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WRRI Technical Completion Report No. 291

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ABSTRACT

The sportfishery comprehensive management system simulation model, RIOFISH, is described in text, diagrams, and mathematic appendix. RIOFISH simulates over 90% of the state fishing at 132 sites. The model has 3 main components (hydrology, biology, economics), which may be run separately or integrated. The hydrologic component simulates historic flows (1975-1992) or synthetic-forecast flows of water and biologically active material in seven flow categories from extreme low to extreme high runoff. Output information about flow and material load serves as input for the biologic component, which simulates ecosystem production and food partitioning for up to 24 fish populations. Output information about fish catch, harvest and mean weight serve as input for the economics component, along with habitat surface area from the hydrology component. The economics component simulates angler use, angler economic benefit and regional income from inputs about site quality, substitute-site quality and angler demand. Model users may modify management and research-related input variables and have access to numerous informative outputs. RIOFISH is run reiteratively; users compare outputs of reference scenarios and alternative scenarios to determine gains or losses in output values associated with management practice or research uncertainties.

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PURPOSE

This report describes the structure of RIOFISH, a numeric simulation of a sportfishery comprehensive management system. RIOFISH is an acronym for River-basin Information Organizer for Fisheries Investigation, Simulation, and Heuristics. The introductory chapter describes the systems simulated and briefly describes possible model uses. A complementary report (Cole et al. In Press) describes model use, input controls and output information in detail and should be referred to as the model is being used. The main body of this report is composed of three chapters, each treating a main model component: hydrology, biology and economics. The mathematics appendix is organized into three parallel chapters.

COMPREHENSIVE MANAGEMENT SIMULATION

RIOFISH simulates a comprehensive management system for sport fisheries in New Mexico. For our purposes, a comprehensive management system for public sportfishery management is defined by the interaction of management policies with resources, publics, and influential social and ecological events (Figure 1). A fishery management program inherits, as system inputs, resource conditions from which it is expected, by mandate and mission, to provide fishing opportunities with beneficial outcomes. The efficiency with which a fishery program benefits resource-user publics depends on various environmental factors including

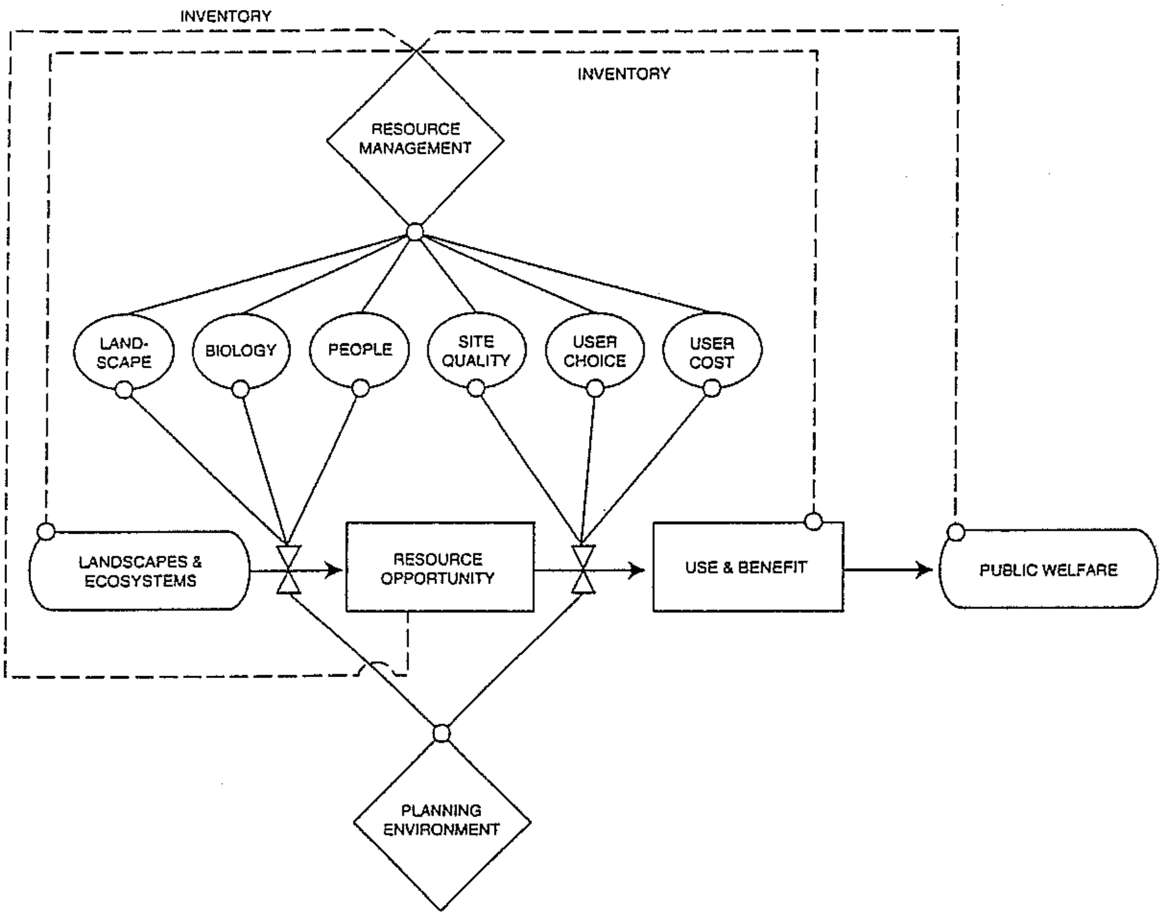

Figure 1. Main elements of a comprehensive resource management system.

habitat status, travel costs, and various demographic changes affecting fishing preferences.

The most progressive fishery management programs focus on the beneficial outcomes of management when establishing objectives and evaluation criteria for management effectiveness. Although progressive fishery managers may be interested in the fishing opportunity provided for diagnostic purposes, they are more interested in the extent that anglers benefit from sustaining fisheries, access, sanitary facilities and other elements that comprise the fishing experience. Progressive programs are easily identified from their reported accomplishments, which are usually reported in terms of the recreational activity supported by management.

Traditional agencies usually do not report the outcome of management; instead they report process--the numbers of fish stocked, violations cited, boat ramps installed, reports published and the like. Whereas progressive agencies can report the efficiency with which they provide for angler needs, often as a fishing-day:cost ratio, more traditional programs report process:cost (e.g., dollars/pound of fish stocked, salaries, travel costs), which cannot be easily linked to angler benefit. The traditional approach allows no way to identify management effectiveness and efficiency in terms of public service missions and mandates.

Progressive sportfishery management programs are built on information integrated across the physical, biological and social sciences. RIOFISH was developed to facilitate such information integration in New Mexico. Until recently, even the most progressive programs assumed that each fishing day was of equal value to anglers, because they had no means to measure benefits precisely until welfare economists provided the theoretical basis. RIOFISH integrates contemporary non-market valuation theory and techniques with predictive understanding of fishery management impact on resource opportunities in New Mexico.

RIOFISH organizes information about sport fishery habitats, aquatic communities, fishery use and fishery value into a coherent and comprehensive whole. It simulates the input effects of management-decisions and natural events on output measures of management effectiveness. RIOFISH can be used to approximately estimate management efficiency (management effect/cost), but encourages more accurate cost accounting to compare to model-estimated benefits. RIOFISH was designed to investigate alternative statewide management strategies in search of the most cost-effective and sustainable management for time periods limited in length only by the needs of model users. It is a comprehensive management planning heuristic based on the incremental changes in outputs found in sequential comparisons of reference management scenarios with alternative management scenarios.

RIOFISH is flexible, It is composed of three components, each of which may be used independently or interactively in an integrated whole (Figure 2). When integrated, RIOFISH links

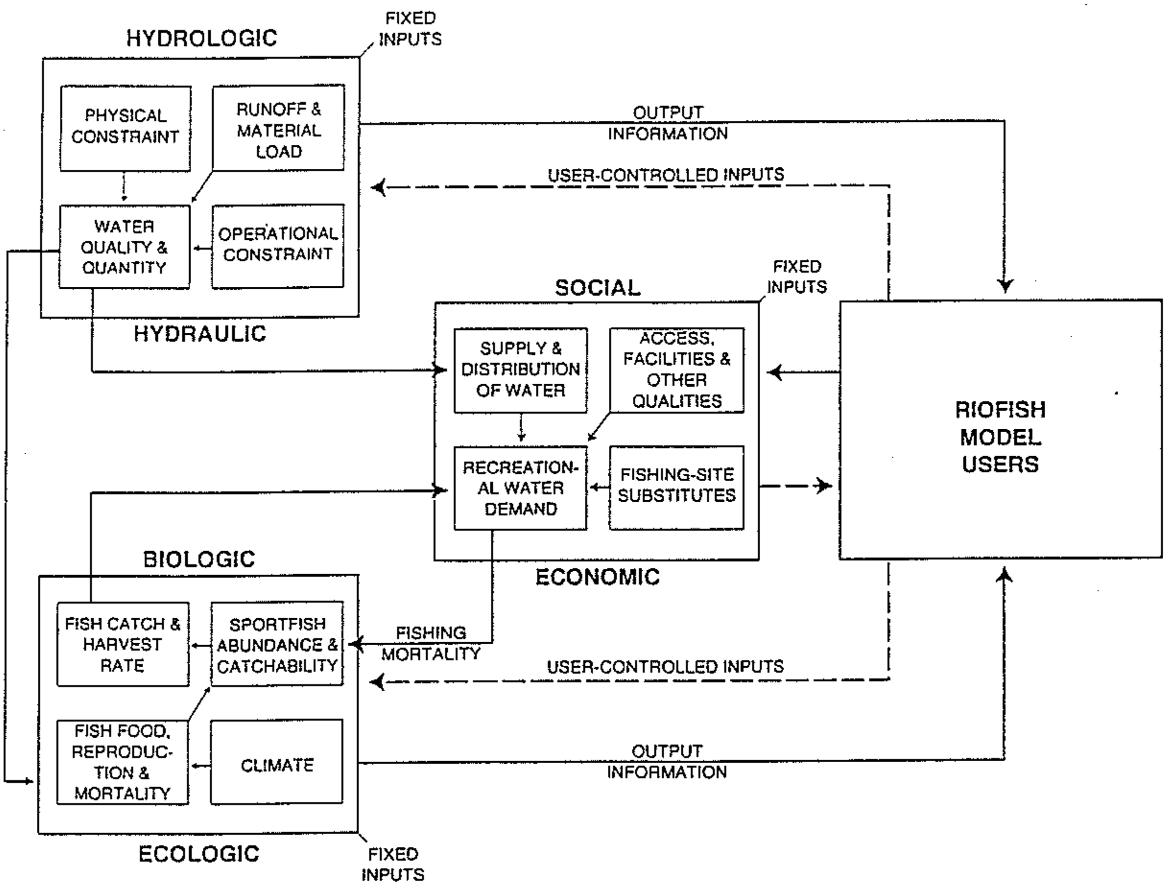

Figure 2. RIOFISH is composed of three components, run separately or integrated and simulating the hydrology, ecology and socio-economics of a sportfishery program management system. Model users have access and control of numerous inputs for each component and receive output information about the consequences of input changes.

hydrologic, biologic and economic components of ecosystem and fishery system process with fishery management process. The hydrologic component simulates habitat dynamics and provides inputs for ecologic and economic components when the model is fully integrated. The biologic component simulates aquatic community production process and partitioning of ecosystem resources into fish populations. The economic component simulates the angler portion of the fishery system, including the angler satisfaction (economic benefits) that drives fishing effort and effects fish populations in the ecologic component.

When the components are run independently, fixed inputs take the place of outputs supplied by other components. The hydrologic component is most self-contained; it does not require inputs from either the biologic or economic components. The biologic component incorporates a fixed (not user accessible) historic or random synthetic flow base when the hydrology model is not run with the biologic component. The biologic component also can be run with number of angler days set independently (user accessible input) of economic component outputs. The economic component can be run independently based on hydrology and fish catch and harvest conditions as they occurred in the late 1980s in New Mexico (both user accessible inputs).

By building on existing data and process understanding, RIOFISH provides an inventory of integrated information for 132 sites supporting over 90% of the present and potential sportfishing in New Mexico. It is a planning, teaching and communication tool, designed to help model users diagnose the reasons behind some of the model output results. RIOFISH has been developed to be useful for fishery managers in decentralized situations. It has a user-friendly, menu-operated format and may be run on contemporary personal-computer hardware. Although RIOFISH is "grounded" in New Mexico, it can be used to analyze out-of-state policy by analogy. A user manual accompanies the software and provides additional insight about model use (Cole et. al. In Press).

When used properly, RIOFISH scenarios are run in pairs and the differences between scenario outputs are calculated to estimate output changes generated by user-modified inputs; sometimes referred to as incremental analysis. For management decision-making purposes, the incremental changes can be compared back with management costs to estimate management effectiveness (e.g., harvest days, annual harvest, economic benefit). To estimate efficiency (harvest/cost, benefit/cost), model users can use rough approximations of management costs provided in RIOFISH, but are advised to provide more accurate estimates for specific conditions. For research decision-making purposes, changes in output can be compared with the degree of uncertainty that exists in various RIOFISH parameters to estimate sensitivity of model outputs to uncertainty of model inputs.

SYSTEM INPUTS

Model users can change temporarily many RIOFISH inputs to analyze for output effects. User modifications remain in effect until the program is closed or the hardware is turned off. User-accessible inputs include qualities of habitats, aquatic communities, sportfish populations, angler activity, angler impact, and angler benefits. A variety of modeled management tactics are available to create input strategies for RIOFISH analysis. In the context used here, a strategy is the full assemblage of specific tactics used to manage a site or group of sites. Model users can redistribute water among modeled lakes and streams, altering habitat availability and form. Certain aspects of water quality can be altered to simulate changes in watershed condition, water treatment, and habitat fertilization. Model users can simulate removal of aquatic vegetation and mixing of stratified waters. Fish populations can be introduced, modified or eliminated. Fish can be stocked according to size categories. Regulations can be imposed, including site closures and numerical, size and terminal gear limits. Various angler amenities can be reduced or increased, including site access, boat ramps, toilets, and campsites.

Certain management possibilities are not included. RIOFISH is not designed to micro-manage habitats, for example, stream improvement structures or lake artificial habitats. It does not analyze the effects of toxic contaminants, certain complex regulations, and site aesthetic qualities. New sites cannot be created nor can existing sites be reshaped (as by dredging) by the model user. The user also has to assume anglers will completely comply with regulations--there is no input for various estimates of non-compliance. Certain inputs present in RIOFISH are not user accessible. These fixed inputs can only be modified through further model development. Although many of the management actions in RIOFISH influence total recreational use of fishing sites, RIOFISH only estimates the recreational benefits accrued by anglers.

Users also may modify various model parameter coefficients to evaluate model output sensitivity to the coefficient estimates and to learn more about parameter interactions. Model users can modify population parameters for all 24 taxa included among the fish populations, and in effect create their own species. A few examples of those parameters are initial fish populations, length-weight relationships, minimum size at maturity, fecundity, production/biomass ratios (growth coefficients) and their environmental controls, egg mortality and other natural mortality.

Users also may investigate catch and harvest effects via catchability and retention coefficients. They also may modify hooking mortality by various terminal gears and the fraction who fish with various gears. In combination with regulation changes, the model user can analyze the uncertainty of various regulation effects on fish survival, density, growth and production.

Users can temporarily modify certain critical aspects of the planning environment for forecasting purposes and contingency planning. They may create various water runoff scenarios (extreme low to extreme high). Users also may adjust the total state human population number and its distribution among counties. The fraction of people who fish may be changed. Travel costs are adjustable, including cost/mile and site fees. All site facilities currently in the model also are adjustable.

SYSTEM OUTPUTS

The output information provided by RIOFISH is used to judge management effectiveness and to diagnose underlying processes effecting management process. Among the more important outputs for decision making are measures of fishing opportunity (stock abundance and diversity), fishery use (angler days, annual harvest) and angler satisfaction. As used here, angler satisfaction is a measure of angler welfare using travel-cost to estimate angler net economic benefit (consumer surplus).

Statewide incremental benefit is the single most important criterion for judging management effectiveness that focuses on maximally satisfying resident anglers, given revenue, conservation and certain other constraints. Aggregate angler satisfaction is best represented by net economic benefit (consumer surplus). Although angler-use rates, catch rates, harvest rates and various other satisfaction measures have been used to estimate management effectiveness, angler economic benefit is the only measure that is directly comparable to cost. Unlike indices that are tied to catch and harvest information, benefits, as measured in RIOFISH, reflect many other qualities that affect angler site use. Angler economic benefit is equivalent to cost savings (consumer surplus) to anglers provided by management in relation to angler willingness to pay for the fishing. Benefit is determined by the combined effects of fishing quality and angler costs. Angler benefit increases as fishing quality improves and angler costs decrease. Benefit also increases when quality and costs remain constant while angler use increases. Although management oriented toward benefiting resident anglers also benefits non-resident anglers, non-residents are not explicitly included in the statewide benefit criterion of RIOFISH.

Economic benefit is most comparable to the product of angler use rate and mean angler satisfaction stated in angler opinion polls, but provides more useful information. When agencies wish to evaluate the cost-effectiveness of their management, the product of use rate and mean satisfaction is more useful for comparative purposes than either use rate or satisfaction-index alone. Satisfaction measures without use rate do not reflect the extent that satisfaction is extended to all anglers. Use rates without satisfaction measures do not fully reflect the quality of use. The most useful angler use and satisfaction data are gathered before and after management changes are made, so that increments in use-satisfaction index (benefits) can be compared to the management cost investment. Because management tactics differ in the extent of their effectiveness, the best use-satisfaction data are gathered over the entire period that management is expected to have its effect. RIOFISH has up to a 10-year planning horizon, which covers most contemporary planning needs.

Incremental angler economic benefit is a more useful use-satisfaction or welfare index than an incremental use-satisfaction index because the economic index is in monetary terms that can be directly compared with management costs to determine a benefit-cost ratio. Use of benefit-cost ratios for policy formation prevents management decisions that cost more than anglers benefit (benefit-cost ratio is less than 1.0). When based on actual data documenting angler behavior, as in the travel-cost methodology used in RIOFISH, angler actions are more likely than angler opinions to demonstrate the relative values anglers attach to their preferences. Unlike simple satisfaction indices, like fish catch and harvest success, statewide economic benefit, as developed in RIOFISH, reflects all important qualities comprising sport fishing, including amenities such as access, camping and sanitation facilities.

Fishing opportunity measures also are output to aid interpretation of the benefit estimated by RIOFISH. Fish status outputs include panfish, sportfish and other catchable fish density, production and mean individual weight. Fish measures are expressed as numbers and weight. Additional measures of opportunity include site size, access, boat ramps, campsites, toilets, and drinking water availability.

Angler use and success outputs are provided, including angler hours fished, catch/hour and harvest/hour, and annual catch and harvest. All success measures are expressed as numbers and weights.

A large variety of diagnostic indicators is provided. Site volumes, discharges, surface areas, elevations, nutrient contents, light transmission, oxygen, temperature and other variables are output. Organic loadings from allochthonous sources as well as primary production are estimated, as are productions of zooplankton, zoobenthos, and herbivorous fish. Detailed outputs about individual fish population behavior and community production are available for instructional purposes.

An economic output of frequent interest is the state income and jobs generated by fishery management. Estimates of regional income are provided for those interested primarily in the statewide distribution of income. This income includes non-resident anglers. Because there is no measure of state resident fishing outside of New Mexico, RIOFISH does not estimate net income to New Mexico associated with sportfishery management.

RIOFISH ECOSYSTEMS

Ecosystems in RIOFISH are simulated to behave as realistically as data and model output needs warranted. Much complex and detailed ecosystem process is collapsed in RIOFISH algorithms for greater processing efficiency while sustaining utility for comprehensive planning purposes. A model default state is created, which can be changed by the model user, and is recovered when the user quits model use or hardware power is interrupted.

The ecosystems in RIOFISH are river-basin and watershed based. The river basins are subdivided into lake and stream segments, forming 132 sites, each of which can be examined alone or in various combinations. The sites were chosen mostly based on fishing use. A few exceptional sites had low fishing use and high potential for future use, depending on management decisions. Stream and lake hydrology is linked within river-basins. Changes in runoff or individual site management are transmitted realistically throughout the basin based on past hydrologic behavior. The hydrologic component operates on the basis of semi-monthly mean-flow dynamics, a time step determined to be most computationally efficient given limited data and output processing needs.

Habitat simulation is based on either historic or synthetic flow simulations. The historic flows are simulated for 18 water years from 1975 through 1992. The historic reference state is not intended to be an exact reproduction of what existed from 1975 through 1992 because no flow records existed at some sites and statistical uncertainty exists in measurements made even at the best monitored sites. RIOFISH "historic" flows are a facsimile of what **could** have existed given the uncertainty of available data. The modeled inventory of site habitat conditions is an extrapolation of observed conditions to all times and places simulated.

As an alternative to historic flow simulation, the model user may select a series of synthetic flows to forecast future conditions. Past flow records were analyzed to estimate flow variations at USGS stations with long monitoring histories. From that analysis, seven flow conditions were identified, representing extreme low, low, low-average, average, high-average, high, and extreme high flows. The model user can assemble the seven flow conditions in any desired sequence. These may serve as background for assembling fisheries and fishing publics in various forecast configurations to analyze the uncertainty of conditions on management effectiveness.

Modeled hydrology drives much of the ecosystem process that supports fishery production (Figure 2). Hydrologic changes influence concentrations of nutrients, light transmission, flushing rate, and sediment size, which in turn influence ecosystem production and the partitioning of ecological resources in the aquatic community. Ecosystem processes are simulated on a semi-seasonal basis to estimate aquatic community and sport fishery outputs on a seasonal and annual basis. Concentrations of nutrients and suspended matter are simulated in each water segment through use of loading-concentration functions (e.g., Chapra and Reckhow 1979, Bolin et al. 1987). In addition to hydrologic factors, inputs of solar energy, elevation-determined water temperature and water-level changes determine primary production. Allochthonous organic loading (organic loading from sources outside the aquatic ecosystem) is added to organic load from primary production to form the trophic base for estimating fishery outputs, sportfish production, and fish biomass.

The total organic load is transformed to fish production and biomass based on energy and mass balance principles and transformation efficiencies. As loading increases, and as light, temperature and oxygen deviate from optimum, the trophic-level efficiency decreases toward zero at the extremes. At successive carnivore trophic levels, the maximum trophic efficiency is expected to be 40% of the underlying trophic-level net production when conditions are optimum (respiration and decomposition requirements are low) and initial biomass does not limit production.

In lakes, herbivore-detritivore production is first partitioned among suspension feeders and benthic feeders, based on water depth. Only benthic deposit feeders exist in streams (including so-called benthic drift feeders). The suspension feeders in lakes are partitioned into invertebrate zooplankton and vertebrate (shad species in New Mexico) groups based on mean concentration of organic matter.

Production in the fish and crayfish populations is partitioned by use of growth, reproduction and mortality coefficients. Environmental factors influence trophic process. To connect to underlying production, growth coefficients are assumed to equal production/ biomass (P/B). Under optimum conditions, each taxon and life stage has a maximum P/B. To attain maximum trophic-level efficiency, all taxonomic groups need to be summed and initial biomass cannot be limiting.

Initial estimates of fish population density, fish size distribution and length-weight relationships are provided in the RIOFISH reference (default) state. When habitat and other conditions created in RIOFISH vary from average, model fish populations adjust to the variant state.

The maximum P/B is reduced when environmental conditions deviate from optimum, which is often. Environmental resistance varies among taxa and lifestage, reducing the maximum P/B according to individual tolerances. Different taxa and lifestage tolerances to variation in water temperature, oxygen, light transmission, velocity, depth and particle size are included in RIOFISH and are user adjustable. Under extreme conditions, such as extreme cold temperature, all production ceases for all species and trophic efficiency drops to zero. Like most calculations in the biologic component, the P/B calculations occur at semi-seasonal intervals and production efficiency changes with seasonal changes in habitat conditions. Diverse RIOFISH fisheries tend to have higher trophic efficiencies than single-population fisheries because of a wider community-level tolerance to limiting conditions.

Fish populations also naturally recruit new adults based on mature female biomass and fecundity relationships, egg survivorship estimates (including effects of water-level fluctuation), and survivorship of larvae, juveniles, and older fish. Larval survivorship is determined by zooplanktonic food availability in lakes and growth to juvenile size within a half-season maximum time allotment. In streams, larval survivorship is determined similarly, but depends on benthic foods because zooplankton are not present. When larvae fail to grow fast enough, they die. Source of death is not defined. Once fish reach juvenile stage, natural mortality becomes constant except for winter kill of juveniles and extremes of temperature, oxygen or drying.

RIOFISH FISHERY SYSTEMS

Fishing mortality is one important link between fishery systems and support ecosystems in RIOFISH. The relationships among site qualities, fish populations and anglers form fishery systems, which link with ecosystems through fish species composition, fish population structure and various habitat attributes that have independent effects on angler use. In RIOFISH, a fishery system includes all those factors that attract anglers to particular sites and all those comparable sites that may serve as substitute fishery choices, depending on fishing quality, angler costs and angler preferences.

RIOFISH simulates fishery system dynamics as a consequence of management, including change in total fishing effort, the movement of anglers among sites as site qualities change, and the consequent changes in fishing mortality. Total annual fishing effort at a site in RIOFISH is only in part a function of fish composition, numbers, size, catchability and retainability. Other important determinants of fishing effort are human population density, site proximity, site size, the availability of substitute sites and a suite of site qualities in addition to fish-related opportunity. Therefore, angler fishing effort can, in reality and in RIOFISH, exceed the capacity of a water body to naturally sustain fish yield over several years, as fishing mortality exceeds population recruitment rate. A feedback loop exists in RIOFISH that simulates angler impact on fish production through a "top-down" effect that can partially to totally counteract the "bottom-up" driven fish production derived from the amount of organic loading. This top-down effect is not transmitted downward to the primary production level, however, and the model cannot be used to analyze biomanipulation of primary producers.

The concept of site substitution incorporated in RIOFISH is an important element in simulating the distribution of angler effort among sites. The basic assumptions are that anglers place greater value on certain fishery qualities than other qualities and make decisions based on those values and personal budgetary constrains. Experienced anglers tend to select their fishing sites from a set of substitution possibilities within a limited cost range and a particular set of qualities. Fish species composition and qualities that foster a particular approach to fishing (e.g., fishing from boats, wading) combine with other attributes to attract anglers. Size, flow and thermal characteristics are among important indicators of suitable fishery substitutes, but availability of various angler amenities also can be important (e. g., large, warm-water lake fisheries with boat access; cold-water stream fisheries accessible by wading; small cold-water pond fisheries accessible from shore). Within the array of preferred site characteristics, fishing sites substitute for one another as conditions change.

