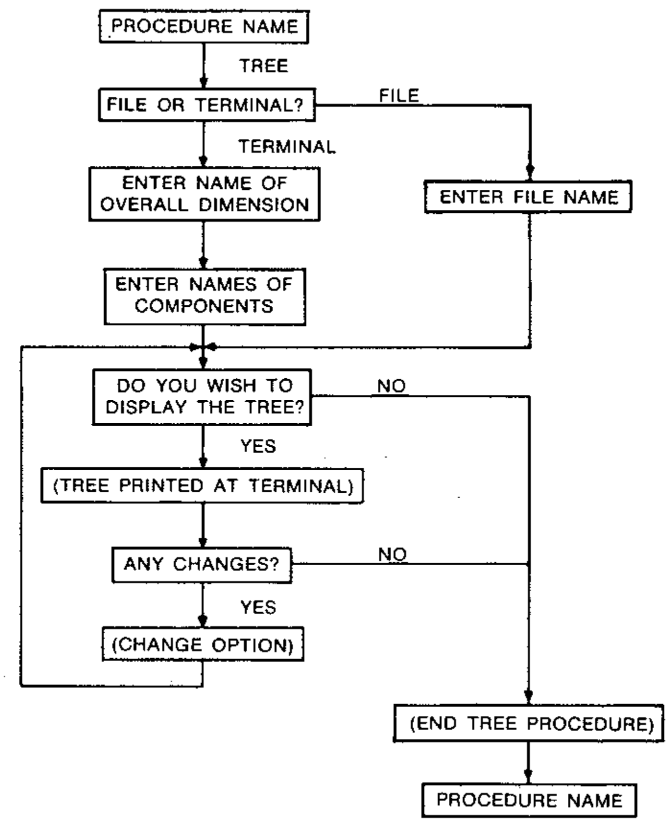

Figure 2. Flow diagram for the interactive TREE procedure

computer prompts the user through a series of questions to obtain input for the TREE (Figure 2).

The planner then specifies and makes use of information about the preferences and values of various public groups as well as the projected effects of alternative plans on the environment. The two types of information are combined to establish a clear rationale for selecting a particular alternative while taking into systematic account uncertainties in the projected effects of alternatives.

The program is currently on line on a commercial computer services facility and can be accessed in either batch or interactive modes. Placing the program on additional computer facilities (such as at WES) to increase availability is under consideration. A draft user manual has been prepared for ESAP that illustrates its usefulness as well as describing how to use it. The draft manual is currently being reviewed by the Office, Chief of Engineers; publication of the user manual is anticipated in the fall.

EC 1105-2-102

Another task in Work Unit IVA centers on providing Corps field offices with information about techniques and methodologies for environmental analysis. Currently Engineer Circular (EC) 1105-2-102, which contains summaries of approximately ninety techniques, is being reviewed by the field offices. Review of the EC will provide guidance as to which techniques should be deleted and which should be further investigated.

SUMMARY

The approach of Work Unit IVA is to identify specific techniques applicable to environmental analysis. Identification of these techniques is primarily guided by two considerations. The first is consistency with the Corps environmental mission as defined in the ER 1105-2-200 series. The second consideration is how easily the technique may be implemented in a field situation. Many environmental assessment techniques that have been developed have not been used due to manpower or other constraints or the highly conceptual nature of the technique. To solve this problem, Work Unit IVA relies on field office input, such as through review of EC 1105-2-102, to furnish proper guidance on potential field implementation.

EWQOS REPORTS

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NOTE: Copies of the above reports will be furnished to individual requestors as long as supplies last. Since it is only feasible to print a limited number of copies, requests for single rather than multiple copies by a single office will be appreciated. Please address all requests to the Waterways Experiment Station, ATTN: Ms. D. P. Booth. When supplies are exhausted, copies will be obtainable from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

This bulletin is published in accordance with AR 310-2. It has been prepared and distributed as one of the information dissemination functions of the Waterways Experiment Station. It is principally intended to be a forum whereby information pertaining to and resulting from EWQOS can be rapidly and widely disseminated to Corps District and Division offices as well as other Federal agencies, state agencies, universities, research institutes, corporations, and individuals. Contributions of any type are solicited from all sources and will be considered for publication as long as they are relevant to the objectives of EWQOS, i.e., to provide new or improved technology to solve selected environmental quality problems associated with Civil Works activities of the Corps of Engineers in a manner compatible with authorized project purposes. This bulletin will be issued on an irregular basis as dictated by the quantity and importance of information to be disseminated. Communications are welcomed and should be addressed to the Environmental Laboratory, ATTN: J. L. Mahloch, U.S. Army Engineer Waterways Experiment Station, P. O. Box 631, Vicksburg, Mississippi 39180, or call AC 601, 634-3635

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