As anglers substitute one site for another, they redistribute their impact on the fisheries and affect the sustainability of future catch and harvest. Thus fishery system boundaries often cross ecosystem boundaries defined by river-basin and watershed boundaries. Although fishery systems depend on ecosystem process, the boundaries of the two system types often do not neatly align. By integrating ecosystem parts with fishery systems, RIOFISH facilitates comprehensive analysis that is otherwise difficult to contemplate.

RIOFISH MANAGEMENT SYSTEMS

RIOFISH is designed to simulate a comprehensive management system, which integrates ecosystems, fishery systems, and fishery management systems. RIOFISH users link with the simulated comprehensive management system mostly through management simulated by RIOFISH. Users also may change many of the model coefficients. Unlike most other fishery models, RIOFISH relates directly to the primary motivation for sportfishery management, the desire to maximize angler satisfaction (benefit-cost) over the long-term within the limits of conservation constraints and social norms. This concept of "wise use" is the basis of long-term strategic planning facilitated by RIOFISH using output measures of opportunities, use and angler benefit over planning periods of up to 10 years and longer. The results of 10-year runs can be used to initiate subsequent runs for as many runs as the user wishes.

Management system inputs include all those tactics generally used by fishery managers in pursuit of management ends; most notably habitat management (excluding micro-management like substrate modification or stream improvements), stocking, regulations, access control, and facilities provision. The management system process focuses on choosing the optimum combination of tactics to maximize benefits given ecosystem, fishery system and social constraints. The model user is provided with a wide array of management-change options, but is responsible for assessing management limitations and costs. Although RIOFISH warns of certain water management constraints, in general the manager must be independently aware of legal and political constraints, such as exerted by interpretation of the endangered species act and interstate agreements pertaining to water management. RIOFISH does not analyze for negative effects of management outside the context of sportfishing, such as possible negative effects on scarce species.

RIOFISH is designed to analyze policy implications of the entire state sportfishery program and program-area subdivisions. In New Mexico, the sportfishery program is subdivided into four program areas based on size, flow and thermal characteristics. RIOFISH facilitates analysis for those four program areas while sustaining the flexibility to create any combination of sites for policy analysis. RIOFISH is most productively used to comprehensively simulate systems of program-area and statewide size for several years. Although single sites may be run for short periods, the model is expected to be most indicative of system responses when a larger number of sites and years is included in the analysis. Cole et al. (In Press) describe RIOFISH use for comprehensive management analysis in greater detail.

The appropriate approach is to define and compare pairs of scenarios, one unmanaged as proposed and the other managed as proposed. Then model outputs are compared to estimate the incremental change, which then can be compared to the user estimated cost for decision-making purposes. RIOFISH answers the general question "if...what would happen if...?" **If** specified reference conditions occurred in the planning period, **what would happen to opportunity, use and benefit if** specific management strategies were applied during the planning period. A simple example follows: **If** the large warm-water reservoir fisheries existed as defined in the reference scenario, **what would happen if** 2 million largemouth bass and 1 million channel catfish had been annually stocked as fingerlings? How would angler benefits, sportfish abundance and angler hours of fishing change at the warmwater sites? In complex scenarios, a model user would enter all proposed management tactics at all sites included in the scenario over the period of time the tactics are expected to have effect. Since many tactics have effects lasting at least a decade, the entire 10 years available in RIOFISH would likely be most appropriate. A manager searching for the most cost-effective scenario would try numerous tactical variations in subsequent model scenarios. The RIOFISH user manual (Cole et al. In Press) explains in more detail how RIOFISH is best used.

One of the greatest decision-making challenges facing agencies is what management tactics to cut back or to add when management revenues fluctuate. These priority decisions are rarely based on quantitative cost-benefit analysis because of the difficulty entailed in their estimation. RIOFISH facilitates such estimates by allowing planner-users to break down strategies by individual tactical contribution to statewide benefits. That is done through reiterative analysis, holding the planning environment in RIOFISH constant except for the specific tactic analyzed.

RIOFISH can be used to anticipate the effects of natural events as well as managed events. For example, if average cold-water lake levels existed as defined in the reference scenario, **what would happen to modeled management effectiveness if** higher water levels were created by higher than average runoff? A project plan might incorporate numerous proposed management changes to a fishery over a period of several years. For a small cold-water lake fishery, for example, the plan might include optimizing stocking of trout in different sizes, several variations of harvest regulations, changing road access and camping facilities, controlling macrophyte growth, and mixing the sites to oxygenate bottom waters. Various combinations of management tactics applied to the project sites would be contrasted with the reference conditions to evaluate the most beneficial strategy for the revenues made available.

Such natural **what...if** scenarios can be used to create a variety of possible planning environments as background for evaluating management effectiveness. For example, stocking in low-water years is likely to generate different fisheries and benefits than the same numbers stocked/site in high or average water years. RIOFISH shows that a project plan proposed for the next five years at numerous sites will generate different results depending on what planning environment actually comes to pass over that period. As travel costs, human population density and habitat amounts shift, the benefits derived from proposed management tactics will change. Through iterative use of RIOFISH, the model user can look for the compromise management strategy that best fits most probable scenarios or seek appropriate responses to changing environments in advance of their actual occurrence. This is sometimes referred to as proactive contingency planning or proactive planning.

MODEL COMPONENT DESCRIPTIONS

The following detailed model description is presented in three chapters based on the main model components: Hydrology, Biology and Economics. Flowcharts accompanying text in Figures 3, 4, 7, 8, 12 and 15 show model unit interactions, which can be linked back to the text and mathematic documentation in the appendix. Figures are intended to provide a conceptual overview, illustrating how elements generally fit together to form a systems whole. They are not intended to represent a programming process. The text is conceptually descriptive and presents rationale and assumptions. The mathematics in the accompanying appendix most precisely represent model content.

The flow charts use symbols (derived from Grant 1986) that represent specific systems process and characteristics. The boxes with bulging sides represent sources and sinks outside the subsystem defined in each figure. Other model components usually act as a source or a sink for a depicted system. Solar energy is a source, for example, outside the model system boundaries, and total public welfare is a sink outside model system boundaries. All other processes are internal.

Rectangles represent state variables within the modeled system. Those habitat features that determine biological production, for example, are general categories of state variables in the system. They vary in dimension as the model operates through its semi-monthly or semi-seasonal time steps. Material and energy pathways depict cause-and-effect connections or pathways between state variables and are defined by solid lines with arrows. Values pathways are depicted for the economic subsystem by bold dashed lines. Fine-dashed lines indicate information transfer. State variable status partially determines status of other state variables. Feedbacks occur, as between the angler use determined in the economic component and fish biomass and production in the biology component.

Relationships between state variables are modified at control points (bow ties) by the effects of driving variables (diamonds) and their accessory variables (circles). Driving variables are linked to control points by fine-dashed lines, rooted in small circles. The driver and accessory variables represent either natural or management process that controls relationships among state variables. Wherever they occur, the model user usually has some control over system function. State variables may act as their own driver variable, creating a feedback control on state variable relationships.

HYDROLOGY COMPONENT

OVERVIEW

Without habitat, fisheries could not exist. The hydrology component simulates habitat characteristics and provides means for the model user to change water distribution and character in order to analyze the effects of such management decisions on fish abundance, fish yield and fishery values. Flowcharts are used to help describe in detail the hydrology component in Figure 3. The detailed model description that follows is organized to match with the flowchart units.

The primary variable driving the hydrology component of the RIOFISH model is the quantity of water entering or leaving reservoirs or stream reaches. Where possible, these data are from USGS or other reporting agencies. For sites that are not monitored by any agency, flows and volumes have been estimated using various techniques. Depending on whether the site is a stream or a reservoir, water amounts may be modified by precipitation, evaporation, irrigation withdrawals, and other hydrologic processes. The hydrology component is comprised of two submodels: one for reservoirs and one for streams. Both models operate on a semi-monthly or two-week step (first half, second half of the month).

The hydrology component of RIOFISH manipulates external data files (flows and parameters) in order to generate a sequence of flows and chemical concentrations. Cochiti Reservoir, for example, has as a primary inflow the Rio Grande measured at the Otowi Bridgegaging station. Flows at the Otowi Bridge gaging station can be estimated, whenever needed, by the Rio Grande at Embudo and Rio Chama below Abiquiu Reservoir flows as corrected by empirically determined constants. The Rio Chama flow, in turn, is controlled by reservoir operations in its subbasin. Therefore, the modeled flows at the Otowi Bridge gaging station can reflect changes imposed by the model user on reservoir

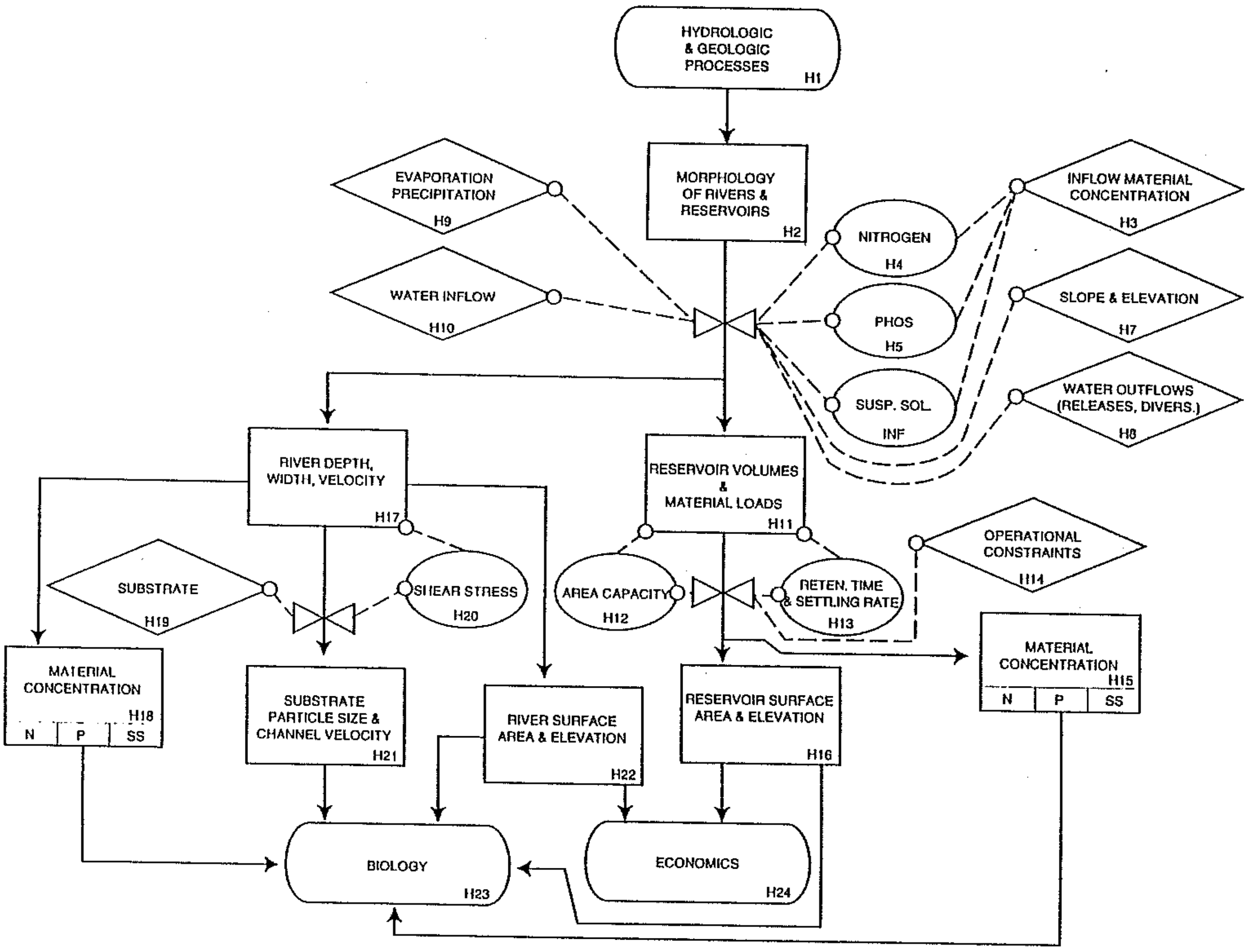

Figure 3. Main elements and process in the hydrologic component of RIOFISH.

operation in the Rio Chama. The model user can make numerous changes of this type.

RESERVOIR SEGMENT

A number of variables and parameters (Table 1) are read into the program. Some variables can be adjusted by the model user to analyze how changes in the reservoir system affect RIOFISH outputs. Some cannot. Upon starting the model, the user is prompted for the names of files needed to define inflows, reservoir parameters (such as, reservoir contents, outflow rates, and evaporation pan coefficients for relating pan and lake evaporation) elevation-area-capacity tables for each reservoir, and coefficients for relating loadings of nutrients and suspended solids to stream discharge.

Morphology (Units 1-2)

Hydrologic and geologic processes have combined to produce the current morphology of river and reservoir sites in New Mexico. The morphology of reservoirs in the models is represented by elevation-area-capacity tables, some of which were provided by various state and federal agencies.

Table 1. List of all hydrologic model parameter inputs for the reservoir model.

Elevation-area-capacity table (feet-acres-acre feet)

Half-month and year for the entire period selected

*Three reservoir inflows: primary inflow can be changed by adding or subtracting a constant amount to the measured flow or by multiplying the measured flow by some number (cfs)

*Three reservoir outflows: primary outflow can be changed by adding or subtracting a constant amount to the measured flow or by multiplying the measured flow by some number (cfs)

Measured volumes for the period selected (acre feet)

*An initial reservoir volume, one time step before the selected period pan evaporation (inches)

Precipitation (inches)

*Maximum allowable reservoir contents for each month (acre feet)

*Maximum allowable reservoir contents for each month (acre feet)

*Maximum allowable reservoir outflow for each month (acre feet)

*Minimum allowable reservoir outflow for each month (acre feet)

*Evaporation pan coefficients: currently set at 0.7 for each month

Empirical coefficients that calculate chemical loadings based on flow

*A multiplier to increase or decrease chemical loadings into the reservoir: currently set at 1.0

If modified flows are used, empirical coefficients that relate downstream flows to upstream flows are read

*/ Variables or parameters that can be changed by the user during model operation

Of the 70 reservoirs in the model, fifty-two had no or incomplete data with respect to inflows, outflows, and storage. A non-dimensional elevation-area-capacity relationship was developed from smaller reservoirs where such data were available. This non-dimensional relationship was used for those sites without such information. New Mexico Department of Game and Fish maps list maximum surface acres for most lakes and reservoirs in New Mexico. Elevations for the reservoirs were estimated from topographic maps when necessary. Using the non-dimensional relationships, maximum volume was computed and increments of storage estimated to create a synthetic elevation-area-capacity table for all reservoirs in the model.

Loads (Units H3-6)

For both the reservoir and stream portions of the hydrology component, inflow loads of suspended sediment, phosphorus and nitrogen are computed from discharge-load relationships. These relationships were developed from USGS data collected at various sampling sites around the state. The best relationships were power equations and, whenever possible, separate relationships are used for each season.

Flow sequence (Units H7-11)

The reservoir portion of RIOFISH is based upon conservation of mass. Inflows and precipitation entering a reservoir in a semi-monthly period causes reservoir contents to increase.

Reservoir outflows through releases and evaporation cause contents to decrease. Ungaged inflows and reservoir leakage can create mass balancing difficulties so that the predicted contents do not match measured contents. These difficulties are particularly severe for Cochiti, Abiquiu, and Brantly (McMillan in earlier years) reservoirs. The model user is provided the option of using original flow records, some part of the original flow records, or modification of inflows based on observations made at an upstream reservoir.

The user, at this point, can select either the historic record or the modified flows as influenced by upstream inflows. If the user elects to modify inflows, the program employs empirically determined water-transfer functions. These functions are simple linear relationships between upstream reservoir releases and/or other streamflows and the streamflow, either a stream reach or a reservoir inflow, being modified by the user. For example, the May monthly flow at the Otowi Bridge gaging station can be estimated as 1.09 times the May flow at Embudo and 1.91 times the May outflow from Abiquiu Reservoir, minus 7 a constant. Similar relationships were developed for each month at each reservoir inflow gaging station. These relationships can be updated or modified as more data are collected at the gaging stations. With these relationships, it is possible to account for changes in inflow at the downstream stream reaches or reservoirs when outflow from an upstream reservoir is modified.

During the last three years, considerable effort has gone into delineating suitable modifications to the hydrology submodel to reflect water, nutrient, and sediment contribution from ungaged watersheds surrounding the modeled reservoirs. In the current version of the model, watershed water inflows have been estimated for the period of record through mass balancing of the reservoir volumes, measured inflows, and measured outflows. The ungaged watershed inflows were estimated after assuming a fixed evaporation pan coefficient of 0.7. The difference between measured and predicted volumes in the reservoir was attributed to ungaged inflows or losses at the reservoir. This technique creates negative as well as positive values. The positive values are interpreted as unmeasured inflows whereas the negative values are interpreted as unmeasured outflows or losses (evaporation). Reservoir leakage is an unmeasured loss. This balanced, third inflow is now part of the measured flow file in Unit H10 (Figure 3). When these flows are used, the computed reservoir volumes almost exactly match the measured volumes. The slight differences are caused by the interactive technique used to find evaporation in the model.

Although simple, the balanced volume technique for finding inflow or outflow was determined to be the best approach with current system knowledge. Research during this last phase of the modeling study indicated a relationship between ungaged inflow at Caballo Reservoir and rainfall measured at various sites in the mountains west of the reservoir. Long-term simulation scenarios for planning and management would be best served if the watershed were modeled. However, for this phase of the project, it was decided to use the balanced volume technique to provide "what if" scenarios using previous conditions.

Mass Balance (Units 11-16)

Once the flow sequence has been established, the computations for mass balances of water are completed. For each two-week time period, the reservoir volume at the end of the previous two-week period is used in computations. The previous reservoir volume is added to the total inflow volume (with up to three inflows) and the total outflow volume (with up to three outflows) is subtracted. This initial estimate of the volume is used to compute reservoir surface area through linear interpolation of the elevation-area-capacity (volume) table (H12; numbers in parentheses refer to flow-chart unit numbers). The initial reservoir surface area is multiplied by the net evaporation depth (determined from the pan evaporation, pan coefficient and the precipitation) to determine reservoir volumetric changes caused by local weather conditions. The initial volume is then modified to reflect net evaporation and a second surface area is then calculated using the elevation-area-capacity tables. A second volume estimate is made from the second surface area estimate, then the first and second estimates are averaged to represent volume at the end of the semi-monthly time period. Previous investigations have shown that the two estimates of volume are usually close because net evaporation is small compared to the inflow and outflows.

The volume estimate is also modified by constraints (H14) such as maximum and minimum reservoir contents, with the volume changes being added to or subtracted from the primary reservoir outflow to meet the constraints. For example, if the model user computed a volume less than the minimum requested by the user, the primary outflow would be reduced down to a limit of zero flow. Similarly, if the computed volume were larger than the constraint set by the user, the primary outflow would be increased. The outflow constraints, if violated, provoke a warning message to the user, but are not used to rebalance volume and flow. After modification for constraints, if necessary, the estimated volume is used to compute corresponding area and elevation (H16) for use in the biology and economic components (Units H23-24).

Once the volume in each time step has been computed, the concentrations of sediment, phosphorus, and nitrogen are computed (H15). Reservoir inflows contain phosphorus, nitrogen, and suspended solids, along with other constituents. USGS data were analyzed from monitored sites to determine relationships between total loads (tons/day) and stream discharges (cfs). The relationships are in the form of power functions. These relationships could not be developed for all reservoir inflow locations because only a few locations are monitored by the USGS for transported materials. Therefore, relationships generated at sites with data were transferred to sites without data to estimate nutrient loadings.

The loadings calculated for each reservoir are converted to semi-monthly reservoir concentrations of total suspended solids, total phosphorus, and total nitrogen by equations developed by Bolin (1985) which have been updated during this phase of the modeling. These equations use a steady-state solution to a chemical mass balance formulation; that is, they are time invariant over the computational period. Loads are converted to appropriate units per area of reservoir surface using the previously calculated reservoir surface areas (H16). Retention of the load is estimated by a water retention-rate term (reservoir volume divided by outflow rate) or a sedimentation rate which is related to average depth and retention rate (H13-14). The relationships were calibrated with data from a subset of reservoirs, because not all reservoirs in the system had data available. Descriptions of the retention models are given in Bolin (1985) and Bolin, Ward and Cole (1987).

Third inflows were computed using a balanced volume as described above, to better define nutrient and sediment loadings from ungaged sources. Such ungaged sources help explain the observation of productivity in excess of that expected if only measured inputs were considered. This is particularly true with low-elevation reservoirs, such as Caballo, which can receive larger inflows of water, suspended solids, and nutrients from summer runoff. When the model is run with the third inflow, computed reservoir concentrations of nutrients and sediments increased to levels that better matched observed values.

STREAM SEGMENT

Morphology-flow (Unit H17)

For the stream submodel, it is assumed that steady, uniform flow occurs in the typical flow reach during the time step. The average discharge for each two-week period is used to compute flow area, average depth, average velocity, top width, average shear stress and the maximum-size sediment particle that can be transported (based on average conditions) in each cell of a stream cross-section. A cell is a portion or slice of a cross-section. A stream site typically has two cross-sections, one representing a pool and one a riffle.

Conceptually, both the stream and reservoir submodels function similarly. Exceptions are noted below. The stream model is used to link reservoirs in a downstream progression and to model sites that are not connected to reservoirs at all.

As in the reservoir segment, the model user is prompted for file names and options. A number of variables (Table 2) are read into the program, some of which can be adjusted by the model user to analyze how changes in the stream system affect RIOFISH outputs. The model can accept file information on measured flows, modified flows from upstream reservoirs, and concentration of total suspended solids, total phosphorus and total nitrogen.

Table 2. List of all hydrologic model parameter inputs for the stream model.

Half-month and year for the entire period selected
*Stream discharge : flow can be changed by adding or subtracting a constant amount to the flow or by multiplying the flow by a coefficient (cfs)
X-Y data pairs that define the shape of the cross-section, no more than 13 data pairs which define 12 cells (feet)

*Percent of each reach that is riffle and pool: currently most reaches are estimated as 75% riffle and 25% pool
Total length, upstream elevation and average slope of the stream reach (miles, feet, dimensionless)

Manning's roughness coefficient (dimensionless)

Coefficients relating discharge to depth of flow in the cross-section (from previous analyses)

Diameter of median particle size and diameter of particle size that is one standard deviation larger than the median particle size in the cross-section (mm and mm)

Empirical coefficients that calculate chemical loadings based on flow or, alternatively, the immediate upstream reservoir outflow concentrations

*A multiplier to increase or decrease chemical loadings into the stream: currently set at 1.0

If modified flows are used, empirical coefficients that relate downstream flows to upstream flows are read

*/ Variables or parameters that can be changed by the user during model operation

Inflow (Unit H10)

The model user chooses either measured or computed inflows. If computed flows are chosen, the model modifies the flows as described earlier in the reservoir submodel section. For numerous reaches of connecting waters, there will be no modification because the reach is immediately downstream from the reservoir. For reaches farther from a reservoir, the outflows are modified by linear equations to develop an estimate flow at that site.

Hydraulics (Units H17, 10 and 7)

Once flow rate is estimated, it is used to compute the hydraulic parameters and can be used to calculate water quality constituents. Manning's uniform flow formula is used in conjunction with representative cross-sections. In addition, representative channel slope and roughness (Unit 7), obtained from channel cross-section data, are used in the computations. The flow rate is used to compute the flow area, average velocity and surface width for each cell and the width and area for the entire cross-section. Total river surface area for the representative cross-section (riffle or pool) is computed in Unit 22 from the width and total length of the cross-section.

Load-Concentration (Unit H18)

Material concentrations are computed from material loads. The material loads (H3-6) are computed from power relationships as described in the reservoir units of the model.

Particle size (Units H19-21)

Maximum transported substrate particle size in each cell is computed for each half-month period. The size of particles remaining in each cell depends on the initial particle size (H19) and the shear stress (H20) generated by the discharge.

Outputs (Units H23-24)

The hydrology component prepares files for use in the biology and economics components of the model. For the lake components, information in these files includes the date, number of days in the time step (13 through 16 days), computed volume, total inflow, total outflow, evaporation, hydraulic retention rate, and concentrations of total phosphorus, total nitrogen and total suspended solids. For the stream component, this file contains the date, number of days in the time step (H13-16), stream length, beginning elevation and slope of the reach, total flow and surface area in the reach. For each cell in a cross-section (there are a maximum of 12 cells per cross-section), the model outputs flow rate, surface area, velocity, top width, maximum and minimum flow depth, diameter of largest particles moved by the flow, percent of material moved, and the median diameter of material not moved by the flow.

For each cross-section for a stream reach, the stream model outputs total flow and phosphorus, nitrogen and suspended sediment concentrations. The concentrations of total phosphorus, total nitrogen, and total suspended sediment are either computed from empirical discharge-load relationships as described in the reservoir submodel (H15), or reservoir outflow concentrations are used for computations when the reach is immediately downstream from a reservoir.

The hydrologic submodel is applied to all five major river basins in New Mexico and selected smaller river basins. The location of model sites in New Mexico are shown on the map included separately with this report.

BIOLOGIC COMPONENT

OVERVIEW

Public sportfishery management typically is expected to provide fishing opportunity that sustains beneficial use. The backbone of sportfishery management remains biologically based, especially stocking and protective regulations. Other biological management is used in specific situations, such as species introduction and removal. A variety of habitat management tactics also are used, the most basic is to obtain additional habitat (simulated in the hydrology component). Other common habitat management including primary production control (both macrophytes and phytoplankton tactics are biologically based), water-level control (mostly to provide for improved reproduction and recruitment), and aeration of oxygen-depleted waters. The primary purpose of the biologic component is to link common management tactics to fish production, density, and angler use and effect.

The main factors controlling fish production in RIOFISH are "bottom up" habitat inputs,"top-down" fishing inputs and management tactics. The main bottom-up factors include mean semi-monthly solar radiation, nutrient concentration (total phosphorus and total nitrogen), light transmission through the water (as determined by the concentration of suspended solids imported into the segment), water temperature, water-level changes, lake flushing rate and stream substrate size. Flow rates and basin morphology interact to determine water-level fluctuation, surface area, and lake flushing rates. The main top-down factors include angler pressure, fish catchability, fish retention once caught, and hooking mortality. Natural predation is assumed to be in equilibrium with prey production; variation in predator abundance does not affect prey production.

Organic loading supports fish forage production. Trophic resources are partitioned among taxonomic groups according to average food fractions in diets, physiological limits determining maximum trophic efficiencies and habitat limitations that act to reduce maximum possible efficiencies. Differential initial abundance, habitat tolerances, population reproductive and mortality characteristics, and fishing impacts act on fish taxa to determine fish biomass and partitioning of food production into fish production and growth. Partitioning of trophic resources becomes more detailed as trophic pathways progress from organic loading through forage to individual fish populations.

Driving inputs either originate from hydrology and economic components or from files fixed in the biology component. The model user can choose to operate the biology component independently or in tandem with the other three components. When in tandem, outputs passed on to the economics component include fish catch and harvest rates by size and the broad angler-based categories of panfish and sportfish. All model mathematics are documented in the Mathematic Appendix.

LAKE ORGANIC LOADING

Shape and Elevation (Units B1-3)

Figure 4 illustrates the conceptual relationships among model components defining lake organic loading. Lake basin shape and elevation (B1) are defined from USGS or other agency records, as described in the hydrology section and are fixed parameters (user inaccessible) in RIOFISH. Water loading, evaporation, and outflow from each water segment are estimated in the hydrology model and described in the hydrology section. Water volume, surface area, depth and elevation changes in water level are determined by the interaction of water mass balances and the morphology of the basin. The simulation of these interactions is described in the hydrology section.

Basin morphology has changed in most basins since depth-volume-area relationships were originally defined for them. This error generally is small and, in most cases, slightly overestimates volume at each elevation because the lakes are continually filling with sediment. These errors contribute slightly to errors in estimating loading concentration components and fish density wherever depth-volume-area relationships were specifically defined. A generic relationship between the depth, volume and area was assumed for some small lakes where no data were available. These sites are the most likely to incorporate significant morphological error.

Semi-monthly mean water temperature (B2) is determined from empirical relationships between air temperature and elevation.

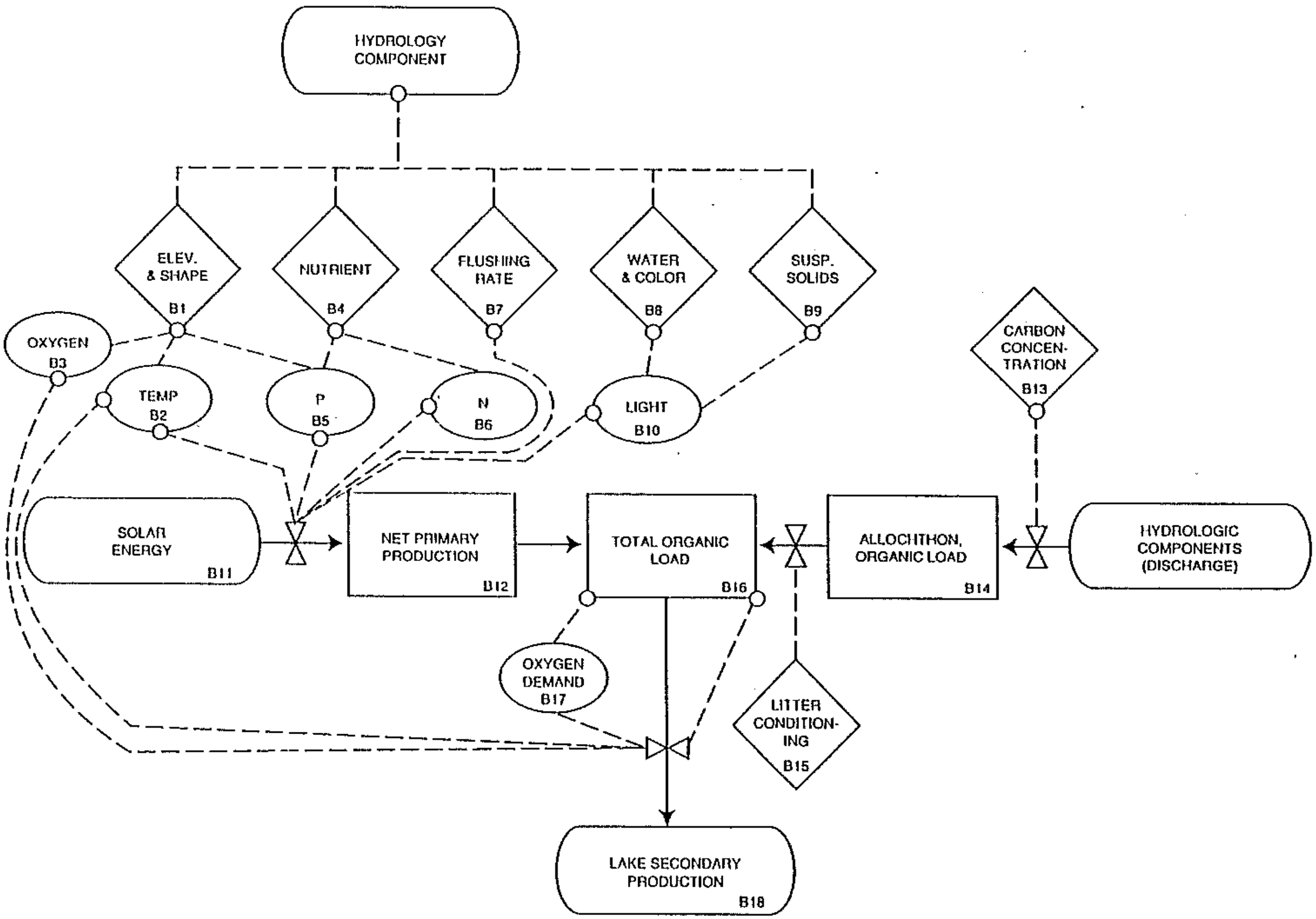

Figure 4. Flow chart of the model segment that simulates lake primary production, allochthonous organic loading and total organic loading.

Except during spring, when snow melt reduces mean semi-monthly water temperature slightly in some reservoirs, the mean semi-monthly water temperature closely approximates the mean air temperature. Unlike mean daily water temperature, mean semi-monthly water temperature is not greatly influenced by inflow temperature because the large time interval in the semi-monthly period mitigates effects. Model users have access to seasonal mean water temperatures through the biology component.

Mean semi-monthly water temperature is a constant from year to year in RIOFISH. Annual variation is relatively small. Water temperature variation of 2°C affects simulated fish production and harvest slightly, and uncertainty in its estimation is not critical. Decisions based on simulations of management effect on fish production and harvest are not expected to be affected by inclusion of actual mean air temperatures.

The thermal profile (distribution of temperature with depth) is estimated semi-monthly in each lake. We assumed that water equilibrated with air temperature in a mixed epilimnion (the surface layer of a thermally stratified reservoir). The mixed zone is a fixed variable function of the lake maximum length (fetch). Where volume is discharged near the lake bottom, water is displaced downward and sustains the same temperature. Every half month, water is drawn further downward toward discharge depth to the extent water volume is discharged downstream. Water discharged from reservoirs is the temperature of the zone from which it is discharged. The thermal profile determines temperatures of reservoir tailwaters, oxygen depletion zones, production efficiency and survivorship of fish species intolerant of warm or cold temperatures (described in the population component).

Surface water oxygen concentration (B3) is determined by elevation because of the combined effect of atmospheric partial pressure and air temperature, which are both functions of elevation over semi-monthly periods. Just as temperature profiles are determined by inflow and outflow balances, the associated oxygen concentration is similarly distributed from top to bottom. Oxygen concentration is also affected by oxygen demand, which is described later (B13). We assumed that primary productivity does not significantly affect half-monthly mean oxygen concentration. Even though some daily variation in oxygen occurs in New Mexico waters, long-term averages approach saturation expected at the prevailing temperature and elevation.

Nutrients (Units B4-6)

Nutrient concentrations (B4) are calculated semi-monthly as described in the hydrology section. The two limiting nutrients included in the model are phosphorus (B5) and nitrogen (B6). Although phosphorus is most often limiting, low nitrogen frequently occurs in New Mexico waters. Mean semi-monthly concentrations of total phosphorus and nitrogen in each reservoir are calculated from loading-concentration functions. Modifications of components reviewed by Bolin (1985) are incorporated to simulate phosphorus concentration from phosphorus loading. The loads are estimated from discharged nutrient measurements recorded in USGS records. These loading-concentration components use measures of hydraulic retention or flushing rate in days, empirically determined net sedimentation rates (Bolin 1985, Bolin et al. 1987) and reservoir depth to simulate the reservoir concentration of nutrients from the measured loadings.

The model user can change seasonal concentrations of total phosphorus or nitrogen to simulate fertilization or nutrient reduction. Uncertain estimation of nutrient concentrations has little effect on primary model outputs (fish production, fish yield, angler days) under most circumstances, mostly because allochthonous organic loading often contributes greatly to trophic support. The impacts of uncertainty are greatest when organic loading is low. The relationships between loading and lake concentration are more certain for phosphorus than for nitrogen. The primary production is simulated with less certainty in those instances where lake production is limited by nitrogen availability. Lake average nutrient concentration is simulated with least certainty for large lakes with complex basins (e.g., Conchas, Elephant Butte).

Flushing (Unit B7)

Lake flushing rate is calculated in the hydrology component of RIOFISH. It is the number of days required to totally flush the mean lake volume at the prevailing release rate (mean volume/discharge). Tributary water replaces discharged water at rates that often differ from the discharge rate. Therefore, lake-water exchange rate and flushing rate are similar but not identical values. Flushing rate is the inverse of storage ratio (discharge/mean volume).

Light Transmission (Units B8-10)

Pure water and the dissolved organic matter that causes color (B8) control light absorption and transmission as fixed (user inaccessible) constants in RIOFISH. Analysis of organic concentration at USGS stations in various locations indicate little variation in concentration of dissolved organic carbon. At low loading rates of allochthonous suspended solids (B9), variation of water color may contribute to light transmission variation and fish production, but assuming constancy is a minor source of error in New Mexico fisheries.

Allochthonous loadings of total suspended solids, calculated and described in the hydrology component, contributes to regulation of primary productivity in lakes by way of its effect on light transmission (B10). Mean concentrations of total suspended solids are estimated for each reservoir using functions described previously in the hydrology section. The model user can change estimated effects on suspended sediment of erosion rates or wind resuspension by changing concentration of suspended solids. With regard to factors that regulate light transmission and primary production, the modeled fish production is particularly sensitive to uncertainty in simulating low concentrations of suspended solids.

Light transmission (B10) is determined by variation in the suspended solids generated by allochthonous loading based on field observations (Bolin et al. 1987). An empirical relationship (Figure 5) between suspended matter and light transmission was developed from spatially variant data gathered from New Mexico lakes; its component intercept and slope are fixed variables in RIOFISH. Concentration of suspended solids is the explicit controlling variable for primary production in RIOFISH while light transmission is implicit. Light transmission also affects the efficiency with which various fish taxa use trophic resources. Solar radiation at the surface is reduced to correct for light reflectance from the water surface, which varies from 12 percent in winter to 6 percent in summer (Cole 1983).

Solar Radiation (Unit B11)

Solar radiation entering the aquatic ecosystem is a required input for generating the energy base for primary (photosynthetic) production. Chemosynthetic production is assumed negligible. Mean seasonal solar-energy inputs (gram-cal/cm^2/day) are based on long-term monitoring at El Paso, Albuquerque and other regional stations and are extrapolated to other locations in the state

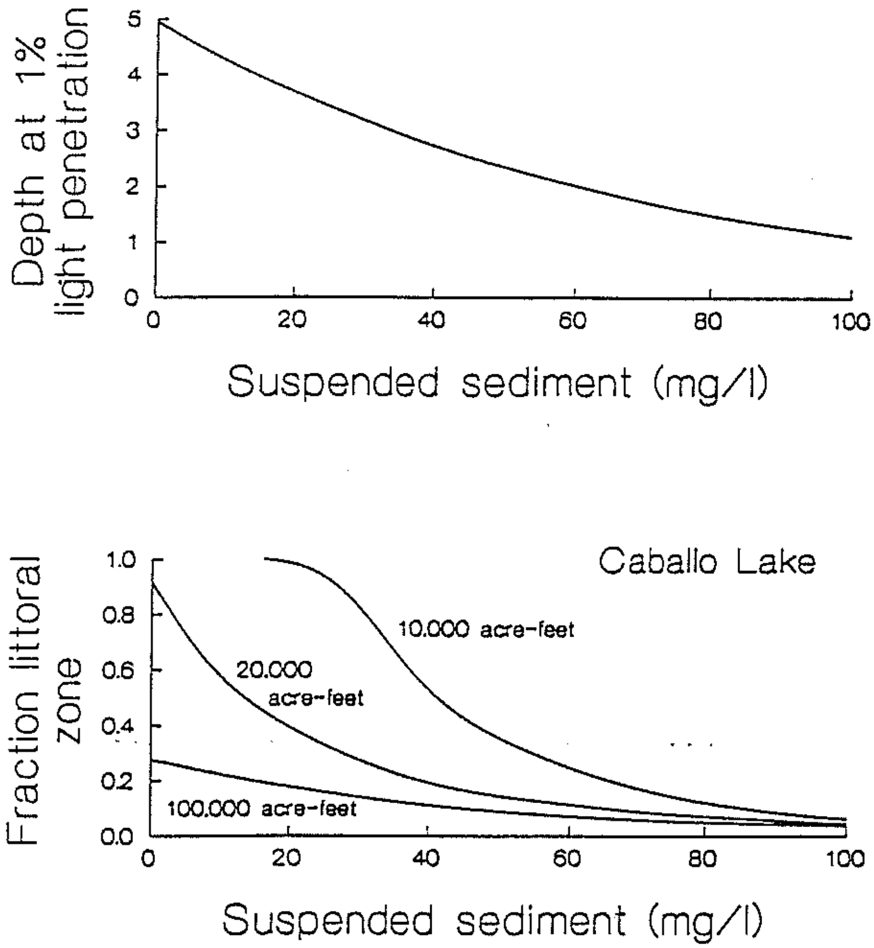

Figure 5. RIOFISH relationships between light transmission and littoral habitat size and the concentration of suspended solids.

(Tuan et al. 1983), based on cloud cover. Light input values used for each reservoir site are estimated from the closest solar monitoring station in a similar ecological biome (e.g., short grass prairie, pinyon-juniper woodland). Real annual variation is relatively small. Therefore, a long-term average solar input is used for default input. Uncertainty in solar radiation simulation has small direct effects on simulations of fish production and yield.

Primary Production (Unit B12)

RIOFISH net primary production is the product of solar radiation and the net effect of factors controlling photosynthetic efficiency. The general form of the equation used to estimate net primary production in lakes is $TL_1 = R (E_{max})(N)(S)(X)(T)$ where TL_1 = net primary production in gCm^{-2}/day for a half-month period, R = daily total solar radiation for the season (expressed as carbon equivalents), E_{max} = the maximum net photosynthetic efficiency at optimum, N is the fractional deviation from optimum caused by nutrient limitation, X is the deviation from optimum caused by high reservoir volume exchange (flushing rate), and T is the deviation from optimum caused by temperature. The radiant energy is converted to grams of carbon based on average energy and carbon content of organic matter (10 calories = 1 gC).

The functions used to estimate the net plant production are based on empirical evidence from a variety of sources. All are fixed variables in RIOFISH. First, a maximum photosynthetic efficiency for aerial production (m^{-2}), as calculated by Dubinsky and Berman (1981) and Morel (1978), was assumed to be 2% of the aerial total solar energy based on the highest efficiency values estimated for lakes (Westlake et al. 1980) and marine field studies (Rhyther 1959). Several tropical lakes attain close to 2% photosynthetic efficiency on an annual basis and certain temperate zone lakes approach a 2% maximum in summer (Westlake et al. 1980). We assumed that the maximum of 2% is reached when the lake is superenriched with nutrients, the euphotic zone is completely mixed, the depth of the euphotic zone is determined only by the autochthonous generation of suspended and dissolved organic matter, the temperature averages 30°C, and the flushing rate is more than 50 days. These conditions are approached at researched lakes (Westlake et al. 1980) with about 2% photosynthetic efficiency.

The limiting nutrient can be either phosphorus or nitrogen. When ratios of total nitrogen to total phosphorus are more than 10:1, phosphorus is considered limiting. Because of extremely rapid turnovers and the fact that nearly 99 percent of all phosphorus is bound in suspended organic matter at any one time (Wetzel 1983), semi-monthly mean total phosphorus and total nitrogen (Kjeldahl N + nitrate nitrite) concentrations were used as suggested by Westlake et al. (1980). The relationship for nutrient concentration and photosynthesis shown in Figure 6 is

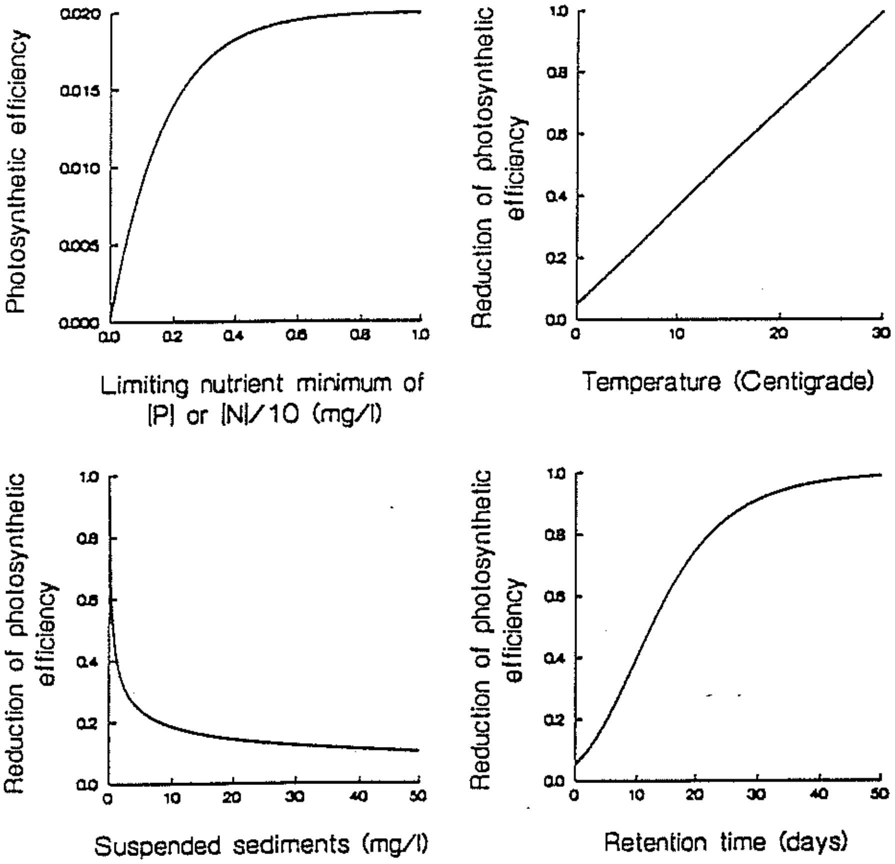

Figure 6. RIOFISH relationships between photosynthetic efficiency and amounts of nutrient, suspended solids, temperature and reservoir flushing rate. A maximum efficiency of 0.02 is assumed (see phosphorus relationship) when all regulatory factors are at optimum amounts.

based on Vollenweider (1979), after modification for lower than optimum temperature and concentration of allochthonous suspended solids. We assumed that the large temperate-zone lakes used in Vollenweider's (1979) relationship averaged 14°C (4° in winter to 24° in summer) and adjusted his relationship upward to a 30°C optimum. We also assumed that the maximum nutrient concentration would be, at 30°C, equivalent to that necessary to sustain an annual 2% photosynthetic efficiency at the equator, resulting in a plant production of about 1500 g C/m^2/year. At the other extreme, productivity was assumed to be 0 when total phosphorus or total nitrogen was 0.

The non-linear relationship between nutrient concentration and photosynthetic efficiency reflects the self-shading limitation that occurs as photosynthetic mass accumulates. This effect on light availability is differentiated from the effects of allochthonous suspended solids, which originate from outside the water column and "compete" (through light absorption) with photosynthetic mass for available solar radiation.

Figure 6 indicates that the maximum production at 30°C (twice as high as the average 15°C) should be 1.9 times higher than at 15°C if there were no allochthonous suspended solids or no limiting exchange rates in Vollenweider's (1979) lakes. In fact, maximum production at 30°C was about 2.5 times greater, indicating either: (1) inaccuracy in estimating mean temperature for Vollenweider's (1979) lakes, (2) light limitation caused by allochthonous suspended solids, or (3) rapid enough flushing rates to reduce production. Vollenweider's (1979) sampled lakes are large and have low flushing rates; therefore, flushing rate was dismissed. Although allochthonous concentrations of suspended solids are likely to be low in large lakes with low flushing rates (e.g., the Laurentian Great Lakes) they could have been great enough to explain the differences we observed in expected and realized productivity. Less than 1 mg/liter (about 0.3 mg/liter) of total allochthonous suspended matter would be enough to cause the observed discrepancy. A small discrepancy in calculated temperature could also contribute slightly to the difference.

The effect of temperature was estimated as indicated in Figure 6. The relationship is based on laboratory data, presented by Aruga (1964), which showed that the plant productivity (growth of laboratory culture) increased an average of about 1.9 x for each doubling of temperature (C^0). This relationship was also suggested by seasonal fluctuation in lakes with relatively low or constant introductions of allochthonous suspended solids and relatively constant seasonal nutrient concentrations over the annual cycle (e.g., Lawrence Lake and Wintergreen Lake reported by Wetzel (1983), Lake Erie reported by Marcus (1972) and Holloman Lake in New Mexico (Cole et al. 1984). They typically vary from seasonal low production values near the winter solstice to seasonally high values near the summer solstice of 4:1 to 5:1 (from 4^0C to 26^0C). The field survey range is similar to the range identified in laboratory studies of Aruga (1964). Therefore, that relationship was used to reduce the photosynthetic efficiency as temperature varied from the optimum at 30°C. Because mean two-week temperature in New Mexico fisheries are not known to exceed 30°C, The relationship was not defined for higher temperatures. An exceptional site, Morgan Lake, is a cooling pond where local temperatures exceed 30°C, but refuges with lower temperatures also exist.

Figure 6 also demonstrates the relationship between suspended solids and photosynthetic efficiency used in RIOFISH. The relationship between suspended solids and the photosynthetic efficiency is defined based on a model illustrated in Wetzel (1983) between the depth of the euphotic zone and concentrations of suspended algal solids. In developing the relationship in Figure 6, we assumed that as the euphotic zone was reduced by addition of allochthonous suspended solids, the primary productivity would be reduced in direct proportion to the diminishment of light energy available.

The last factor considered in the estimation of photosynthetic efficiency was the flushing rate (reciprocal of hydraulic retention and storage ratio). In some half-monthly intervals, certain reservoirs have relatively low water retention. In those lakes, water may be completely replaced in as little as six days. Flushing rates of more than a month have small to no effect in RIOFISH. Effects typically are most evident in spring months when primary production ordinarily peaks. In a few small lakes in New Mexico, the annual average flushing time is less than one month.

Little empirical information exists to develop the functional relationship between flushing rate and primary production. Figure 6 shows the relationship we used for flushing effect when environmental factors were otherwise optimum and phytoplanktonic productive mass entering the lake was low. We assumed a logistic rate of biomass accumulation to the equilibrium biomass.

For flushing times shorter than 10 days, the reduction is inversely proportional to hydraulic retention. At a very rapid flushing rate, a lake resembles a river with little true phytoplanktonic productivity and too deep for significant periphytic production. This function underestimates primary production for high flushing-rate lakes, whenever a significant part of the lake bottom supports substantial benthic primary production. At a 10-day flushing rate, an average productivity of about 0.5 times the equilibrium level of productivity is attained and the photosynthetic efficiency is reduced 50%. As the hydraulic retention increases, the effect of equilibration period at the upper end of the reservoir diminishes. At a 50-day flushing rate, the effect in the model becomes negligible.

We assumed that negligible phytoplankton biomass survived transport through connecting waters to other downstream lakes and that periphyton production was very low. Both of these assumptions, if incorrect, are likely to underestimate productivity when rapid flushing occurs. Such conditions occur only in certain months of certain large reservoirs and more constantly in a few small lakes. The error is small in comprehensive multi-site analysis.

The abiotic determinants of primary productivity sometimes counteract one another. High flushing rates often accompany high loadings of nutrient and suspended solids and lower than average solar radiation available for photosynthesis. Generally, the uncertainty of primary productivity simulation has greatest impact in low-runoff and low-water scenarios. The sensitivity of the fish production and yield outputs decreases as loadings and water levels increase.

Allochthonous Organic Load (Units B13-15)

Organic carbon concentrations (B13), estimated by USGS (e.g., USGS 1980) and others (Cole et al. 1986a and 1990, Bolton et al. 1991), were used to estimate mean half-monthly loadings of allochthonous organic matter. Little spatial variation occurs in mean organic concentrations in perennial flows reported throughout the state, but concentrations in intermittent flows tend to be greater at lower elevations (Cole et al. 1990). For any particular season, loadings vary only with discharge because concentration is constant. In the model default version, mean concentrations vary from season to season, but do not vary from year to year.

The simulation of fish production and yield is particularly sensitive to loads of allochthonous organic matter over the range in variation that is possible. We have observed high and variable estimates of organic concentrations in unmonitored intermittent discharges (Cole et al. 1986a, Cole et al. 1990). Unmonitored watersheds often contribute less than 5% of the annual water volume in larger lakes, but estimated nutrient and organic contributions may exceed half of the annual total load, depending on annual runoff variation. Some small lakes are entirely supplied by intermittent runoff.

The allochthonous organic matter in RIOFISH is not immediately useful to consumers. It requires microbial colonization and conditioning (B15). Colonization and conditioning enhance nutrient content and palatability for consumers. Studies by Cole et al. (1986a) show that watershed litter had little biological oxygen demand and developed oxygen demand slowly at room temperatures. Only after 850 degree days of conditioning is allochthonous organic matter in lakes consumable in RIOFISH. Much allochthonous organic matter is carried over to subsequent semi-monthly periods before it becomes consumable. Consumption and decomposition efficiency of material is temperature dependent in RIOFISH, based on Q_{10} estimates of 1.9. For the most part, materials entering in late summer to early fall are stored throughout the colder months, then enter the trophic process during the following spring.

Although conditioning and consumption of detritus has been studied in detail in stream ecology, little quantitative information exists for lakes. The least known aspect in the fate of detrital organic matter is the extent to which it is buried in deep sediments and indefinitely stored. We assume that detrital organic matter is no more or less likely to be stored in deep sediments than phytoplanktonic organic matter. Permanent storage of organic matter is not explicitly defined in RIOFISH, but is implicit in the trophic efficiency calculations, which follow.

Fish production estimates are sensitive to the uncertainty attached to simulations of organic load and its contribution to trophic process. This part of RIOFISH is among the most influential and least certain.

Organic Load and Oxygen (Units B16-18)

The total organic load is the sum of the net primary production and the conditioned allochthonous organic load for each semi-monthly interval. Total organic load is the first trophic level production equivalent, the basis for all consumer production in secondary trophic levels.

The organic product of net plant production and the allochthonous organic load is assumed to be equally distributed throughout lakes by production, mixing and sedimentation processes. Secondary production of invertebrate zoobenthos, zooplankton, and fish therefore is not explicitly distributed according to geographical regions. When secondary production efficiencies decrease as habitat conditions vary from optimum, as described later, the effects are lake-wide but are differentiated among populations according to specific habitat tolerances to be defined later.

In RIOFISH lakes, oxygen is depleted in any non-mixed zone that occurs below the epilimnion because of temperature stratification, as described for Unit B2. We assumed that non-mixed zones are deeper than the euphotic zone and no significant net oxygen gain is generated there by photosynthesis. Oxygen depletion is a function of temperature and the combined calculated load of conditioned allochthonous organic matter and dead phytoplankton generated by primary production. The depletion of oxygen continues as water layers are drawn down to bottom. Therefore, the oxygen concentration is not uniform throughout the hypolimnion unless drawdown rates are fast enough to release the entire hypolimnion within the two-week period.. Oxygen released from the reservoir, like temperature, is a weighted average of each of the layers that contributes to the release.

The oxygen profile influences the trophic efficiency of populations in upper trophic levels and determines the initial concentration of downstream tailwaters. As will be later described, the oxygen profile also determines survivorship of fish species intolerant of lowered oxygen concentrations and restricted by temperature to zones where oxygen concentrations can fall.

The greatest error in oxygen simulation occurs when thermal stratification is inappropriately established by model simulation. Uncertainty in the exact size and duration of a hypolimnion has small effects on simulation of fish production and catch.

Total organic load and initial fish density is the basis for estimating fish production, growth and other population parameters. Before realized production is estimated within taxonomic categories, the potential secondary production is estimated for trophic categories based on trophic efficiencies. Herbivore trophic efficiency pertains mostly to invertebrate production, but includes fish production at those sites where herbivorous fish occur. Herbivore trophic efficiency in converting total organic load to potential production is a function of organic load, temperature and the oxygen concentration in both modelled lakes and streams. This relationship is defined in the section on initial resource partitioning, which follows description of stream organic loading.

STREAM ORGANIC LOADING

Physical-Chemical (Units B19-28)

Figure 7 shows the general sequence of events in the stream organic loading segment of RIOFISH, which is similar to lake loading with some important variations. The mean stream elevation (B19), calculated from source information in the

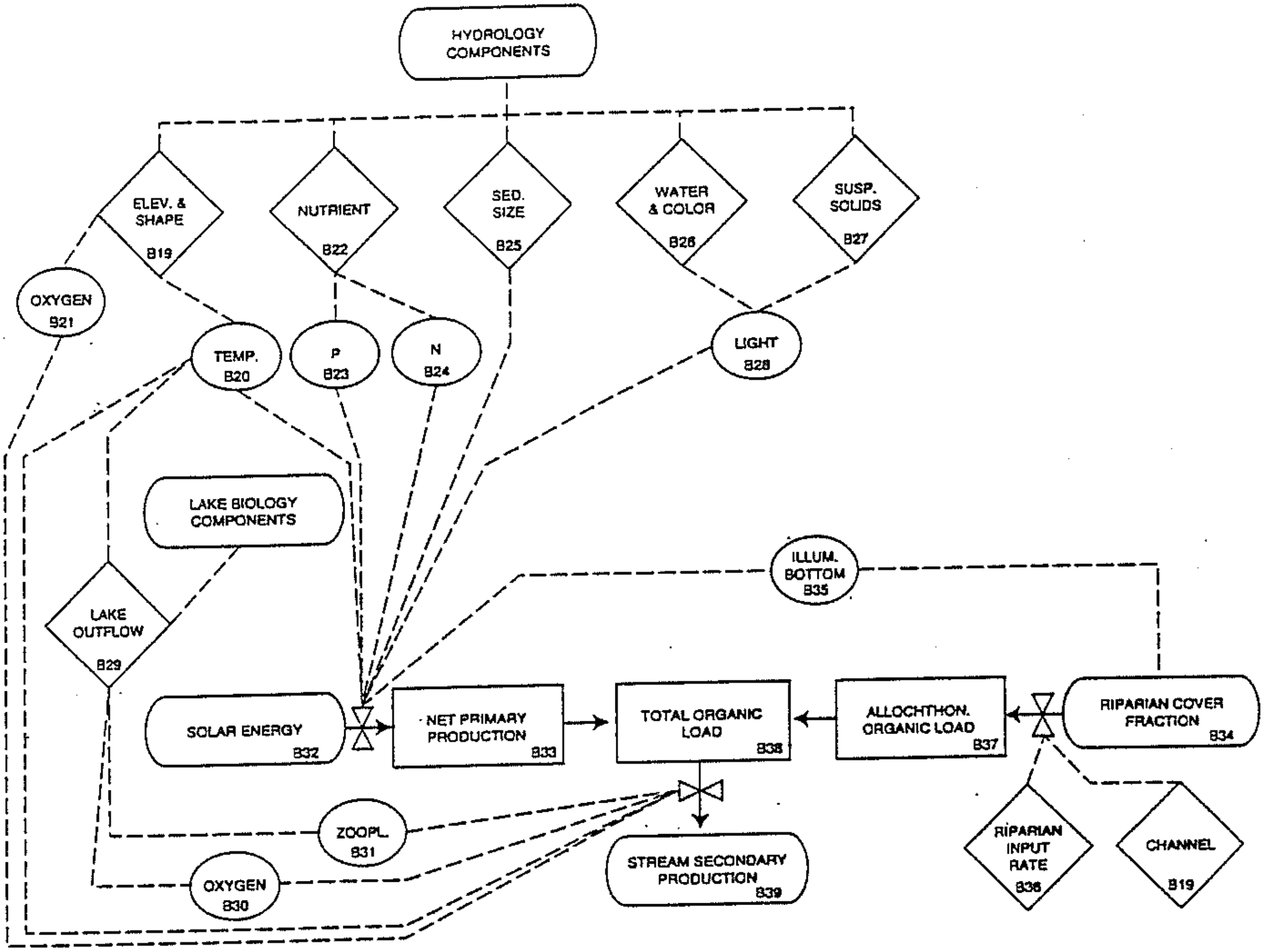

Figure 7. Flow chart of the model segment that simulates primary production, allochthonous organic loading, and total organic loading in streams.

hydrology model, as for the lake model, determines the mean semi-monthly water temperature (B20) and the 100 percent saturation concentration for oxygen (B21). Mean elevation is calculated from the upper-most reach elevation, mean channel slope, and length to reach midpoint. Where there is no upstream lake effect, elevation, temperature and oxygen relationships are the same as in mixed epilimnetic layers of lakes. Temperature and oxygen come into an elevation determined equilibrium throughout the water column. Each stream cell has the same oxygen concentration and temperature.

Nutrient concentrations (B22-24) are calculated semimonthly as described in the hydrology component. As in the lake component, total phosphorus and total nitrogen are the only nutrients identified. Each stream cell has identical nutrient concentration.

The sediment particle size (geometric mean diameter in millimeters) is calculated semi-monthly (B25) in the hydrology component based on the stream depth, slope and original material size distributions. Substrate sizes in each cell change as discharge changes, based on the unique depths identified for each cell.

Pure water, water color and suspended solids (B26-28) concentrations interact to determine light transmission just as for lakes (Figure 5).

Tailwaters (Units B29-31)

Conditions in reservoir outflows (B29), tailwaters below impoundments, are determined by lake processes. The temperature (B2) and oxygen (B30) at the upper end of the reach is determined by tailwater condition. When depressed below elevation-equilibrated conditions, the oxygen and temperature gradually return to the elevation-determined values, based on observed rates of recovery. A simple distance-related recovery is used in the model. Turbulence is similar in most New Mexico tailwaters.

The zooplankton in released lake water is added to zoobenthos production supporting benthos-feeding fish (B31). Based on observations in relatively short tailwaters (which need further configuration), the zooplankton are assumed to be totally consumed or die and decompose in the tailwater segment; none are transported further downstream. Exported zooplankton are assumed inert and equivalent to dying and dead stream benthic drift. The lake zooplankton concentration, calculated semi-monthly, is based on a mean production/biomass ratio applied to the lake zooplankton volumetric production simulation. Dead imported zooplankton are assumed to be consumed as efficiently as live invertebrate benthos in the tailwaters and their loading rate is added to the invertebrate zoobenthic production to serve as forage for benthivores.

Photosynthesis (Units B32-35)

The estimation of solar energy input (B32) and photosynthetic efficiency is as described for the lake component

(B11-12) except for riparian shade (B35), substrate size (B25) and flushing effects (B7). The shaded areas are assumed to have no primary production. The 2% maximum photosynthetic efficiency of unshaded bottom area is reduced by applying limitation effects of nutrient, temperature, suspended solids and sediment particle size.

Particle size is an index to substrate stability in currents. The function used is based on observations by McConnell and Sigler (1959), Duffer and Dorris (1966) and Donaldson (1987). Photosynthetic efficiency decreases as the natural logarithm of the geometric mean particle diameter decreases. Flushing rate has no effect in streams, where periphyton replaces phytoplankton.

Primary production is first estimated for each of the parallel cells (described in the hydrology component) and varies with the characteristics of each cell. Then the production estimates are summed for each cell to estimate the total primary production for the stream site.

The riparian cover (B34) over the channel is a required model input. This is the percentage of leaf and branch cover over the channel that can influence shade and organic input. It is not identical to the cover over the stream flow because the stream flow usually does not fill the channel. The cover percentage does not vary seasonally. The amount of riparian shade is calculated from the fraction of cover over the stream flow (B35). When the stream is low, a low fraction of the cover shades the stream channel. Shade reduces primary production. Riparian vegetative cover also is the source of allochthonous organic load.

Riparian Input (Units B36-38)

The allochthonous organic load in RIOFISH is assumed to be derived entirely from riparian cover (B34) and all of the riparian input is assumed to be distributed evenly over the stream cells. All riparian input is retained by each site; none is explicitly imported or exported. We assume in RIOFISH that upstream import and downstream export are identical. Although this assumption is questionable for small streams, error probably decreases as stream size increases. Streams in RIOFISH are in fourth-order channels or larger. USGS concentrations of particulate carbon in New Mexico streams change little within stream-order category, once water reaches larger streams of the sizes modeled in RIOFISH. Because we assume that the efficiency with which all organic loading is consumed is identical, the sources and forms of the imports and exports are irrelevant and the import and export cancel out when identical.

The riparian input rate (B36) to channels varies seasonally in RIOFISH and is constant from year to year. Annual input for full riparian cover is assumed to be 500 $g/C/m^2/year$, and decreases in proportion to the amount of cover over the channel. The annual input is allocated disproportionately among seasons, favoring autumn inputs. The default values are fixed values.

The riparian input depends on channel width and stream width. Channel shape (B19) is fixed and, as water discharge varies within the channel, depth and width change as described in the hydrology component.

When riparian material drops into dry channel margins in RIOFISH, some is stored and some is decomposed before the stream elevation returns to full channel. A constant fixed fraction (75%) is stored from one semi-monthly interval to the next. When water levels rise in the stream channel, the remaining stored riparian organic matter is added to primary production and becomes equally available to herbivore-detritivore consumers.

The total organic load available for consumption (B38) in a RIOFISH stream is equal to the organic matter in the riparian input (B37) plus the primary production (B33). Total organic load within each site is the basis of all secondary production in streams and lakes in RIOFISH. There is no net immigration or emigration among sites that results in export and import of consumers in secondary trophic levels. In New Mexico, there is little evidence that this assumption creates significant simulation error.

Present understanding of stream trophic process does not clearly demonstrate differences in the efficiency with which decomposer-conditioned litter and periphyton are consumed, assimilated and converted to production. If detritivores are less efficient than herbivores in converting conditioned organic matter to net production, as may be suggested by certain estimates of assimilation efficiency, this assumption results in an overestimation error for benthic production, depending on the allochthonous organic contribution.

INITIAL RESOURCE PARTITIONING

Herbivore Efficiency (Units B16, B18, B40-42)

Figure 8 illustrates the general process by which organic load is portioned among trophic categories to determine a potential production of fish populations. The energy transfer coefficient (trophic-level efficiency) used to convert organic load to herbivore production is a function of organic load (B16,18), temperature (B41), and the fraction of time and space in lakes and streams when oxygen (B40) is less than 1.5 mg/liter (Figure 9). The temperature is derived from calculations described for units B2 and B20. The oxygen fraction is derived from calculations described for units B2, B3, B17, B20, and B21.

The trophic efficiency ranges downward from 50% at low organic loadings and optimum temperature (28°C) and oxygen to less than 1% at very high loadings, low temperature, and low oxygen. The maximum efficiency is determined by inefficiency of assimilation and metabolism (respiration loss) when consumption efficiency approaches 100% under optimum conditions. The efficiency relationship to organic load rate is based on observations (Ocean studies) in marine coastal areas showing a decreased trophic efficiency with increased organic loading. The causes are unclear, but where they occur in well-aerated waters

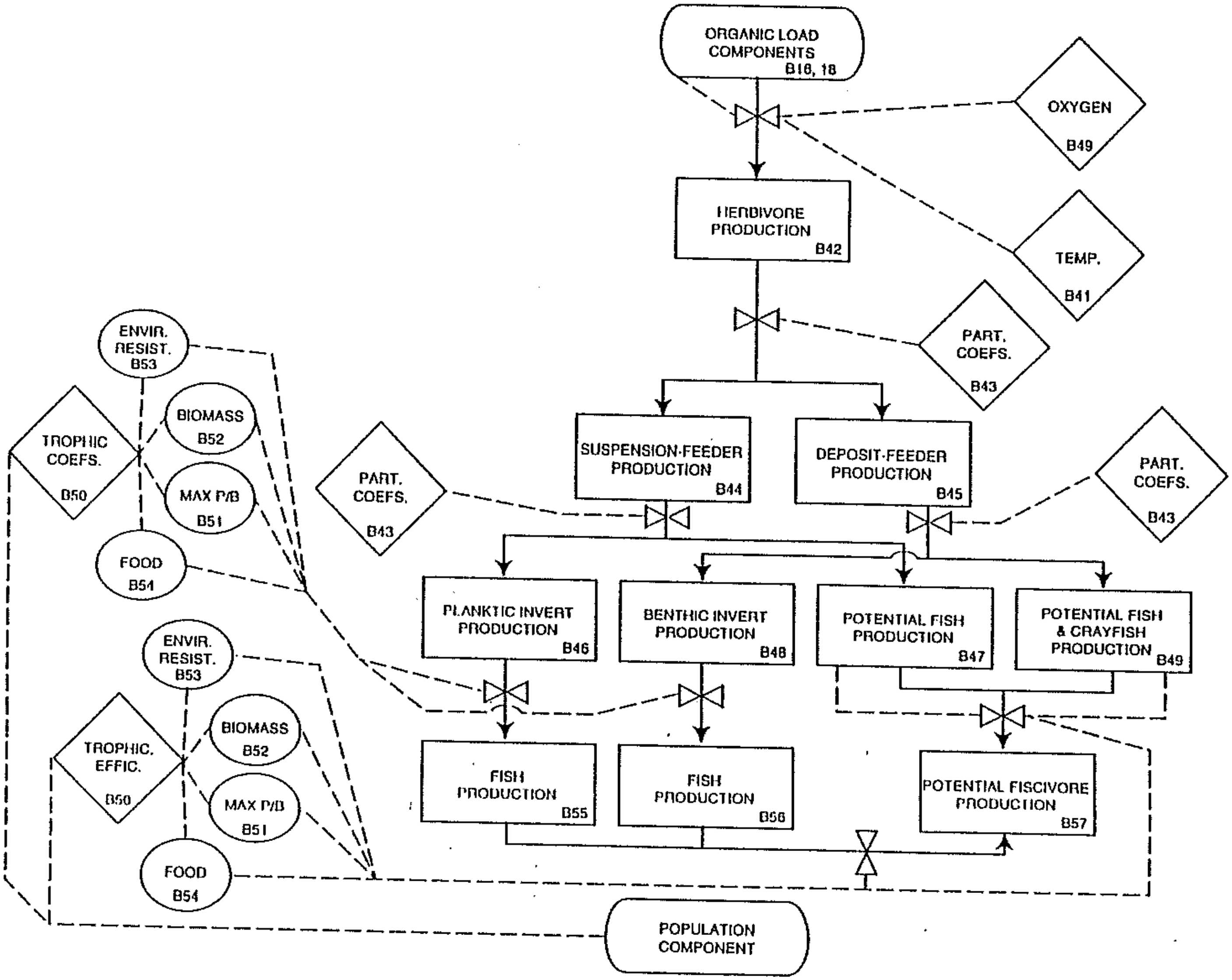

Figure 8. Flow chart of the model segment that initially partitions lake secondary production based on feeding behavior.

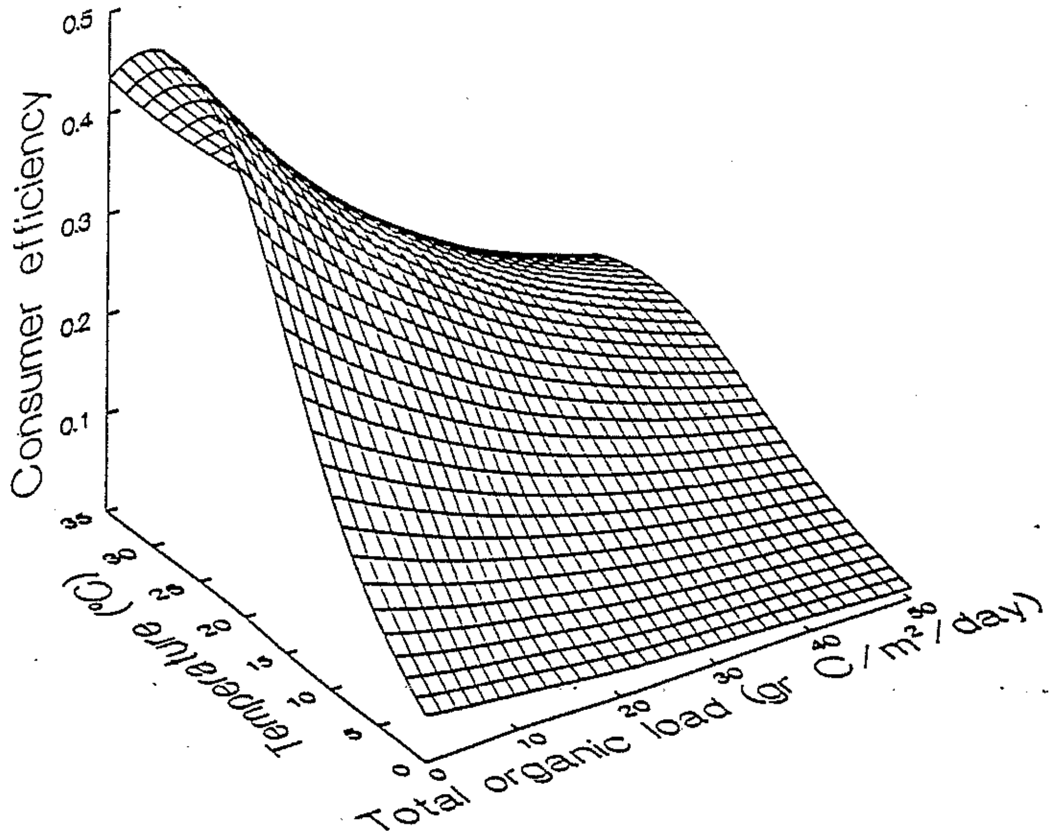

Figure 9. The relationship between organic loading, temperature and trophic efficiency used to estimate transfer of carbon to sportfish production in the simulated reservoir communities.

they are independent of oxygen depletion. One explanation is that accelerated organic loading tends to fluctuate more than at low loading rates. Consumer response to fluctuating food availability is slower than that of microbial decomposition. Deep sediment storage may also increase where total heterotrophic efficiency drops, as it may under extreme conditions. This function has been estimated by difference between calculations based on temperature and oxygen and estimated efficiencies in New Mexico waters.

Maximum efficiency of about 50% under otherwise optimum conditions decreases as temperature decreases from optimum at 28°C, following the Q_{10} rule. The amount of oxygen-depleted water also depresses trophic efficiency. The depressive effect is a linear function of the fractional volume depleted of oxygen to 1.5 mg/liter or below in each half-season. The total annual affect is the sum of half-seasonal results.

The fraction of water volume depleted below 1.5 mg/liter indicates the proportion of the aquatic consumer community that is excluded from using organic load and favoring decomposition and deep sediment storage. In lakes, this depends on the dimension and persistence of a hypolimnion. Where oxygen becomes limiting in tailwaters, the fraction of the total stream distance that is affected in each time unit determines the extent to which trophic efficiency is limited.

The efficiency with which the total organic load is converted to secondary producers (consumers) under optimum consumer conditions allows little decomposition as ingestion efficiency approaches 100 percent. The net effect of assimilation and metabolic inefficiency (respiration) under optimum consumer conditions is a maximum 50% efficiency for net population production/ingestion and a similar trophic level efficiency when low initial biomass is not limiting.

For consumers with high production-biomass ratios, such as small invertebrates, biomass is unlikely to be an important limiting factor when a half-seasonal time step is used to estimate the production. Production of larger consumers, especially in fished environments where biomass often is reduced to low levels, is much more likely to be biomass limited. RIOFISH ignores the possibility of biomass limitation for simulation of small invertebrate zooplankton and zoobenthos, but it accounts for fish and crayfish biomass in the population component.

Most trophic studies occur under conditions that vary from optimum for consumers, substantially reducing efficiency (excluding exported organic matter) to levels usually below 15%. Maximum efficiency is likely to be rare for extended time periods. Odum's (1957) study conditions in Silver Springs approached closer to optimum for consumers than most other study conditions. There the estimated annual efficiency (secondary production/organic loading) for conversion of non-exported material was 24.5%. The difference between Odum's (1957) observation and the theoretical maximum of 50% may be due to measurement error and the existence of consumer limiting factors that to some extent favor decomposers or permanent storage.

Total fish production simulation and fish catch rate are sensitive to this estimate of maximum trophic efficiency. Calibration of RIOFISH starts with adjustment of this value. Based on trophic theory, the efficiency should decrease as habitat conditions vary from optimum. In RIOFISH the realized efficiency of secondary producers and the partitioning of secondary production among populations is jointly determined by the extent to which environmental constraints reduce the maximum growth attainable for the existing biomass of consumers and the existing consumable organic loading.

Herbivore Partitioning Process (Units B43-44)

A similar resource partitioning process (Figure 8) applies to both lakes and streams, with certain differences. Herbivore production (42) in RIOFISH lakes is first partitioned into two categories: suspension-feeder production (43) and deposit-feeder production (44). Resource partitioning is simpler in RIOFISH streams because no suspension feeding exists there; all herbivore-detritivore feeding is benthic deposit feeding (drift feeding is considered a form of deposit feeding).

The fraction of organic matter diverted into suspension feeders from benthic feeders depends on lake depth (Figure 10). At depths over about 5 m, a nearly constant 90% of the organic matter enters the suspension-feeder group and nearly 10% is

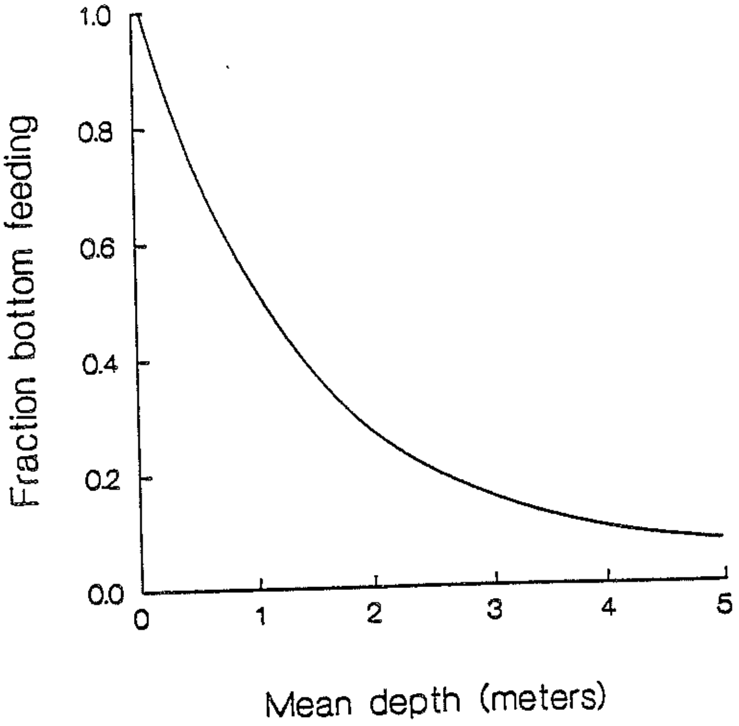

Figure 10. The partitioning of secondary production (second trophic level) comprised of suspension feeders and benthic feeders as reservoir depth varies in RIOFISH.

partitioned into the deposit feeders. In waters less than 5-m deep, the fraction partitioned into suspension feeders decreases as shown in Figure 10.

While in most New Mexico lakes suspension feeders are invertebrate zooplankton (B45), in some lakes a fraction of the suspension feeders (B46) are fish that also consume zooplankton. Two shad species occupy this role in certain warm-water habitats in New Mexico. When both zooplankton and suspension-feeding fish are present, the potential production is partitioned as shown in Figure 11. Whether or not shad potential production is realized depends on their initial biomass and environmental resistance (estimated in the population component). Shad in streams feed only on zoobenthic foods (including the lake-exported zooplankton in tailwaters and detrital drift).

Planktivorous fish in lakes take proportions of the calculated production as shown in Figure 12 when conditions are optimum for the fish and they are most competitive with zooplankton. Constraints developed in the population component usually reduce this maximum production potential as habitats vary from optimum. The surplus between potential and realized shad production, based on organic load is added to the zooplankton production. Low shad biomass or rigorous habitats result in most potential shad production being transferred to zooplankton production. The function represented in Figure 11 is based on the relative production that shad comprise in lakes of different

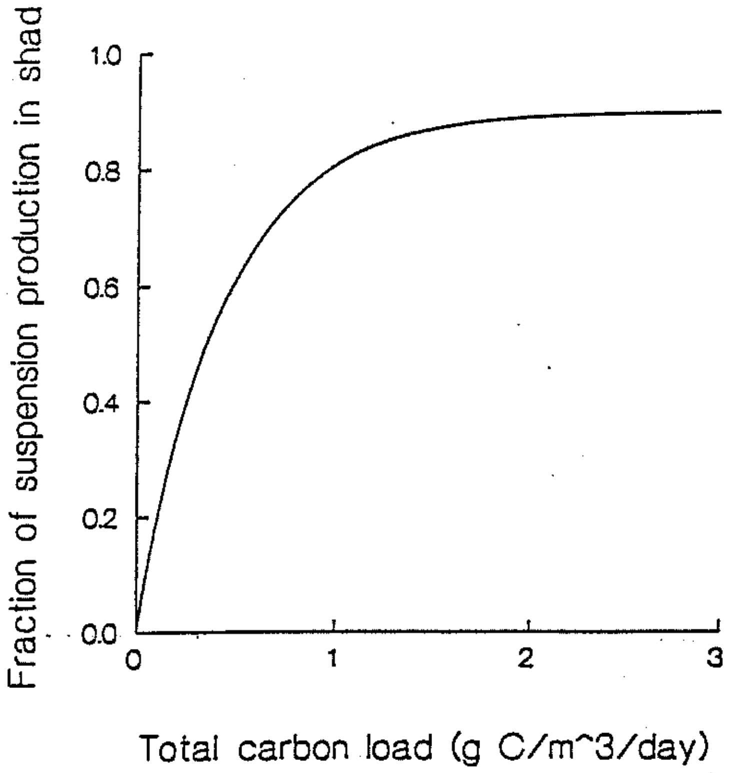

Figure 11. The partitioning of herbivorous suspension feeding fish production and invertebrate zooplankton suspension feeders in RIOFISH.

trophic status in New Mexico (Cole et al. 1985) where conditions are favorable for shad. Shad feeding effectiveness approaches maximum at high organic loads, when particle size and abundance are assumed to be most appropriate for shad filter feeding. No data were available for shad dynamics in extreme high organic loads.

The partitioning of herbivore-detritivore production into small invertebrate deposit feeders (B47) and deposit-feeding fish and crayfish (B48) directs a constant 90% to fish and crayfish when conditions are optimum for them. Not all of this production may be realized, however, depending on the deviation from optimum defined in the population component. When the maximum production of fish and crayfish is not realized, the surplus production is assumed to be in the form of invertebrate zoobenthos, thereby simulating competition for food resources. Partition fractions are based on estimated relative production of crayfish, carpsuckers, and small invertebrate zoobenthos in New Mexico waters (Cole et al. 1985).

Carnivore Partitioning Process (Units B50-56)

Based on estimates of assimilation and respiration efficiency (e.g., Leidy and Jenkins 1977), the maximum expected carnivore trophic level efficiency (B50) is about 40% at each level when carnivores are able to ingest all production in the underlying level and none is decomposed or permanently stored. The 40% trophic efficiency is used to assess the potential production firstly of fish feeding on zooplankton (B53) and fish feeding on small invertebrate benthos (B54). Piscivore potential production (B55) is estimated to be the sum of 40% conversions of all fish and crayfish realized production. The realized production is estimated in the population segment, which is described next.

In the population segment, RIOFISH partitions production among individual populations in lakes at efficiencies dependant on initial biomass, maximum possible population growth rates, and habitat conditions. The connection is through the maximum production/biomass (B51) assigned to each population (B52), population biomass, and the environmental resistance (B53) that reduces the maximum P/B value as habitat varies from optimum.

FISH POPULATION SEGMENT

Potential Population Production (Unit B57)

Figure 12 shows the general concept used in the population component of RIOFISH. The main aim of this component is to distribute production among identified fish populations and simulate fish numerical biomass and density, mean individual growth, and reproduction and mortality due to natural and fishing sources. The time step is half seasonal.

Potential production (B48,B49,B54-56) is distributed to taxa at three stages in population life cycles: larvae, juveniles, and older fish (B57). Potential production drives fish growth and reproduction dynamics. In Figure 12, the calculations for

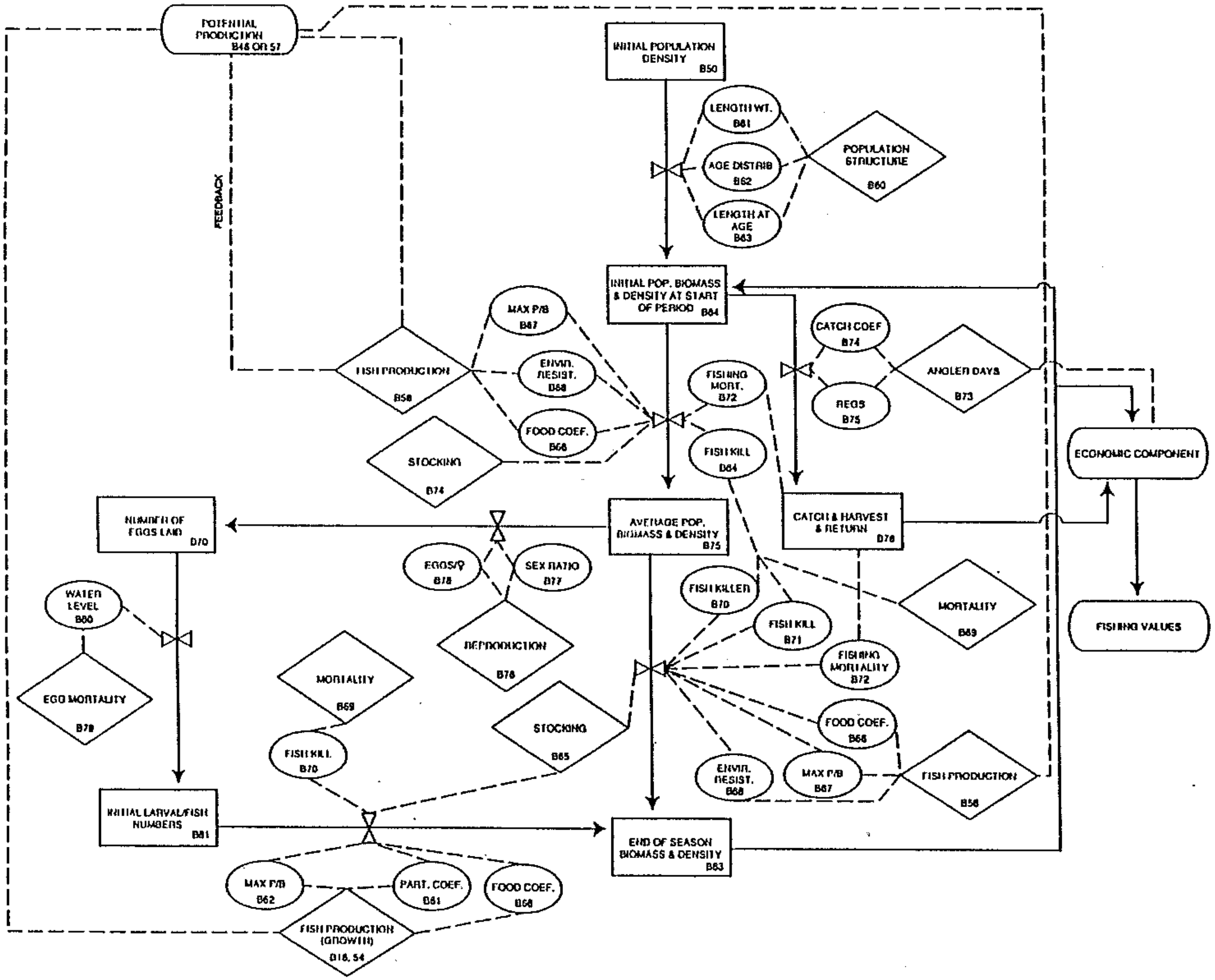

Figure 12. Flow chart of the model segment that simulates population dynamics of fish for streams and lakes.

production distribution are symbolized separately for larvae and older fish. For older fish, calculations occur twice within a time step, once before female biomass is estimated for reproductive potential in mid season, and once more after reproductive potential is estimated. All population parameters are user accessible.

Initial Population Structure (Units B58-59)

Before production can be allocated to populations, the biomass and other population structures need determination. An initial population density (B58) and population structure (B59)90 are provided in the default version. They may be changed to fit model user needs. An initial default density for each age class (age 0-15) of each fish population present (including crayfish) is defined for each site in RIOFISH (Figure 12) at the end of summer season (September 30 in RIOFISH). Up to 24 default taxa are included for each site: largemouth bass, smallmouth bass, white bass, striped bass, crappie, sunfish, channel catfish, bullheads, walleye, yellow perch, northern pike, salmon (modeled after Kokanee salmon here), rainbow trout, brown trout, lake trout, carp-sucker (common carp and warm-water suckers), white sucker, gizzard shad, threadfin shad, cyprinids, golden shiner, smelt, gar, and crayfish. A taxon is composed of more than one species when individual species are difficult to differentiate (e.g., white and black crappie) or when taxa perform ecologically similar roles in RIOFISH (e.g., carp and warmwater suckers, cyprinids). When more than one species is incorporated, population parameters represent an approximate average for the species. We aggregated to reduce model processing time and to reflect data availability. Data are scarce for many cyprinids, for example.

The model user may change initial densities, add species (adding density to a taxon with none in the default version), and remove species (by setting density at 0). In addition to density, the model user can change all population parameters that make a population behave uniquely.

An entirely new species can be created, but the name of the old species it replaced cannot be changed. Someone may suggest introducing a new species into a reservoir, for example. Any one of the default species not present in a reservoir (smelt is a good candidate because it does not presently occur in New Mexico) can become the new species, once the population parameters are altered to "make" the new species. The name will remain as it was, smelt, even though the parameters now simulate the new species.

It is neither necessary nor possible for the initial density and population structure to be exactly identified in any historic or forecasting scenario. The default version represents an approximate average density for each of the sites, sometimes based on very little information at the site (such as reported harvest rates). The modeled population eventually comes into equilibrium with the modeled environment, just as in a real lake a fish population eventually equilibrates with new habitat conditions when they occur. The rate of equilibration depends on how far removed the initial population structure is from the equilibrium structure.

Estimates of initial density that vary widely from equilibrium with model conditions usually take longer to equilibrate with the modeled conditions than estimates that are closer to equilibrium. The effect of deviation from modeled equilibrium is most obvious when modeled conditions are constant and differ greatly from the carrying capacity needed to support the initial population. When the initial density is high for the modeled carrying capacity, most taxa will decrease toward equilibrium. Low populations will increase as expected if similar conditions existed in real habitats. RIOFISH can be used to simulate nearly constant average conditions for which an approximately equilibrated population can be generated. An approximation of this "average" population is the initial density used in the RIOFISH default version. Because the proper use of RIOFISH is to calculate differences generated by management or research scenarios, the output effects of initial population estimation are mitigated, especially when scenarios extend more than a few years.

Population Structure (Units B60-63)

The population structural parameters transform numeric density to biomass density by size and age class within populations. The distribution of biomass among sizes contributes to determining reproductive potential and the production realized by each population. Mean weights per individual are estimated from constant length-weight relationships (B61), which are the same for each species at all sites in the default version. The default length-weight relationships were obtained from a combination of sources in New Mexico and surrounding states (Carlander 1969 and 1975, Cole et al. 1985), but a typical length-weight relationship was used for each species with an emphasis on those sampled site conditions that dominate in New Mexico.

From the total densities provided, by the default value or the user's value, the relation of densities among age groups (B62) is the same as the natural mortality (described later) until fish reach catchable size. Above catchable size, initial fish density is depressed to simulate the effect of fishing mortality and the density is lower than would exist in an unfinished state at a constant natural mortality. For example, if the annual density of each age class decreases by 0.5, the relative density of each age class decreases by 0.5 in the initial population until the catchable size is reached. The initial density distribution changes to reflect a new natural mortality when that value is changed by the user.

Default initial lengths at each age (B62) are provided for each species and apply universally to all sites. The default version represents an approximate average condition for New

Mexico fish populations. Model users can create unique initial structural characters for each population by modifying initial densities, length-weight relationships, age-density distributions, and lengths at each age.

In the default version, the total density of each population is distributed into each age class, including the 0 age class, at the end of summer (end of September) according to the total natural mortality coefficient. In doing so, we assume that the default population is stationary and unfished. As the model operates, the relative proportions in each age class shift as population recruitment changes. Whenever scenarios are run in which the populations are fished, the fishing mortality causes shifts in population structure, which typically result in changing biomass and production dynamics over time in a multi-year run of the model, much as would occur in a virgin fishery first opened to fishing. The dynamic that results at each site is a function of the underlying productivity, habitat fluctuations, the initial species composition, and the fishing intensity.

The initial distributions of biomass among age categories are determined once the initial density is distributed among age classes by length categories and weight is assigned to each length. This age and size distributed population biomass is the basis for population production and individual fish growth when production/biomass and mortality are applied.

Population Production (Units B58, B66-68)

The distribution of potential production (B58) in each general feeding category among fish life stages and taxa in each trophic level depends on the fraction of diet assigned to each life stage of each taxon as zooplankton, zoobenthos, fish, and plant-detritus (B66). Maximum production/biomass (B67) and environmental resistance (B68) determine the population production and the individual growth once biomass is calculated. Depending on the population status and environmental constraints, all to none of the potential production may be realized in the fish population production.

Fish in each lifestage are assigned diet coefficients. Fish may feed from up to five food categories: primary producers, detritus, invertebrate zooplankton, invertebrate zoobenthos (excluding crayfish), and other fish (including crayfish). When a lifestage diet is diverse, the fractions of each food type are defined and sum to 1.0. Assigned fractions are constants. As with other population parameters, model users may create new diet fractions. Default values are based on literature integration and local observation.

The "competitive" impact a lifestage and species has on food partitioning is a product of its production potential (biomass, maximum P/B, environmental tolerances) and dietary fraction. In the default version, for example, larval fish are entirely zooplanktonic feeders and are, therefore, sensitive to the presence of older zooplankton feeders. A very abundant and tolerant species with a low fraction of zooplankton in its diet, "competes" strongly with larvae for zooplankton production during those few semi-seasonal periods when larvae are present in RIOFISH.

The maximum P/B (B67) is equivalent to a maximum population growth coefficient (natural logarithm of the growth increment of a cohort). In RIOFISH, the maximum growth increment occurs in natural populations under optimum growth conditions, when neither food nor environmental factors limit physiological potential. The maximum P/B parameter simulates growth under optimum conditions. When biomass is low and potential for production is high in RIOFISH, the biomass may limit production even under optimum growth conditions. Mean individual fish growth in RIOFISH nears maximum when biomass in all feeding categories is low, food production in all categories is high and environmental resistance is low (e.g., temperature is optimum). Population production in RIOFISH is constrained by harsh habitat conditions independent of initial biomass, resulting in low individual growth.

In most respects the population component of the stream and lake model segments are the same. Certain of the habitat factors controlling the P/B ratio differ. An example of the maximum P/B distribution for different size groups in the older life stages is provided for largemouth bass in Figure 13. Larval and juvenile values are constant for the entire life stage and

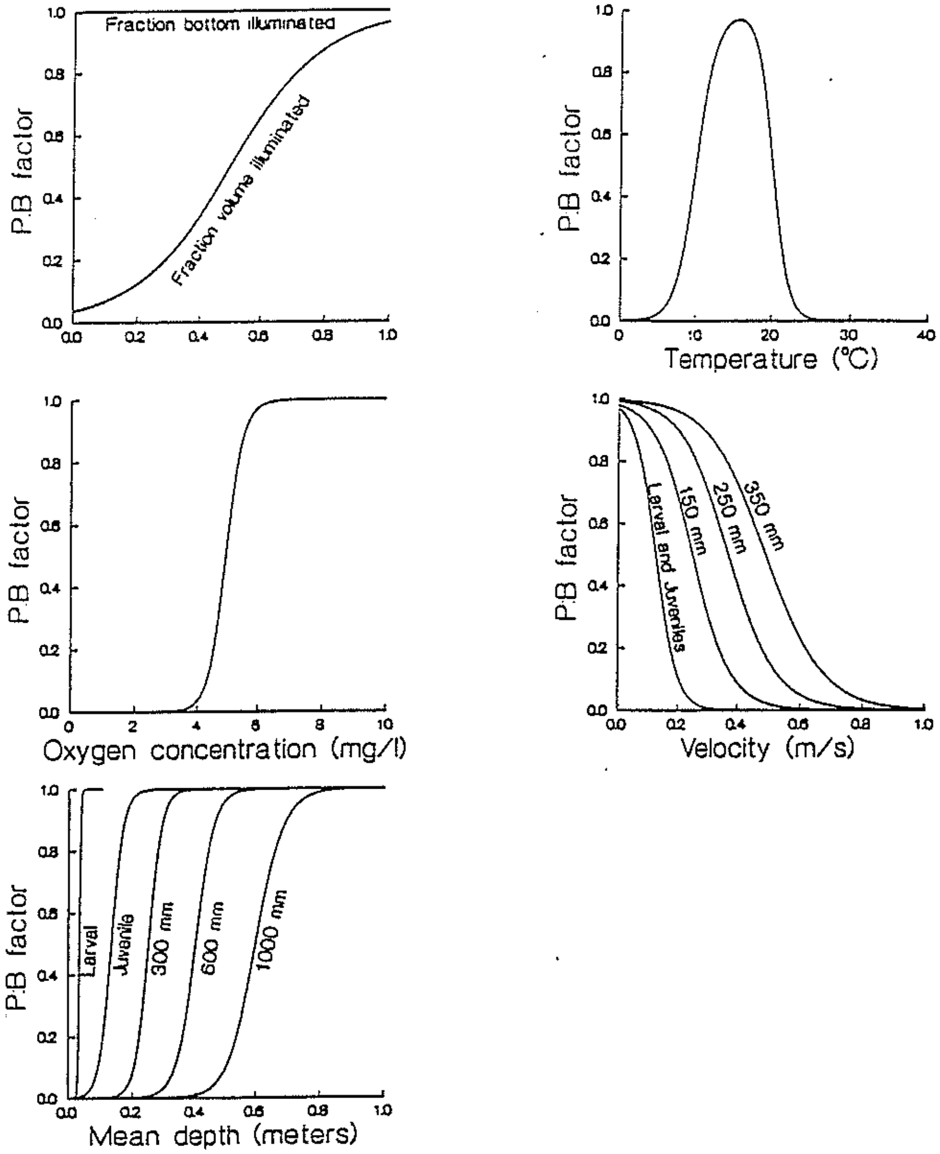

Figure 13. One species example illustrating the maximum distribution of production among the biomasses (P/B ratio) of different weight classes of fish in guilds inhabiting reservoirs, and the relationship between water-level, change/season, and mean egg survivorship.

independent of size changes within the life stage. The functions used were derived from observed growth rates presented in Cole et al. (1985) and data summarized in Carlander (1969,1975).

In RIOFISH, the extent that maximum P/B is realized depends in part on the environmental resistance (B68). Maximum P/B is reduced as habitat varies from optimum for each life stage in each taxon (larvae, juveniles, age 1 and older). Production in each dietary category is distributed differentially among taxa and life stages based on differences in environmental tolerances. The relationships between P/B and habitat are logistic. The constraining environmental variables included for both lakes and streams in RIOFISH include temperature, oxygen, the volume and bottom area illuminated above 1% of the surface light. Velocity and sediment size are additional variables in streams.

Figure 14 shows general example set of relationships for a representative cold-water taxon. These relationships sustain maximum possible population production for the potential forage production available and the population biomass present when the value is optimum. The "capture" of production by a population decreases as the environmental resistance functions vary from optimum. The relationships are analogous to habitat suitability weighing factors developed for instream flow preference models (Bovee 1986, Orth 1987), but go an additional step by linking habitat conditions to fish trophic efficiencies.

In streams, all calculations are done for each stream cell in the stream segment. Up to 12 cells of riffle and pool

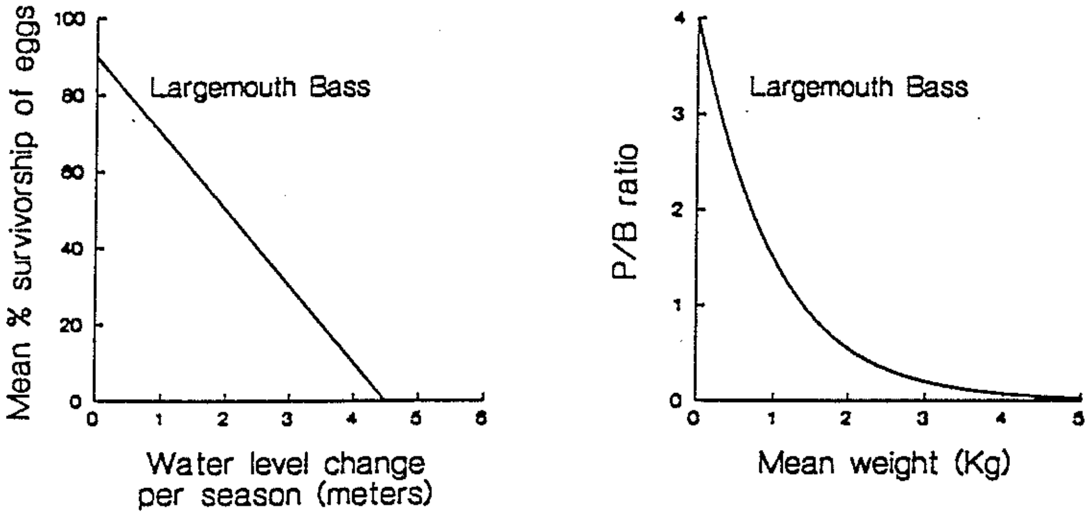

Figure 14. Examples of the functions used to estimate the effect of environmental resistance on the maximum P/B of a cold-water taxon as determined by tolerance to volumetric illumination, temperature, oxygen, depth and velocity in a modeled stream.

categories exist in each stream. Illuminated volume and bottom, mean depth, mean velocity, mean particle size, temperature, and oxygen tolerances are calculated for conditions in each cell. Potential production is assumed to be equal for each cell, but is diminished as environmental factors vary from optimum in each cell. When taxa and life stages exist with identical P/B relationships, the production is distributed in proportion to initial biomass and variation in population dynamics depends on other population parameters (no two model populations have completely identical parameters).

No attempt is made in RIOFISH to separate food resources by size category. As long as food sizes within a food category are distributed in proportion to the total consumptive demand of the different fish sizes present, the food will be shared in proportion to the consumptive demand. The P/B index will distribute production into growth appropriately to the extent the proportionality assumption is correct. Shortages or excesses in appropriate food sizes of a particular diet category, for example, would in reality reduce or increase the growth of fish sizes disproportionately from the amount indicated by maximum P/B.

In RIOFISH, as in reality, fish diets commonly change, sometimes resulting in somewhat abrupt growth changes as fish pass from juvenile to older age categories. For example, older piscivorous fish may grow at different fractions of their maximum possible growth than younger benthivorous fish in the same population.

Total sportfish production is not sensitive to the assigned maximum P/B ratio until the maximums are reduced to values below the fish production available for the fish biomass present. Only where food production is high for the fish biomass present will the total sportfish production output be sensitive to the assigned P/B.

The relative maximum P/B assigned to larval fish and juvenile fish are the least well documented values. The proportional amounts of zooplankton foods made available to larvae in relation to older fish is not as accurate as it might be with greater study of maximum growth rates. The major net effect of inappropriate distribution of production among biomasses is to increase or decrease survivorship of larvae, eventual recruitment, and size structure of older age groups.

The initial density chosen for each population influences the total production possible because the maximum P/B at any age is constant. When a population density is grossly overestimated relative to other populations present, production also will be overestimated because proportionally more production will be partitioned based on the overestimated biomass.

At this point in the model development, the addition or deletion of fish predators, other than anglers, does not alter the size composition and the population P/B ratio. Predation is assumed to be in equilibrium with the size distribution of prey populations present. New introduction of a piscivore on top of existing predators has no net effect on prey structure, mortality rate or production. Predators in RIOFISH are not allowed to accelerate mortality by eating up the biomass capital in prey. Although this concept appears to be reasonably valid for diverse fisheries, where predators are missing, the addition of a predator is likely to modify prey population structure. This "top-down" phenomenon is not incorporated into RIOFISH and may be the most important limitation associated with the prediction of population responses to modeled management strategies.

For example, intense over-harvest of predators (e.g., largemouth bass) would in reality result in increased survivorship of prey fish and a greater accumulated total biomass distributed more in older prey, without much overall change in population production. Such predator/prey impacts are not reflected in the model and can affect the estimate of the harvestable biomass present.

Non-larval Natural Mortality (Units B69-71)

With certain important exceptions, natural mortality for age zero and older fish (older than larval stage) is assumed to be a constant that is unique for each species based on "typical" reported natural mortality rates (Leidy and Jenkins 1977, for example). Natural mortality occurs constantly throughout each season and does not vary among seasons. For an unfished population, the mortality and the fraction that survives from year to year remains constant for all fish over age 1, except for certain intolerable conditions (low oxygen or high temperature, for example).

Exceptional mortality occurs in RIOFISH through exposure to intolerable temperatures or low oxygen, which kill intolerant fish outright (B70). Cold-water species are killed, for example, when no water layer in a lake has temperatures below 25°C and oxygen is above 4 mg/liter. Threadfin shad are killed when no winter water layer exceeds 4°C. Partial kills can be incorporated in the model to simulate a refuge effect (such as a localized spring-upwelling effect). The model user has the option of creating a partial kill and estimating the percentage of the population killed to determine the kill effect on population recovery rate.

Another exceptional source of natural mortality occurs in the first winter of fish life (B71), if juveniles do not grow to a certain minimum size before winter onset. All juveniles do not grow equally, a normally distributed pattern of growth is modeled into the juvenile populations. Natural mortality is increased in those circumstances where juvenile density is high with respect to food production. The slowest growing fish die (are deleted). The density and size of fish recruited into age 1 is thus determined by the total mortality of the fish that were recruited as juveniles.

The source of natural mortality is not always explicit in RIOFISH. Although starvation may be implied by insufficient juvenile growth before winter, those fish may or may not be consumed by other fish. When piscivore P/B and biomass are both relatively high, the source of mortality is implicitly predation. When piscivore P/B and biomass are low, some other source occurs because mortality usually is constant. Because of this assumption, RIOFISH does not simulate prey population density and biomass responses to variation in predator:prey ratios. This aspect of RIOFISH becomes most important in lightly fished communities with low biodiversity.

Fishing Mortality (Units B72-76)

Angler days of effort (B72), fish catchability and retention desirability (B73), protective regulations (B74) and resulting harvest and return of fish (B75) determine the fishing mortality (76). Both harvest mortality and hooking mortality of returned fish contribute to the fishing mortality. Angler effort is determined in the economic component of RIOFISH. Fishing mortality is additive to natural mortality in RIOFISH and the sum of the two mortality sources determines the total mortality acting on each fish population. The total mortality reduces density and biomass when it exceeds population replacement by reproduction and growth. When total mortality exceeds replacement, biomass decreases and may reduce production, depending on whether biomass is limiting the production. Fishing mortality in RIOFISH typically reduces both biomass and production from what they are in the unfished RIOFISH populations.

Angler days of fishing effort (B72) are calculated during the previous time step in the economics component (described later). The fishing effort is generated based on fishing success and other socio-economic parameters described later in the economics component of RIOFISH. Fishing success is characterized by number of fish caught, number of fish harvested, and weight of fish harvested in panfish and sportfish categories. Independent of number and size caught, sportfish are more attractive than panfish. Panfish include non-bass sunfishes, bullheads, and yellow perch. Sportfish include all basses, walleye, catfishes, pike, and salmonids. The fish connection to angler effort was estimated from angler effort-yield data (collected by researchers at NMGF) and fish biomass data (collected by researchers at NMSU) gathered at New Mexico lakes (Cole et al. 1985, for example).

The coefficients for catchability and retention (B73) in an unregulated population determines what the catch, harvest and return will be, given population density and structure. Each species has potential for unique catchability and retention coefficients (both are user accessible). A minimum catchable size is determined for each species and for the type of terminal gear used (bait, flies, other artificial lures). The catch and return algorithm assumes that anglers catch fish of different size in proportion to their relative density at the site and return fish based on size and the retention coefficient value.

The retention coefficient is the net result of all factors determining the harvest desirability of a species and size.

Regulations (B74) modify the relationship between catch, harvest and return. Numerical regulations set average limits on fish harvest, regardless of size caught. Anglers do not have equal probability of catching fish. The distribution of success follows a truncated Poisson distribution and many anglers have no success in the average angler day. An alternative distribution, the negative binomial used by Wagner and Orth (1991) would result in a greater number of zero success anglers and a somewhat lower retention of caught fish than the model chosen here. Numeric limits truncate the harvest of the most successful anglers increasing the return fraction of the fish caught. Length limits require all fish under the harvest distribution within the length categories to be returned. Maximum, minimum and slot limits may be defined. Another regulation determines terminal gears. This affects the resulting catch, harvest relationship and return (B75) and the condition of the returned fish with respect to hooking mortality, which is incorporated in fishing mortality before total mortality is estimated. Sites may be closed in seasonal blocks, thereby prohibiting all fishing and eliminating fishing mortality.

The default version in RIOFISH assumes regulations are in place. Model users can modify regulations as they deem fit.

Stocking (Unit B77)

Fish stocking is entered at the beginning of a time step. Stocking occurs in any size range expressed in millimeters. The population density and structure is modified to the extent of stocking and all entered stocking is assumed to be successful (no stocking-related mortality). Once stocked, fish behave like those born there. Two versions exist in RIOFISH: unstocked and historically stocked. The default version assumes stocking based on history rates, but the model user can insert different stocking rates. To change stocking, the model user provides numbers of stocked fish in different size classes to estimate the effect of stocking.

In each time step, initial population density, biomass and structure are modified by the unique combination of production and mortality and management forces to determine a mid-step population density, biomass and structure (B78). This serves as input to the reproductive part of the model.

Reproduction (Units 79-82)

The mid-step distribution of fish biomass by age class and size (B78) is the basis for estimating number of eggs laid (B82) by the population during the reproductive period. Reproduction occurs only in the designated reproductive seasons when fish of reproductive size occur in the RIOFISH community. Model users may select reproductive seasons and maturity lengths different from the default version. The calculated average seasonal biomass in each reproductively capable age group of females is determined by the sex ratio for the mature population (B76). The number of mature eggs per unit biomass is used to calculate the fecundity per age-class (B77).

Reproduction is assumed to occur at mid-season. Unless altered by the model user, a sex ratio of 0.5 is assumed as a default value. The minimum size at maturity is also controllable by the model user, as is fecundity and the season of spawning. Egg number/female is a function of mature body weight. Fish are assumed to spawn uniformly throughout the season. Default values for these parameters are unique and "typical" values for each species based on literature surveys (Carlander 1975, for example). From fecundity information, the total potential egg number for each species is calculated by multiplying weighted mean egg counts per female times total female biomass.

Egg Mortality (Units B83-85)

Survivorship of each species starts with egg mortality (B83), which is modified by water-level fluctuation (B84). Figure 13 shows an example of such a relationship. Only spawned eggs and yolk-sac larvae are assumed to be vulnerable to water drawdown.

Because of inadequate quantification in the literature of the direct impacts of water-level flux on early life survivorship, a logical process approach was used to estimate the values of the parameter. The egg and larval vulnerability is based on the estimated distances that spawning occurs from shore, length of time that spawning occurs, and the development rates of egg and yolk-sac larvae at the typical temperatures occurring during spawning. The parameter used to estimate water-level effects is based on life history information primarily and is secondarily related to the approximated effects of water-level fluctuation on fish egg and yolk-sac larval survival.

The intercept in the egg mortality algorithm is always less than 1.0 in the default values, representing losses due to teratogenic effects, incomplete fertilization and predation. The egg and larval mortality from water-level fluctuation is exacted before other sources of mortality take their toll in the model. Model users can change the intercept and the slope in the egg mortality algorithm.

After natural egg mortality and water level effects are calculated, the initial number of post-yolk sac larvae is estimated (B85). Data for these early life history values is sparse and estimates of impacts are necessarily rudimentary for most species. However, the controlling factors for survivorship may not occur at this stage under most conditions. Food availability and the critical period following yolk absorption are assumed in RIOFISH to be a more critical.

Larval Growth and Death (Units B58, B66-68, B70, B86, B87)

Post-yolk-sac larval loss is determined by fish growth rate (B58,B66-68) and mortality (B86,B70) induced by extreme conditions as already described for older fish. Growth is a variable function of diet (B66), which is entirely zooplankton for lake larvae in the default version of RIOFISH and. In the stream model larvae share benthic invertebrates with older fish. The food production (B46) and existing competition during the seasons of larval development is critical for determining larval growth and survival. As already described for older fish, larval fish production and growth on its zooplankton diet is a function of the maximum P/B of larvae (B67), the environmental resistance (B57), and the competitive effect of all other zooplankton feeders in other life stages.

Natural mortality does not operate constantly on larvae as it does for older fish. All larval fish not growing more than a minimum rate are eliminated by starvation by the end of the season of birth. All larvae are presumed to be equally capable of converting their zooplanktonic food into biomass regardless of species category (no competitive advantage is assigned one species over another). The production of zooplankton food in the seasons when larvae are born is the major control of larval fish mortality whenever water levels are reasonably stable. Under stable water level conditions, high zooplankton production and low reproduction rate, the total natural mortality of larvae may approximate 0. Under those circumstances all modeled larvae grow rapidly enough to attain the size necessary to qualify as juvenile fish.

A large starvation mortality occurs when fish population fecundity is high and zooplankton production is low. This is determined by a required growth function. Larvae must grow from early post-yolk sac to minimum juvenile size (25 mm for all species in this model) within the season. Average larvae, therefore, have about 3 weeks to grow the prerequisite amount. The model user can control the initial post-larval size and the larval growth necessary to reach juvenile size.

Older zooplankton-feeding fish compete with larvae for food and reduce their chances for survival to juvenile size. Competitive advantages are determined by relative tolerance to environmental conditions (resistance) and relative maximum P/B. All larval fish parameters are model-user adjustable. When different tolerances exist, larval fish are often favored in the default version. For example, in streams, rapid velocity is assumed not to limit larval fish maximum P/B because relatively small backwater or other habitat fractions provide suitably slow velocities in New Mexico waters.

Modeled recruitment into adult populations is most sensitive to the survivorship of larvae into juvenile ages. These estimates are also among the most poorly documented and accordingly deserve much more research attention. The larval growth coefficients were, therefore, calibrated to attain reasonable simulations of juvenile and adult recruitment.

At the end of the time step (B87), the population structure, density and biomass are reestimated to serve as the initial structure for the next time step (B64). The time steps are repeated as necessary to complete the total number of years designated. At least one complete year must be run in RIOFISH and a maximum of 10 years can be run at once. The result at the end of a 10-year run can be used to initiate a second and subsequent runs, if desired, so there is no limit on the total number of years included in a scenario.

Table 3 provides a summary for all biological parameters in RIOFISH and whether they are accessible to the model user.

Table 3. Biological parameter inputs. Those marked as user inaccessible can not be modified by the model user.

Input variables	Variable description	No user access
Community production and partitioning parameters		
1.	Air temperature, Julian date and elevation	X
2.	Oxygen saturation at temperature and elevation	X
3.	Kcal conversion to grams carbon	X
4.	Maximum photosynthesis efficiency	
5.	Nitrogen:phosphorus ratio (Redfield ratio)	
6.	Water temperature reduction of photosynthesis efficiency	
7.	Suspended solids reduction of photosynthesis efficiency	
8.	Limiting nutrient reduction of photosynthesis efficiency	
9.	Flushing rate reduction of photosynthesis efficiency	
10.	Degree days required to condition allochthonous carbon	
11.	Fraction of allochthonous carbon consumption as function of temperature	
12.	Table of epilimnetic/hypolimnetic temperature	X
13.	Oxygen depletion rate in the hypolimnion	X
14.	Depth of 1.0% and 0.01% light penetration	X
15.	Function for relationship of organic loading and trophic efficiency.	
16.	Oxygen that excludes herbivores and reduces trophic-level efficiency	
17.	Temperature relation to herbivore trophic-level efficiency	
18.	Riparian cover fraction over stream channel	X
19.	Loss rate of riparian leaf litter in dry channel before flooding	

Input variable	Variable description	No user access
20.	Bottom-feeders as a function of mean depth	
21.	Benthic detritus-feeder fraction as fish	
22.	Fraction of suspension feeders as shad	
23.	Carnivorous fish maximum efficiency	
24.	Piscivore-pley efficiency relationship	
25.	Lake export as a function of production	
	Fish species and life stage parameters	
26.	Maximum temperature tolerated	
27.	Minimum temperature tolerated	
28.	Minimum oxygen tolerated	
29.	Maximum possible Production/Biomass	
30.	Diet composition	
31.	Natural mortality	
32.	Fraction spawing by season	
33.	Sex ratio	
34.	Weight at sexual maturity	
35.	Fecundity as function of body weight	
36.	Water level decrease effect on egg survival	
37.	Growth rate of larvae required to survive	
38.	Minimum weight needed for juvenile survival	
39.	Length-weight relationship	
40.	Bounds for length-frequency relationship	
41.	Minimum size caught	
42.	Initial larval fish weight	
43.	Initial population lengths by age class	
44.	Angler fraction using different gear types	
45.	Catchability by anglers	
46.	Relative likelihood of retention by anglers	
47.	Hooking mortality by lure and bait type	

ECONOMIC COMPONENT

OVERVIEW AND PROBLEM

A central goal of public sportfishery management is to provide maximum possible benefits to the fishing public consistent with resource constraints brought about by budget, personnel, and competing demands that are placed on the natural resource base. Effective management of a sport fishery can be seen as an attempt to identify and implement management actions that best serve the public welfare.

An essential part of wise management of a sport fishery is to identify, formulate, and implement actions that maximize the benefits of sportfishing to anglers consistent with constraints that preclude providing perfect fishing experience to all anglers at zero cost. This implementation requires developing a measure of public benefits of various fishery management policies. Achieving the goal of maximum public benefit is constrained by numerous limitations including budget, personnel, hatchery capacity, habitat availability, and management impacts on rare species. Fishable habitat is a particularly limiting factor in New Mexico because habitat is scarce and unpredictable. The unpredictable nature of fishable waters, more than any other factor, may constrain the meeting of fishery management objectives in New Mexico.

COMPONENT DESCRIPTION

Biology and Hydrology (Units E1-2)

Figure 15 is a flow-chart of the fishery management linkages to statewide angler benefits, as determined by the economics component. When RIOFISH is run fully integrated, the biologic and economic components provide outputs that serve as inputs for the economics component. The biologic component (E1) generates the essential measures of fish quality that affect the angler's demand for and benefits of the fishing experience. Changes in water distribution and amount can also be simulated by the manager. These changes are processed in the hydrologic component (E2) and become a driver in the economics component.

Fishing Quality (Unit E3)

Fishing quality affects the demand for and benefits from fishing, and can be changed by the model user in RIOFISH, either indirectly through the biologic component or directly through the economics component when run alone. As described in Table 4, the three fish quality factors used in RIOFISH include average weight of fish harvested, average fish number harvested per day, and average number caught per day. For all three measures of fishing quality, game fish are weighted twice as heavily as pan fish. Game fish include trout, salmon, bass, pike, and walleye. Pan fish include crappie, sunfish, catfish, bullhead, yellow perch, suckers, carp, and all other species. When RIOFISH is fully integrated, changes in fish variables induced by management or

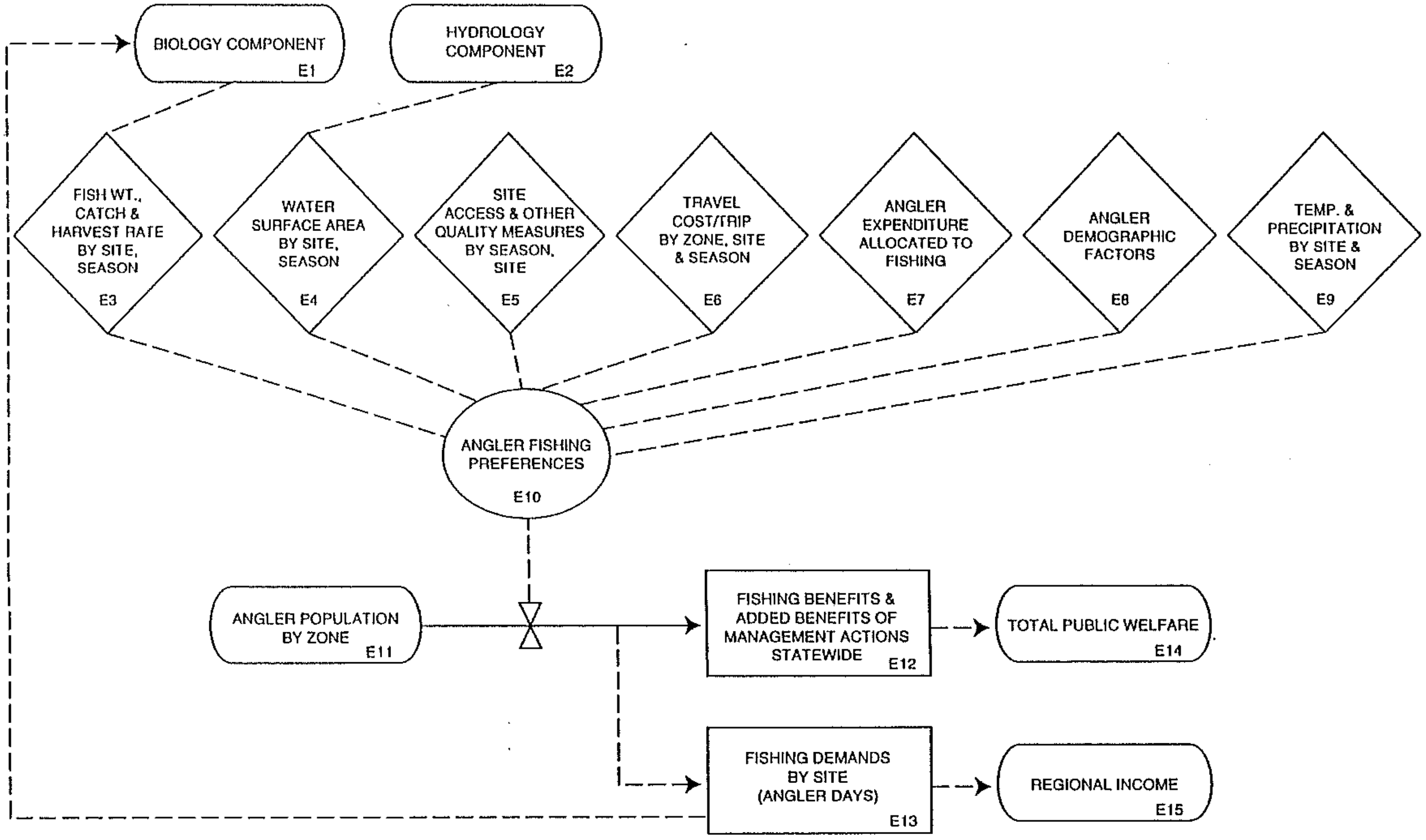

Figure 15. Main elements and process in the economics component of RIOFISH.

Table 4. Factors in the RIOFISH economic model that affect the benefits of fishing management actions in New Mexico.

Input	Site quality variable	Units	User access
1	Access	Percent of shoreline accessible within a 1/4 mile walk from vehicle	X
2	Average weight kept	Average weight of harvested fish (grams); game fish weighted twice pan fish	X
3	Boat ramps	Number of concrete boat ramps at a site	X
4	Developed campsites	Number of developed campsites within 10 miles of site	X
5	Drinking water	0-1 dummy; 1 = drinking water available at site	X
6	Fish/day kept	Fish number harvested per day; game fish weighted twice pan fish	X
7	Fish/day caught	Fish number caught per day; game fish weighted twice pan fish	X
8	Macrophyte	Aquatic vegetation, rated by fishing managers from 0 (none) to 10 (dense)	X
9	Precipitation	Seasonal precipitation at site, inches	
10	Modern toilet access	Number of modern toilets within 10 miles of site	X
11	Surface area	Average site surface acres, by season	X
12	Tailwater	Number of river miles with good fishing below a dam	
13	Tempsite	Site temperature by season	
14	Turbidity	Water turbidity rated by fishery managers, 0 (none) to 10 (muddy)	X

Input	Site quality variable	Units	User access
15	Cold river	Large cold stream fishing site	
16	Forest lake	Nearest lake within a National Forest to a city with more than 50,000 people	
17	Kokanee lake	Lakes that support Kokanee Salmon and have less than 10,000 surface acres	
18	Mid-Elevation lake	Lakes with elevation between 1200 and 2000 meters and have 1 or 2 boat ramps	

natural events are processed in the hydrology and biology components, which then became driving variables in the economics component, where they impact visitation rates and angler use.

Water Surface Area (Unit E4)

The economics component uses estimated surface area for both lakes and streams produced by the hydrology component. Numerous natural resource decisions in the southwestern United States affect water surface area, and therefore affect the demand for and benefits from sport fishing. Important examples of such policies include leases, rental, purchase, or other methods for acquisition of water or water rights for fishing. Water distributions can be modified by engineering decisions by water management agencies, such as the U.S. Army Crops of Engineers or Bureau of Reclamation, for reasons including drought management, water rights transfer, or providing critical habitat for endangered fish and wildlife species.

Site Access and Quality (Unit E5)

Numerous measures of site quality affect the demand for and benefits from fishing. As shown in Table 4, some of these attributes are determined outside the control of management, while managers can change others directly or indirectly, thus affecting fishing benefits.

An improvement in quality at a particular site causes additional anglers to use the site and reduces angler demand at substitute sites. Several measures of site quality are included in addition to the water and fish quality that was described above. Included are shoreline access, boat ramps, catch and release regulations, number of developed campsites, availability of drinking water, status as a lake or stream, presence of macrophytes (aquatic vegetation), water turbidity, restroom facilities, river miles of tailwater fisheries and other fishing site attributes that affect fishing demand, including site status. Site status is measured by the following four factors: whether or not site is a large, cold-water stream, whether or not it is a reservoir located in a national forest, whether it is a lake supporting Kokanee Salmon, or whether it is a lake with elevation between 1,200 and 2,100 meters. Additional details are in Table 4.

Travel Cost (Unit E6)

The travel cost an angler incurs when traveling to fish has an important impact on angler benefits. Angler travel costs are most importantly affected by driving distance to each site from angler zones-of-origin, defined as sets of continuous counties in New Mexico. Distance patterns between anglers and fishing sites influences the values of benefits produced by a management action. Other things remaining equal, improvements in fishing quality have a smaller impact on total angler fishing trips and fishing benefits for remote fishing sites where angler travel costs are high than for sites nearer to population centers where average travel costs are lower. In New Mexico and elsewhere, improving the quality of fishing near population centers often is most beneficial.

Angler Expenditure (Unit E7)

Fishing effort is affected by angler income. The measure of income used for the economics component is total direct angler expenditure. Angler expenditure is measured as travel costs per trip multiplied by average observed number of trips per site, summed over all sites. Average angler expenditures per fishing household are estimated for each of nine zones-of-origin and four seasons per year for all years 1974-1992. Zones or seasons that generate greater amounts of total angler expenditure produce more fishing trips to all sites. Although fishing policies are assumed to have no affect on total expenditure in RIOFISH, policies do affect the allocation of angler expenditure among the 132 study sites, and thus contribute to the allocation of trips among sites.

Demographic Factors (Unit E8)

Numerous demographic factors that vary by zone-of-origin affect the demand for and benefits of fishing trips. These are fixed variables including the 1) percentage of a zone-of-origin of Hispanic origin, 2) percentage of a zone with people of age 65 or older, 3) percentage of people under 25 with a college education, 4) percentage of households with children and single females, 5) percentage of households with married childless couples, 6) percentage of households with married couples with children, and 7) percentage of households that are single males without children.

Climate-Topography (Unit E9)

Several climatic-topographic factors affect the demand for fishing, including the site's elevation, temperature by season, and precipitation by season. Increased seasonal precipitation directly reduces fishing demands, although by producing more runoff, it indirectly increases demand through its effect on available water. During spring and summer, cooler sites, usually at higher elevations, have the greatest fishing demand; increased temperatures reduce demand.

Fishing Preferences (Unit E10)

Angler fishing preferences act as a filter that controls the impact of the variables described in units E4-9 above. These variables include water, fish quality, site quality, expenditure, travel cost, demographic factors, and climatic-topographic factors. Angler demands occur as consequence of these factors influences on angler fishing preferences.

Angler Population (Unit E11)

Managers can use RIOFISH to estimate the impact of future shifts in the structure of angler population. These shifts alter the effect of changes in any given management action or angler demand and fishing. For example, if angler populations are projected to move away from cities to rural areas, or to migrate to desert climates, improvements made at rural or less mountainous fishing sites would produce greater benefits to anglers than equivalent improvements at urban or mountain fisheries. The benefit to anglers of management actions depend on the size and distribution of the angler population.

Angler Benefits (Unit E12)

As a result of improvements in fishing opportunities made by managers, the economics component predicts total statewide angler benefits for policy changes at any desired combination of all 132 fishing waters in RIOFISH.

Total statewide angler benefits only have meaning when defined for a particular fish management action. For example, benefits can be defined for additional fish stocked at Heron Reservoir in summer 1988 compared to fish actually stocked in Heron Reservoir in summer 1988, based on stocking records.

To be applied correctly, benefits should be compared over two successive runs of the economics component, in which the model is configured for an identical set of fishing sites and years for both model runs. This method for implementing RIOFISH is consistent with the "with versus without policy" principle that underlies a correctly done cost-benefit analysis of any natural resource management action.

Fishing Demands (Unit E13)

The economics component predicts total fishing demand in angler days at each of the 132 fishing waters. A 132 site travel cost demand model was estimated using regression methods which identify (1) why some sites receive more fishing trips than others, (2) why some angler zones-of-origin produce more fishing trips than others, and (3) why fishing trips change by season. Factors included in the model that affect trips are quality of fishing, surface area, site quality, travel cost, angler budget constraints, and angler demographics. The model has 8,316 observations, with 9 New Mexico county aggregates, 132 New Mexico waters and 7 seasons in 1988-89 for which there are origin-destination visitation data. Although estimated over a continuous period of seven calendar seasons during two years, the model is implemented in RIOFISH over the period 1974-1992. It can also be implemented over future time periods for which hydrology is forecast using synthetic flows.

Parameter estimates from the demand models are used in constructing an angler benefits model. This benefits model is based on the theoretically correct expenditure function using a demand model consistent with underlying angler preference. Details are provided in the mathematical appendix.

Mathematical expressions are specified and estimated for the anglers' fishing demand equation and benefit function, providing a theoretical foundation for a series of empirically estimated demands for fishing quality from observed data. The benefits function permits the fishery manager to identify a credible objective, and testable angler benefit from changes in several dimensions of fishing quality, which are induced by management or by outside forces. Outside forces beyond the control of managers include changes in travel costs, demographic patterns, and numerous features of the aquatic ecosystem.

There are significant implications for fishery management in having an explicit mathematical expression for the angler benefits function. Benefits are derived from a demand model consistent with an underlying angler preference map. Thus, estimated values of complex policies are consistent with underlying angler decision processes and economic constraints that govern angler behavior, especially angler income and time available. Benefits also can be computed for management actions that simultaneously adjust both fishing cost and fishing quality. Mathematical details are provided in the appendix.

Public Welfare (Unit E14)

Fishing benefit is the essential component of total public welfare controlled by the fisheries manager. Fishing benefit that results from management-induced or natural events are summed over all in-state anglers for New Mexico.

Regional Income (Unit E15)

A change in a site's fishing demand (measured by angler days) affects the county through a recirculation of added angler spending to produce added income and employment in the local area where the site is located. These income and employment changes are estimated from a regression model based on the relationship between county incomes, angler days, and other factors that affect county incomes, such as manufacturing, service, and export base; education levels; county population; and the county's relation to national economic trends.

Travel Cost (Units E16-22)

A model element was developed to explain the factors influencing travel costs from zone to site (E22), including driving distance (E16), gasoline price (E17), miles per gallon (E18), other vehicle operating costs (E19), site entry fee (E20), and travel time value (E21). The method used is similar to the one described in Rosenthal, et al. (1986).

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APPENDIX

HYDROLOGIC COMPONENT MATHEMATICS

OVERVIEW

The driving variable of the hydrology submodel is water volume per unit time. The time resolution of the model is bimonthly. The first half of a month is a constant 15 days, but the last half will vary between 13 and 16 days depending on the month and year. Spatial resolution of the model is not critical because the time period exceeds travel times of water flows between any two contiguous points in the system. Therefore, a routine to hydraulically route stream flow is not necessary for model functioning. Instead increments of water, volumes in the bimonthly period, are moved from point to point in the system. Conservation of mass is the primary physical process that is modeled, as explained by the following description. An important model form is the regression equation, which is used in several places.

RESERVOIR MODEL

Unit 8 and 10

The user may modify historical inflows and outflows by the basic equation:

(1) $Q_m = A_m Q_0 + B_m$

where:

Q_m = modified discharge, desired by model user (cfs) (m = inflow or outflow) (cfs)

Q_o = original measured discharge, inflow or outflow (cfs)

A_m = flow multiplier > 0 which represents a fraction increase or decrease in the flow (1 represents no change)

B_m = absolute flow increment (mean cfs) which can be positive or negative to indicate additions or withdrawals from the flow, (0 represents no change)

The parameters A_m and B_m can be modified on a monthly basis by the user. For example, if new irrigation withdrawals are to be considered, the user can set the months of the withdrawals and the amount in each. Up to three inflows and outflows at each reservoir can be specified in this manner. If the user has modified upstream flows, either directly or by altering reservoir operations, these modifications can be used to better represent the inflows to the reservoir under consideration. This is done by linear transfer functions as deduced from system configuration or found from regression analyses of monthly flow data. The primary inflow (#1) is related to one or more primary upstream flows by

$$Q_{I1} = A_t Q_x + B_t \tag{2}$$

where:

Q_{I1} = primary inflow 1 to the reservoir under consideration (cfs)

Q_x = index flow, usually the primary upstream outflow (cfs)

A_t, B_t = the deduced or regression derived transfer parameters (Table A1)

The calculated reservoir inflow, Q_{I1} , is only used if it differs by more than three cubic feet per second from the measured flow at that reservoir and time.

Unit 11

The total inflows and total outflows per month are converted to acre-feet for the period and added to the reservoir volume at the end of the previous time period (or initial volume) in the case of inflow and subtracted if outflow. If the user wishes to consider a volume constraint, the primary outflow (#1) is modified as needed. A warning message is displayed if the maximum outflow is exceeded. The volume determined at this step is

$$(3) \quad V_c = V_{(i-1)} + Q_{inflow} - Q_{outflow}$$

where:

V_c = computed volume (acre-feet)

$V_{(i-1)}$ = volume at end of previous period (acre-feet)

Q_{inflow} = total inflow (adjusted as needed) (acre-feet)

$Q_{outflow}$ = total outflow (adjusted as needed) (acre-feet)

The surface area (Unit 16) for this volume is

$$(4) \quad A_1 = f(V_c)$$

where:

A_1 = initial estimate of surface area (acres)

$f(V_c) =$ an interpolated area from a table of elevation, area, and volume values unique to each reservoir (acres)

A first estimate of the volume is

$$(5) \qquad V_1 = V_c - A_1 (K_p E - P)$$

where:

V_1 = initial estimate of volume (acre-feet)

K_p = pan coefficient for the reservoir (=0.7)

E = pan evaporation (inches)

P = precipitation (inches)

Equation (5) accounts for the net weather effects (Unit 9) in the bimonthly period. At this point, V_1 is used in place of V_c in equation (4) to calculate A_2. The new area, A_2, is used in equation (5) to obtain a new estimate of volume, V_2. A better estimate of volume is the average of V_1 and V_2 or

$$(6) \qquad V_c = \frac{V_1 + V_2}{2}$$

The new V_c is then checked for minimum volume constraints, and, if necessary, primary outflow is decreased down to zero (a warning message is displayed) and the volume increased as a result. After this adjustment, the corresponding surface area and elevation are found in the same manner as in equation (1.3). The surface area and volume estimates are passed to the economics component which is used to predict angler use and benefits at reservoirs.

Unit 15

Another step involves computing the water quality constituent concentrations in the reservoir. Water quality constituents are total phosphorus, (P), total nitrogen, (N), and total suspended sediment, (SS). Loadings to the reservoir are found from (Units 3-6):

$$(7) \qquad L = A_i Q_i^{B_i}$$

where:

L_i = mass load of the constituent P, N, or SS entering the reservoir from a source input (tons per day)

Q_i = channel inflow i (i = 1, 2, or 3 inflow sources, depending on reservoir) (cfs)

A_i, B_i = coefficients for each inflow, chemical constituent, and season.

The computation of reservoir concentration uses reservoir volume, area and outflow, and constituent loadings to estimate the in-reservoir concentrations. The general equation is

$$(8) \qquad C_i = \frac{nL}{V_s + Q_s}$$

where:

C_1 = is the concentrations of the constituent in the reservoir (mg/l)

n = a modifier to adjust the concentration to levels observed in New Mexico reservoirs, it is 1.0 for phosphorus and nitrogen and 0.25 for total suspended solids (TSS)

L = load to the reservoir of the relevant constituent in g/m^2 of reservoir surface/half-month

v_s = settling velocity (m/half-month) of constituent which is a variable function of exchange rate (r), areal loading of constituent (L/Z), depth (Z) and areal loading, or water loading (Qs)

Q_s = areal water loading = Z/T (m/half-month)

Z = hydraulic depth = V_c/A (m)

V_c = computed volume (in millions of cubic meters)

A = surface area corresponding to volume, V_c (km^2)

T = retention time = $V_c/Q_{outflow}$ (half-months)

r = exchange rate = 1/T

$Q_{outflow}$ = outflow rate (volume (cubic meters) in the bimonthly time period)

The settling velocity, v_s, is computed for each constituent from equations (Table 1) which depend upon reservoir retention time.

Table A1. Equations for computing constituent settling velocity, vs. Retention Time

	Less than 30 half-months	More than 30 half-months
Total Phosphorus:	$v_s = 25.1*(1/T)**0.845$	$= 320.4*(L/Z)$
Total Nitrogen:	$v_s = 1.71 - 0.234*Q_s$	$= Z*0.648*(L/Z)**0.618$
Total Suspended Solids:	$v_s = 7.82*Q_s**0.88$	$= 2465*T**0.05$

A different equation is used to compute TSS in Cochiti and Elephant Butte reservoirs. The equation is based on trap efficiency. The percent of sediment retained in the reservoir water column at these reservoirs, R, is :

$$R = 0.142\,Y^{(-0.525)} \qquad (9)$$

where:

R = percent of sediment retained in the reservoir water column

$Y = \dfrac{XL * W}{V * D}$ (seconds)

XL = length of the reservoir (ft)

W = average particle size of sediment entering the reservoir (ft)

V = a settling velocity computed as XL/T (ft/s)

T = water retention time computed as volume/outflow (sec)

D = average reservoir depth computed as volume/area (ft)

Table A2. Index Flows and Transfer Function Parameters for Each Reservoir. Equations of the form $Q_{j1} = A_t * Q_x + B_t$.

Reservoir	Q_x Index Flow	At	Bt
Rio Grande System			
Heron	None*	1.0	0.0
El Vado	Heron Outflow + La Puenta	1.0	0.0
Abiquiu	El Vado Outflow	R	R
Cochiti	Abiquiu Outflow + San Juan Pueblo	R	R
Galisteo	None*	1.0	0.0
Jemez Canyon	None*	1.0	0.0
Elephant Butte	Cochiti Outflow**	R	R
Caballo	Elephant Butte Outflow	1.0	0.0
Canadian System			
Eagle Nest	None*	1.0	0.0
Conchas	None*	1.0	0.0
Ute	None*	1.0	0.0
Pecos System			
Santa Rosa	None*	1.0	0.0
Sumner	Santa Rosa Outflow	R	R
McMillan	Sumner Outflow	R	R
Avalon	McMillan Outflow	R	R
San Juan System			
Navajo	None*	1.0	0.0

*/ Reservoirs not affected by upstream reservoir operations, Heron is affected by transmountain diversion.

**/ Combinations of Cochiti outflow, Jemez River, Galisteo Creek, Rio Puerco, and Rio Salado indicate that the Cochiti outflow explains almost all the variance of the Elephant Butte inflow.

R/ Regression parameters which vary from month to month.

The equation to calculate the concentration of suspended sediment in the reservoir is:

$$(10) \quad TSS = \frac{LSS * R * 704.12}{V_c}$$

where:

LSS = suspended sediment entering into the reservoir (tons/half month)

V_c = reservoir volume (acre-feet)

The results from these computations are written to two files. One file is for the biologic (Unit 23) and economic (Unit 24) components, and the other file is for use, as needed, in tailwater computations.

STREAM MODEL

The stream model is structured similarly to the reservoir model. However, there are some unique differences. The stream model will compute various parameters at defined cross sections of one or more river reaches. Figure 1 shows a typical cross section. Generally, a reach will be broken into two (2) cross sections: one for riffles, and one for pools. At each cross section, a series of X-Y data

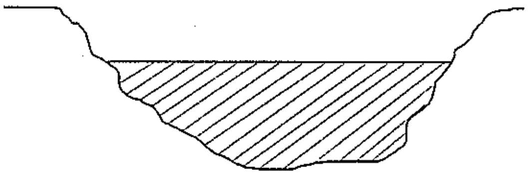

Figure 1 Typical cross section

pairs will define the geometry of the cross section. Straight lines are drawn between the X-Y data pairs, and vertical lines are drawn from y=0 to each X-Y data pair; thereby subdividing the cross section into triangular and trapezoidal cells. Figure 2 shows how a typical cross section is subdivided into cells. The parameters described below are computed over a user specified period of time in approximately one half month time-steps. The first time-step for a month consists of 15 days, and the second time-step for that month consists of the total number of days in the month minus 15.

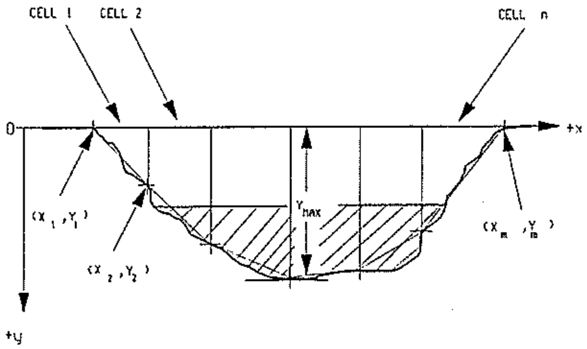

Figure 2 Cross section subdivided into cells

The parameters output from the model for each reach are:

a) 7-digit reach ID

b) reach name

c) number of cross sections in the reach

d) the length of the reach (km)

e) the beginning elevation of the reach (ft)

f) the slope of the reach

g) the total surface area of the reach (km^2)

h) an identifying name for each cross section

i) the number of cells in each cross section

The parameters output from the model for each cross section at each time-step are:

a) beginning date of the time-step

b) number of days in the time-step

c) total flow (cfs)

d) phosphorus concentration (mg/l)

e) nitrogen concentration (mg/l)

f) suspended sediment concentration (mg/l)

The parameters output from the model for each cell of a cross section at each time-step are:

a) flow (cfs)

b) surface area (km^2)

c) velocity (m/s)

d) top width (m)

e) minimum depth (m) of flow in the cell

f) maximum depth (m) of flow in the cell

g) diameter (mm) of largest particles moved by the flow

h) percent of material moved by the flow

i) median diameter (mm) of material not moved by the flow

The calculations used to derive these parameters are described in the following sections.

Units 2, 3, and 10

The model reads the parameters specific to the selected reach:

a) 7-digit reach ID

b) reach name

c) number of cross sections in the reach

d) length of the reach (mi)

e) beginning elevation of the reach (ft)

f) slope of the reach

The model reads the parameters specific to each cross section of the selected reach:

a) cross section name

b) Mannings roughness coefficient

c) slope of the cross section

d) flag indicating how the Y data values were measured (Y values ascending: 1, 3.5, 5.5,...; or y values descending: 100, 95, 91,...)

e) coefficients relating flow rate to depth of flow in the cross section

f) diameter of median particle size in the cross section D_{50} (mm)

g) diameter of particles equal to the median particle size plus 1 standard deviation of the particle sizes D_{84} (mm)

h) number of XY-data pairs

i) fraction of reach represented by the cross section (0.0 to 1.0)

j) flag indicating type of X data (feet or meters)

k) flag indicating type of Y data (feet or meters)

l) X-Y data pairs

Cross-section input data, including the X-Y data pairs define the channel geometry. If necessary, the model standardizes the Y data points so that both banks are at Y=0, and adjusts the data to make sure X=0 at one of the banks. A reach may have up to 2 sets of cross section data, one for riffles and one for pools. If the Y data values are descending (i.e., 100, 95, 91...), the maximum Y value is found:

$$Y_{MAX} = MAX(Y_1,\ Y_m) \tag{11}$$

where:

Y_{MAX} = maximum Y data point for the cross section

Y_1 = Y value at the left bank (first point)

Y_m = Y value at the right bank (last point)

Y_j is adjusted as follows:

$$Y_j = Y_{MAX} - Y_j \tag{12}$$

If ($Y_j < 0$) then $Y_j = 0$. If the Y data values are ascending (i.e., 1, 3.5, 5.5,...), then the minimum Y value is found:

$$Y_{MIN} = MIN(Y_1,\ Y_m) \tag{13}$$

where:

Y_{MIN} = minimum Y data point for the cross section

Then Y_j is adjusted as follows:

$$Y_j = Y_j - Y_{MIN} \tag{14}$$

If ($Y_j < 0$) then $Y_j = 0$. The model also standardizes all of the x-data points to make sure that X=0 on one bank. For each cross section, the minimum value of X is found by:

(15) $$X_{MIN} = MIN(X_1, X_m)$$

where:

X_{MIN} = minimum X data point for the cross section

X_1 = x at left bank

X_m = x at right bank

Each X is adjusted as follows:

(16) $$X_j = X_j - X_{MIN}$$

Unit 10

Water inflow for a reach may be measured flows or flows transformed by the user. The model checks to see whether or not the current reach is a tailwater reach. If it is a tailwater reach, an outflow file from the upstream reservoir is used to assign flows and water quality concentrations. If it is not a tailwater reach, either measured flows or flows altered by the user are used for the reach.

Unit 18

Phosphorus, nitrogen and suspended sediment concentrations in non-tailwater reaches are computed using power equations for load-discharge relationships developed for USGS water quality sampling stations. When the total flow to the cross section is greater than zero, loadings to the reach are found from

(17) $$M = A_i Q^{B_i}$$

where:

M = mass load of the constituent P, N, or SS (tons/day)

Q = total flow in the cross-section (cfs)

A_i, B_i = coefficients for each reach, chemical constituent, and each season

If M is less than or equal to zero, then M = 0. If Q is equal to zero, then M = 0. Equation (17) is similar to equation (7).

The model will then convert the mass load of the water quality constituent(s) to concentration(s) as:

(18) $$W_i = \frac{M_i}{Q*0.0027}$$

where:

W_i = concentration of the constituent P, N, or SS (mg/l) and 0.0027 is a conversion factor

Unit 17

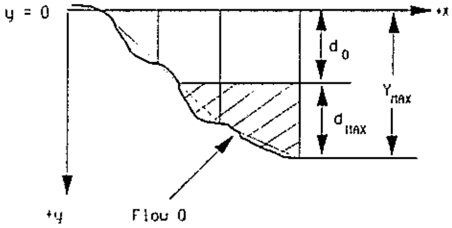

Figure 3 Partial cross section

The model also calculates the maximum depth (Y_{MAX}) in the cross section. Figure 3 represents a partial cross section that shows the maximum depth of flow in the cross section (d_{MAX}); and the height in the cross section with no-flow (d_0). In this figure some cells will have no flow in them and some cells will have a partial amount of flow. The cells with flow will be either triangular or trapezoidal in shape. The flow into the cross section is saved as Q_{orig}, and used to ensure that the total computed flow of the cross section will be within 5% of the original flow. The model repeats the following steps until the computed flow is within 5% of the original flow.

(1) Using the flow value for the cross section, the maximum depth of flow is calculated as follows:

$$(19) \qquad d_{MAX} = aQ^b$$

where:

d_{MAX} = maximum depth of flow in the cross section (ft)

a,b = coefficients relating depth of flow to flow in each cross section (**<u>unique to each cross section</u>**)

(2) The corresponding height in the cross section with no flow is:

$$(20) \qquad d_0 = Y_{MAX} - d_{MAX}$$

where:

d_0 = height in the cross section with no flow (ft)

(3) For each cell that has some flow in it, the sequential model procedures are to:

a) Calculate the maximum width of the cell:

$$(21) \qquad X = X_{i+1} - X_i$$

where:

X = absolute value of the width of cell at y=0 (ft)

X_i = beginning X data value for a cell (ft)

X_{i+1} = ending X data value for a cell (ft)

b) Determine if the cell is triangular or trapezoidal in shape. Based on the shape of the cell, determine the top width, wetted perimeter, area, and minimum and maximum depth of flow in the cell.

c) Get the diameter of the largest particles moved in the cell (critical diameter).

d) Get the percent of material moved in the cell, and the median diameter of the material not moved.

e) Calculate the hydraulic radius for the cell:

$$(22) \qquad R_C = \frac{A_C}{P_C}$$

where:

R_C = hydraulic radius for the cell (ft)

A_C = area of the flow in the cell (ft^2)

P_C = wetted perimeter of the flow in the cell (ft)

f) Calculate amount of flow in the cell:

(23) $$Q_C = 1.486\sqrt{S_R}\left(\frac{A_C}{n}\right)R_C^{\frac{2}{3}}$$

where:

Q_C = amount of flow in the cell (cfs)

S_R = slope of the reach

n = Mannings roughness coefficient for cross section

g) Sum the flow in each cell:

(24) $$Q_T = \Sigma Q_C$$

where:

Q_T = sum of flow in each cell (cfs)

g_4 = 0.3048 m/ft

h) Calculate the velocity of flow in the cell:

(25) $$V_C = \frac{Q_C g_4}{A_C}$$

where:

V_C = velocity of flow in the cell (m/s)

i) Calculate the surface area for this cell and cross section:

$$(26) \qquad A_S = \frac{L_R P_i TW_C}{1000m/km}$$

where:

A_S = surface area of cell (km^2)

TW_C = top width of cell (m)

(4) Compare the total flow of the cross section (Q_t) with the original flow (Q_{orig}). If there is more than 5% difference, adjust the flow, and return to step (1):

Given the x-width and the y-values, the model will compute the top width, wetted perimeter, area and depth of flow for a triangular cell. See Figure 4 for geometry and notation used.

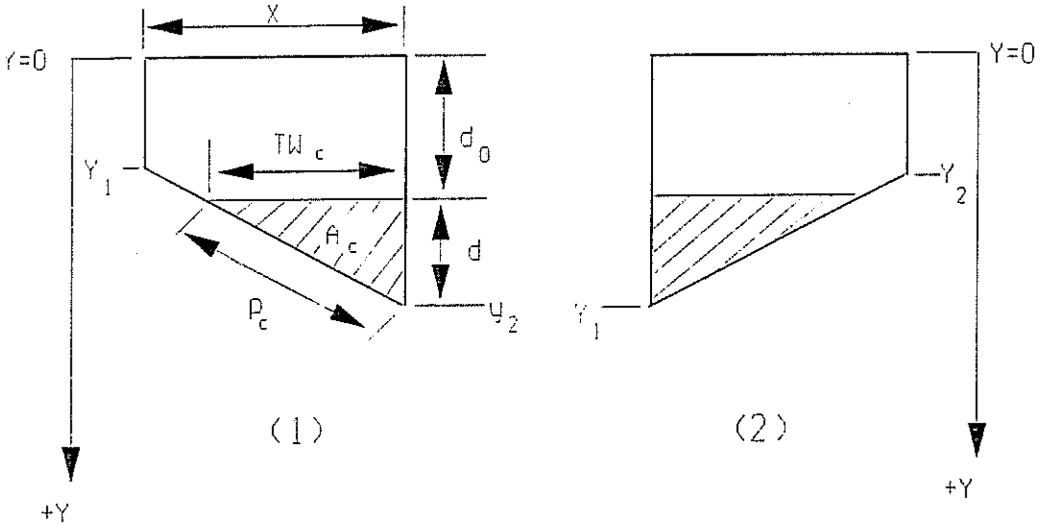

Figure 4 Triangular cell geometry

If d_0 is greater than y_1, then triangle (1) of Figure 4 is used for reference. The depth of flow in the cell is:

$$d = y_2 - d_0 \quad (27)$$

where:

d = depth of flow in the cell (ft)
y_2 = maximum y-value of cell (ft)

The inverse slope of the triangle is:

(28) $$S_T = \frac{X}{y_2 - y_1}$$

where:

S_T = inverse slope

y_1 = the minimum y-value of the cell (ft)

If d_0 is less than y_1, then the parameters shown in Figure 4, triangle (2) are used for reference. The depth of flow in this cell is:

(29) $$d = y_1 - d_0$$

where:

y_1 = the maximum y-value of the cell (ft)

The inverse slope of the triangle is:

(30) $$S_T = \frac{X}{y_1 - y_2}$$

where:

y_2 = the minimum y-value of the cell (ft)

For both triangles shown in Figure 4, the top width of the cell is:

(31) $$TW_C = dS_T g_4$$

For both triangles, the wetted perimeter of the cell is:

$$(32) \qquad P_C = d\sqrt{1 + S_T^2}$$

For both triangles, the area of the cell is:

$$(33) \qquad A_C = \frac{d^2 S_T}{2}$$

Convert the depth of flow in the cell to meters:

$$(34) \qquad d_{(m)} = d\ g_4$$

where:

d(m) = maximum depth of flow in a triangular cell (m)

Given the x-width and y-values, the model will compute the top width, wetted perimeter, area, and depths of flow for a trapezoidal cell. See Figure 4 for geometry and notation used.

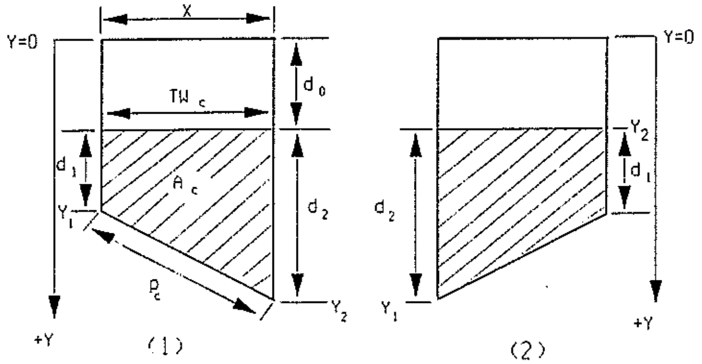

Figure 4 Trapezoidal cell geometry

The wetted perimeter of the cell is calculated as follows:

(35) $$P_C = \sqrt{(y_2 - y_1)^2 + X^2}$$

The area of the trapezoidal cell is calculated as follows:

(36) $$A_C = \frac{1}{2}(y_2 - y_1)X + (y_1 - d_0)X$$

which reduces to

(37) $$A_C = \frac{1}{2}(y_2 + y_1 - 2d_0)X$$

If y_1 is less than y_2, then use trapezoid (1) of Figure 4 for reference. The minimum depth of flow in the cell is:

(38) $$d_1 = (y_1 - d_0)\,g_4$$

where:

d_1 = minimum depth of flow in the cell (m)

The maximum depth of flow in the cell is:

(39) $$d_2 = (y_2 - d_0)\,g_4$$

where:

d_2 = maximum depth of flow in the cell (m)

If y_1 is greater than y_2, then use trapezoid (2) of Figure 4 for reference. The minimum depth of flow for this case is:

(40) $d_1 = (y_2 - d_0)\, g_4$

The maximum depth of flow for this case is:

(41) $d_2 = (y_1 - d_0)\, g_4$

The top width for both trapezoids is:

(42) $TW_C = Xg_4$

Unit 21

Given the area and top width of a cell, and the slope of the reach, the diameter of the largest material that will move can be computed. First the average depth of the cell is calculated:

(43) $d_c = \frac{A_C g_4}{TW_C}$

where:

d_c = average depth of flow in the cell (ft)

Using the average depth of flow, the shear stress is computed:

(44) $\tau_c = \gamma\, d_c S_R$

where:

τ_c = the shear stress (lb/ft^2)

γ = 62.4 lb/ft^3 (specific weight of water)

The specific gravity of the sediment is:

$$(45) \qquad \gamma_s = \gamma s_s$$

where:

γ_s = specific weight of sediment (lb/ft^3)

s_s = 2.65 (specific gravity of sediment)

The critical diameter for the material in the cell is then calculated as follows:

$$(46) \qquad D_c = \frac{\tau_c g_5}{\tau^* (\gamma_s - \gamma)}$$

which is equivalent to

$$(47) \qquad D_c = \frac{\tau_c g_5}{\tau^* \gamma (s_s - 1)}$$

where:

D_c = the diameter of the largest particles that will move (mm)

τ^* = 0.03 (dimensionless shear stress)

g_5 = 304.8 mm/ft

The model also computes the substrate value, or percent of material moved, for each cell given the diameter of the largest particles moved. The model will also calculate the median diameter of the material not moved. These computations are based on the assumption that the particle sizes are log-normally distributed, as shown in Figure 5.

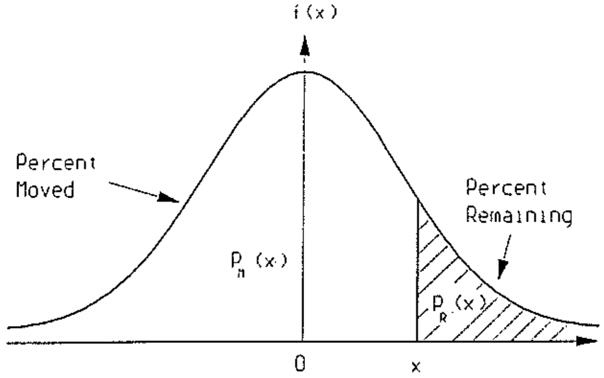

Figure 5 Normal curve for distribution of grain sizes

Units 19 through 21

Substrate Calculations

The standard deviation of the sediment diameters is computed as follows:

$$S = \log_{10}\left(\frac{D_{84}}{D_{50}}\right) \quad (48)$$

where:

S = standard deviation of sediment diameters (mm)

D_{50} = median diameter of sediment (mm)

D_{84} = particle diameter for which 84% by weight of sediment is finer (mm)

The minimum and maximum particle sizes based on the median particle size are assumed to be between 0.05 mm and 2,540 mm. A minimum particle size is calculated as follows:

(49) $$D_{MIN} = 10^{(\log_{10}(D_{50}) - 3S)}$$

where:

D_{MIN} = diameter of particles 3 standard deviations smaller than the median particle size (mm)

If D_{MIN} is less than 0.05 mm, then D_{MIN} = 0.05 mm. A maximum particle size is calculated as follows:

(50) $$D_{MAX} = 10^{(\log_{10}(D_{50}) + 3S)}$$

where:

D_{MAX} = diameter of particles 3 standard deviations larger than the median particle size (mm)

If D_{MAX} is greater than 2,540 mm, then D_{MAX} = 2,540 mm. If the diameter of the largest material that is moved is less than D_{MIN}, then no material is moving and the median diameter doesn't change:

(51) $$D_{50NEW} = D_{50}$$

If the diameter of the largest material that is moved is greater than D_{MAX}, than all of the material is moving and the median diameter is equal to the maximum diameter:

(52) $$D_{50NEW} = D_{MAX}$$

If some, but not all, of the material is moving, the number of standard deviations to the largest particles moved is computed as follows:

$$(53) \qquad X = \frac{\log_{10}(D_C) - \log_{10}(D_{50})}{S}$$

where:

X = number of standard deviations

The value on a normal curve for 'X' standard deviations is:

$$(54) \qquad f(x) = \frac{1}{\sqrt{2\pi}} e^{\frac{-x^2}{2}}$$

The area under the curve that represents the fraction of material not moved is:

$$(55) \qquad P_R(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{\frac{-t^2}{2}} dt$$

A polynomial approximation[1] is used to calculate the value of the integral in equation (55):

$$(56) \qquad t = \frac{1}{1+r|X|}$$

---

[1] Reference: Abramowitz and Stegun, *Handbook of Mathematical Functions*, National Bureau of Standards, 1970.

with:

$$M_R = f(x)\,(b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5) \tag{57}$$

where:

M_R = approximation for fraction of material remaining (0.0 to 1.0)

r = 0.2316419

b_1 = 0.319381530

b_2 = -0.356563782

b_3 = 1.781477937

b_4 = -1.821255978

b_5 = 1.330274429

To determine the fraction of material remaining, the sign of X must be checked. If X is negative, then

$$P_R(x) = 1 - M_R \tag{58}$$

otherwise

$$P_R(x) = M_R \tag{59}$$

where:

$P_R(x)$ = fraction of material remaining (0.0 to 1.0)

The substrate, or fraction of material moved is then:

$$(60) \qquad P_M(x) = 1 - P_R(x)$$

where:

$P_M(x)$ = fraction of material moved (0.0 to 1.0)

MEDIAN OF REMAINING MATERIAL CALCULATIONS

In order to calculate the median diameter of the remaining material, the area under the curve to the right of the new median needs to be computed, as shown in Figure 6.

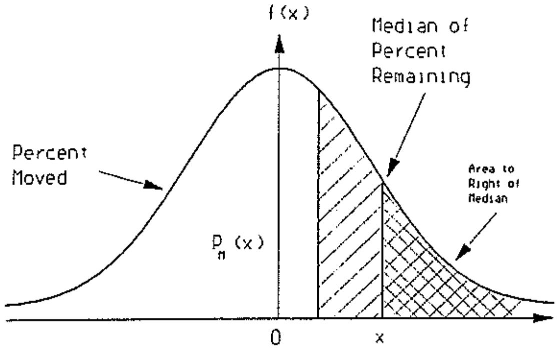

Figure 6 Median of remaining material

The area to the right of the new median is calculated as follows:

$$(61) \qquad A_R = 1 - \left(\frac{1 - P_M(x)}{2} + P_M(x) \right) = \frac{1 - P_M(x)}{2}$$

where:

A_R = area (fraction of material) to the right of the new median (0.0 to 1.0)

Once this area is known, the number of standard deviations, X, corresponding to this area may be found from the following approximation method[2]:

(62) $$t = \sqrt{\ln \frac{1}{A_R^2}}$$

with:

(63) $$X = t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}$$

where:

c_0 = 2.515517

c_1 = 0.802853

c_2 = 0.010328

d_1 = 1.432788

d_2 = 0.189269

d_3 = 0.001308

This X is then used to calculate the diameter of the material at the new median:

(64) $$D_{50NEW} = 10^{(\log_{10}(D_{50}) + XS)}$$

where:

---

[2] Reference: Abramowitz and Stegun, *Handbook of Mathematical Functions*, National Bureau of Standards, 1970.

D_{50NEW} = the diameter of the particles at the new median (mm)

Unit 22

The length of the reach is changed from miles to kilometers:

(65) $$L_R = L_0 g_2$$

where:

L_R = total length of reach (km)

L_0 = total length of reach (mi)

g_2 = 1.6093 km/mi

The total surface area of the reach is calculated:

(66) $$A_T = L_R g_3 \sum_{i=1}^{k} P_i (X_m - X_1)_i$$

where:

A_T = total surface area of the reach (km^2)

k = number of cross sections in the reach

P_i = percent of reach in ith cross section (0.0 to 1.0)

X_m = last X data point in cross section (ft)

X_1 = first X data point in cross section (ft)

g_3 = 0.0003048 km/ft

Units 23 and 24

Files are written to pass relevant information to the biology and economic models.

RESERVOIR MODEL SYMBOLS

The following symbols are used in this document for the reservoir model:

A = surface area corresponding to volume (km^2)

A_m = flow multiplier

A_t = transfer parameter

A_1 = initial estimate of surface area (acres)

A_2 = new estimate of surface area (acres)

B_t = transfer parameter

C_1 = concentration of chemical constituent in reservoir (mg/l)

D = average reservoir depth (ft)

E = pan evaporation (inches)

$f(V_c)$ = an interpolated area (acres)

K_p = pan coefficient for reservoir (=0.7)

L = mass load of chemical constituent (tons/day);
= load to reservoir of relevant chemical constituent (g/m^2)

LSS = suspended sediment entering the reservoir (tons/half month)

n = modifier to adjust the chemical concentrations to levels observed in New Mexico

P = precipitation (inches)

Q_i = channel inflow, $i=1,2,3$ (cfs)

Q_{inflow} = total inflow (acre-feet)

Q_{I1} = primary inflow 1 (cfs)

Q_m = modified discharge, desired by user (cfs)

$Q_{outflow}$ = total outflow (acre feet or m^3)

Q_s = areal water loading (m/half-month)

Q_x = index flow (cfs)

Q_0 = original measured discharge, inflow or outflow (cfs)

r = exchange rate

R = percent sediment retained in reservoir water column

T = water retention time (sec);
= retention time (half-month)

TSS = concentration of suspended sediment in reservoir

v_s = settling velocity (m/half-month)

V = settling velocity (ft/s)

V_c = computer reservoir volume (acre-feet or $10^6 m^3$)

V_{i-1} = volume at end of previous period (acre-feet)

V_1 = initial estimate at volume (acre-feet)

V_2 = new estimate of volume (acre-feet)

VOL = reservoir volume (acre-feet)

W = average particle size of sediment entering the reservoir (ft)

XL = length of reservoir (ft)

Z = hydraulic depth (m)

STREAM MODEL SYMBOLS

The following symbols are used in this document for the stream model:

a = coefficient relating depth of flow, to flow in a cross section

A_c = area of flow in a cell (ft^2)

A_i = coefficient for water quality constituent relationship

A_R = area (fraction of material) to the right of the new median (0.0 to 0.5)

A_S = surface area of flow in a cell (km^2)

A_T = total surface area of a reach (km^2)

b = coefficient relating depth of flow, to flow in a cross section

b_1 = 0.319381530

b_2 = -0.356563782

b_3 = 1.781477937

b_4 = -1.821255978

b_5 = 1.330274429

B_i = coefficient for water quality constituent relationship

c_0 = 2.515517

c_1 = 0.802853

c_2 = 0.010328

C_i = coefficient for water quality constituent relationship

d = maximum depth of flow in a triangular cell (ft)

d_c = average depth of flow in a cell (ft)

$d_{(m)}$ = maximum depth of flow in a triangular cell (m)

d_{MAX} = maximum depth of flow in the cross section (ft)

d_0 = height in cross section with no flow (ft)

d_1 = 1.432788;
= minimum depth of flow in a trapezoidal cell (m)

d_2 = 0.189269;
= maximum depth of flow in a trapezoidal cell (m)

d_3 = 0.001308

D_C = diameter of largest particles in a cell that will move (mm)

D_i = coefficient for water quality constituent relationship

D_{MAX} = maximum particle diameter (mm)

D_{MIN} = minimum particle diameter (mm)

D_{50} = median diameter of sediment particles in the cross section (mm)

D_{84} = diameter of particles in the cross section for which 84% by weight of sediment is smaller (mm)

D_{50NEW} = median diameter of particles not moved by the flow in a cell (mm)

g_1 = 0.0027 (mg/l) (ft^3/sec) / (tons/day)

g_2 = 1.6093 km/mi

g_3 = 0.0003048 km/ft

g_4 = 0.3048 m/ft

g_5 = 304.8 mm/ft

L_R = total length of the reach (km)

L_0 = total length of the reach (mi)

m = number of XY-data pairs

M_i = mass load of water quality constituent concentrations in the cross section (tons/day)

M_R = approximation for fraction of material not moved by the flow in the cell (0.0 to 1.0)

n = number of cells in the cross section;
= Mannings roughness coefficient for the cross section

P_C = wetted perimeter of a cell (ft)

P_i = fraction of reach in the cross section (0.0 to 1.0)

$P_M(x)$ = fraction of material moved by flow in the cell (0.0 to 1.0)

$P_R(x)$ = fraction of material not moved by flow in the cell (0.0 to 1.0)

Q = total flow in the cross section (cfs)

Q_C = amount of flow in a cell (cfs)

r = 0.2316419

R_C = hydraulic radius of a cell (ft)

s_s = 2.65 (specific gravity of sediment)

S = standard deviation of sediment particle diameters (mm)

S_R = slope of the reach

S_T = inverse slope of the bottom of a triangular cell

TW_C = top width of flow in a cell (m)

V_C = velocity of flow in a cell (m/s)

W_i = concentration of water quality constituents in the cross section (mg/l)

X = number of standard deviations to largest particles moved by the flow in a cell;
= maximum width of a cell (at Y=0) (ft)

X_{ADD} = additional X-distance when extrapolating to right or left bank

X_i = beginning X-data value of a cell (ft)

X_{i+1} = last X-data value of a cell (ft)

X_j = each X-data point from j=1,m

$X_{j(FT)}$ = each X-data point from j=1,m (ft)

X_m = last X-data point of a cross section

X_1 = first X-data point of a cross section

y_1 = minimum Y-value of a cell (ft);
= maximum Y-value of a cell (ft)

y_2 = maximum Y-value of a cell (ft);
= minimum Y-value of a cell (ft)

Y_j = each Y-data point from j=1,m

Y_{MAX} = maximum Y-data point for the cross section (ft)

Y_{MIN} = minimum Y-data point for the cross section (ft)

γ = 62.4 lb/ft^3 (specific weight of water)

γ_S = specific weight of sediment (lb/ft^3)

τ_C = shear stress for a cell (lb/ft^2)

τ^* = dimensionless shear stress

SYNTHETIC FLOW FILES

In order to create synthetic flow files for use in the RIOFISH model, flow values at key gaging stations were analyzed and statistically divided into seven (7) flow regimes of: 1) extremely dry, 2) very dry, 3) dry, 4) average, 5) wet, 6) very wet and 7) extremely wet. Once a flow was assigned to one of the seven regimes, the years associated with the flow also were assigned to that regime. This grouping allowed selection of specific years corresponding to each regime at each key gaging station. This document describes the method used to divide the flows (and years) into the regimes.

Statistical Analysis

A large amount of data was manipulated to do the flow regime groupings. The flows were assumed to follow either a normal or a log-normal distribution. The minimum, maximum, sample standard deviation, and sample mean of the untransformed and the $\log_{10}$ values were determined. These values were used to set the intervals for each flow regime. Based on a normal distribution, the flows were divided by the following percentages: 1) the lowest 5% were assigned to extremely dry, 2) the next highest 10% were assigned to very dry, 3) the next highest 20% were assigned to dry, 4) the next highest 30% were assigned to average, 5) the next highest 20% were assigned to wet, 6) the next highest 10% were assigned to very wet and, finally, 7) the very highest 5% were assigned to extremely wet. Listed below are the calculations used to determine the ranges of each interval. The upper and lower range values were computed from the flows as:

Flow Regime	**Lower Range**	**Upper Range**
Extremely Dry	Minimum of flow	X - 1.645 S
Very Dry	X - 1.645 S	X - 1.0365 S
Dry	X - 1.0365 S	X - 0.385 S
Average	X - 0.3854 S	X + 0.3854 S
Wet	X + 0.3854 S	X + 1.0365 S
Very Wet	X + 1.036 S	X + 1.64 S
Extremely Wet	X + 1.645 S	Maximum of flows

where
X = mean value of the untransformed or $\log_{10}$ of the flows
S = sample standard deviation of the untransformed or $\log_{10}$ of the flows.

In order to determine which years corresponded to the flow values in each regime, the flow values were sorted in ascending order, along with their corresponding years. With the sorted values the years were picked out for each regime. The sorted and grouped lists of years were examined. Because of the long record that now exists in the RIOFISH model, those years for water years 1975 through 1992 which were found to be in a flow regime were selected as potential "synthetic" years. By making a selection from the existing record, no additional discharges or reservoir volumes needed to be computed. In previous generations of synthetic flows, considerable effort was spent creating values from a composite of regime years then "routing" the water through the stream-reservoir system. Such an approach added little to the primary purpose of the role for synthetic flows: to simulate extreme conditions.

Discharge records for five key discharge sites were examined. These stations are listed in Table XX along with their corresponding "synthetic" regime water years as selected during the screening process.

Table A3. Water Years Selected to Represent Synthetic Flow Regime

Regime	Rio Grande Embudo, NM	Pecos River Pecos, NM	San Juan River Carracas, CO	Canadian River Sanchez, NM	Gila River Gila, NM
Extremely dry	77	81	77	78	*
Very Wet	92	81	81	75	*
Dry	89	89	88	89	77
Average	91	84	84	86	82
Wet	83	82	75	79	86
Very Wet	79	86	86	85	83
Extremely Wet	87	85	85	87	79
** Mixture of records					

These five stations were selected because they closely represented the response of their entire river basin. Some modifications were made in the selection as evidenced by the years selected. The extremely dry and very dry regimes are both represented by 1981 in the Pecos River basin. This was done because a better choice of 1977 did not include records for Santa Rosa Reservoir (completed post 1977). Another problem was a lack of base data years in the extremely and very dry regimes for the Gila River basin. In that case, stream flows from 1971 and 1974 were used for the two lowest regimes, respectively, but 1977 was used for the small lakes in the basin.

Some interesting aspects of the across basin comparison is that in general, the regime years are very consistent among the stations. The dry year of 1989 was consistent as were the very and extremely wet years of 1985 and 1987. The Gila River station was the most different from the others.

Once the years were selected then the non-reservoir related stream flows were ordered from extremely dry to extremely wet. The reservoir files were also ordered, but were then adjusted. At the beginning of each water year, a base value was used to compute a base set of synthetic values using the hydrology component of RIOFISH. The base values ranged form zero acre-feet at Grindstone Reservoir to 1.2 million acre feet at Navajo Reservoir. Depending on the inflow and outflow records of the representative "synthetic" year, the final (24 steps later) value could be more, less or about the same. The important aspect of the records, however is the magnitude and timing of inflows and outflows which do vary between regimes. If the model user wishes to explore other changes to the regime, the flows can be modified by the additive (subtractive) constants and multiplier value.

BIOLOGICAL COMPONENT MATHEMATICS

PHYSICAL CHEMICAL FACTORS

Light transmission (units 8-10)

Transmission of light through the water column depends on light extinction rate, which is determined by suspended solids concentration. Water depth for any percentage transmission is independent of total irradiation at the surface and decreases exponentially as suspended solids increase. The equation:

$$D_1 = b_{depth,0} e^{b_{depth,1} S}$$

represents depth (m) at one percent transmission. S is the concentration of suspended solids.

Air temperature (units 1-2)

Mean air temperature (T_a) for any given day is expressed by the equation:

$$T_a = b_{airt,0} + b_{airt,1} \cos\left[\frac{2\pi}{365}(D-200)\right] + b_{airt,2} E,$$

where D is julian day and E is elevation. This equation assumes that the hottest mean daily temperature is always julian day 200

(19 July or, for leap years, 18 July). The parameters were found by regression on selected sites in New Mexico.

Lake Illumination (units 8-10)

The littoral zone of a reservoir is defined as the portion of the water body that receives at least one percent of the surface light at its bottom. From depth at 1% light transmission described above, elevation at 1% transmission is found. Lake area-capacity tables are used to find the littoral area. This value (I_{bot}) is expressed as a percentage of the total surface area of the lake. Area-capacity tables are also used to determine the percentage lake volume that is illuminated (I_{vol}).

Reservoir thermal profile and oxygen concentration (units 1-3)

The thermal profile of a lake consists of a variable number of strata, say N_{strata}. Each of the strata has an associated volume, temperature, and oxygen concentration (V_i, T_i, O_i). The first stratum is the top-most, or only, layer representing the epilimnion, and the last stratum is the bottom-most layer or hypolimnion. Any strata in between represent the expansion of the previous time step's epilimnion due to reservoir drawdown. The algorithm that produces the profile has four steps: 1) addition of reservoir inflows, 2)subtraction of outflows, 3)creation of a theoretic epilimnion, and 4)checking if this epilimnion can be established.

Modifications begin with the previous time step's profile. The initial time step profile (last half of september) is assumed to be completely mixed having one stratum with temperature equal to the mean daily air temperature for that period and oxygen concentration at 100% relative saturation.

Inflows are added to the stratum that is closest in temperature to the inflow temperature. For this version of the model, T_{in} is assumed to be at air temperature and O_{in} is assumed to be at 100% relative saturation.

Outflow (V_{out}) is subtracted from the bottom stratum. If the outflow volume is greater than the volume of the bottom stratum, the number of strata is reduced by one and the excess of the outgoing volume is subtracted from the new last stratum. If the outflow volume is still greater than the sum of the two strata, the process is repeated until all of the outflow volume is accounted for. Temperature and oxygen concentration of the outflow is an average of the strata removed weighted by the volume contributed by each stratum to the outflow.

Epilimnetic depth is estimated as the fourth root of reservoir fetch in <u>meters</u>. The volume of this epilimnion is estimated using the area-capacity tables of the reservoir. The profile is adjusted so that the theoretical epilimnetic volume is the first stratum and all strata below that are left intact. Epilimnetic temperature is assumed to be the same as mean time step air temperature or 4 degrees centigrade, whichever is warmer.

Similarly, oxygen concentration of the estimated epilimnion is at 100% relative saturation.

Oxygen concentration at 100% relative saturation is based on water surface elevation and water temperature by the equation:

$$O_{sat}=e^{b_{osat,0}+b_{osat,1}T+b_{osat,2}T^2+b_{osat,3}T^3+b_{osat,4}E},$$

where T is temperature and E is elevation. This equation was obtained by (log) regression using published tables of oxygen concentrations at different elevations and temperature.

The final step in the process is to compare the epilimnetic temperature with the temperature of the stratum immediately below that. A file is checked to determine if the epilimnetic stratum is warm enough to stratify. If it is, the process is finished. If not, the first two strata are combined into one. Temperature and oxygen concentration of the new first stratum is an average of the two old strata weighted by volume. This process is repeated downward among the strata until a temperature difference large enough to warrant stratification is encountered or until there is only one stratum in the entire profile (the entire water column is uniformly mixed).

The above algorithm results in a temperature profile for the reservoir and outflow. Oxygen concentration is reduced by the oxygen demand model described below.

Stream Illumination (units 26-28)

This component depends on the hydrology component to provide a description of the geometry and hydraulics of the reach through semi-monthly time steps. These variables are described in the hydrology component section. In addition, this component requires inputs of mean seasonal solar radiation, mean seasonal riparian loading into channel, and percent channel area influenced by riparian loading.

Additional calculations are made to estimate the fraction of bottom illuminated (I_{bot}), which is computed by comparing the depth of one percent light transmission (D_1) with the depth of each cell in the reach. The geometry of each cell has two depths associated with it (say $Y_{max,k,j}$ for the greater depth and $Y_{min,k,j}$ for the lesser depth). If D_1 is less than $Y_{min,k,j}$, none of the bottom is illuminated, if D_1 is greater than $Y_{max,k,j}$ the entire cell is illuminated. Otherwise a fraction of the cell is illuminated. I_{bot} is found using the following algorithm:

Define:

$$F^*_{k,j} = \begin{cases} 0 & \text{if } Y_{\min,k,j} > D_1 \\ \dfrac{Y_{\max,k,j} - D_1}{Y_{\max,k,j} - Y_{\min,k,j}} & \text{if } Y_{\min,k,j} < D_1 < Y_{\max,k,j} \\ 1 & \text{Otherwise} \end{cases}$$

Then:

$$I_{bot} = \frac{\sum_{j=1}^{N_{sct}} \sum_{k=1}^{N_{cell,j}} F^*_{k,j} A_{k,j}}{A_{..}} .$$

Percent volume illuminated is similarly computed. Water volume in a cell is average depth multiplied by the surface area of the cell. Average depth for the entire cell is the average of the maximum and minimum depth. Average depth that is illuminated is the depth of one percent light transmission if none of the bottom is illuminated, the average depth of the cell if the entire bottom is illuminated, the average of D_1 and $Y_{\min,k,j}$ if a fraction of the cell is illuminated. This is described by the following algorithm:

$$Y^*_{\min,k,j} = \min[D_1, Y_{\min,k,j}]$$
$$Y^*_{\max,k,j} = \min[D_1, Y_{\max,k,j}]$$

$$I_{vol} = \frac{\sum_{j=1}^{N_{sct}} \sum_{k=1}^{N_{cell,j}} \frac{Y^*_{\min,k,j} + Y^*_{\max,k,j}}{2} A_{k,j}}{\sum_{j=1}^{N_{sct}} \sum_{k=1}^{N_{cell,j}} \frac{Y_{\min,k,j} + Y_{\max,k,j}}{2} A_{k,j}} .$$

Stream Temperature (units 19-20)

Average water temperature ($T_{k,j}$) is computed for each cell k within a section j. Change in water temperature through time asymptotically approaches ambient air temperature. The instantaneous rate is proportional to the length of the stream stretch and inversely proportional to stream velocity. Initial water temperature (T_0) is constant for each cell within a section and is computed by the reservoir model if the reach is a tailwater, otherwise it is ambient air temperature at the beginning elevation of the reach. Average water temperature (°C) for each stream cell k within a section j is computed using the equation:

$$T_{k,j}=T_a-(T_a-T_0)\,e^{\frac{-0.1098L}{2V_{k,j}}},$$

where L is the length (Km) of the stream segment and $V_{k,j}$ is the velocity (m/sec) of each cell within a section. T_{amb} is ambient air temperature (°C) at average elevation of the stream segment. T_{ambl} depends on the average julian day for the time-step in question and the average elevation of the reach which is E_0-3280SL/2 where E_0 is beginning elevation of the reach, S is average slope of reach, and 3280L/2 is the average length of the reach in feet.

Stream Oxygen Concentration (units 19-21)

Oxygen concentration ($O_{k,j}$) is computed similarly to water temperature. Initial oxygen concentration (O_0) is provided by the reservoir model for tailwaters and is otherwise at 100% relative saturation. Average oxygen concentration (mg/liter) for each cell k within a section j during period t is:

$$O_{k,j}=O_{sat}-(O_{sat}-O_0)\,e^{\frac{-0.1386L}{2V_{k,j}}},$$

where L and $V_{k,j}$ are described above. O_{sat} is relative oxygen saturation at the average elevation of the reach. This depends on the water temperature computed above and the average elevation described above.

PRIMARY PRODUCTION AND OXYGEN DEMAND

Lake primary productivity (units 11-12)

The rate of primary production is the product of solar radiation on the water and photosynthetic efficiency. Actual photosynthetic efficiency (E_1) is thought to be a maximum efficiency (E_m) under optimum conditions which is reduced as several factors vary from optimum: water temperature (E_t), nutrient availability (E_n), suspended solids (E_s), and lake volume flushing rate (E_x). These factors operate independently to reduce the maximum efficiency by a given fraction. The equations for each factor are:

$$E_t = b_{t,0} + b_{t,1} T_1$$

where T_1 is temperature (°C) of the epilimnion and E_t is restricted to be between 0 and 1;

$$E_s = \begin{cases} b_{s,0} S^{-b_{s,1}} & if\ S>0 \\ 1.0 & otherwise \end{cases},$$

where S is average concentration (mg/liter) of suspended solids;

$$E_n = 1 - e^{-b_{n,1} N},$$

where N is the limiting nutrient concentration (mg/liter) -- the lowest of two possible values, [P] and [N]/10.0, and [P] and [N] are average total phosphorus (mg/liter) and total nitrogen (mg/liter);

$$E_x = e^{b_{x,1} e^{b_{x,2} X}},$$

where X is the flushing rate of the basin expressed in days. Photosynthetic efficiency (E_1) is the product of maximum efficiency and the above equations or:

$$E_1 = E_m E_t E_s E_n E_X .$$

Primary productivity is expressed as:

$$P_1 = L_0 E_1 b_{pconv},$$

where P_1 is primary productivity in dry weight per unit area, L_o is average light intensity per unit area at the water surface and b_{pconv} is a conversion coefficient from energy to weight.

Lake allochthonous organic matter (units 13-15)

The hydrology component calculates a total volume of water that enters the reservoir at a certain time from three sources. Generally, the first two sources are river inputs and, by convention, the last source is watershed inputs. If there is only one river input, the second source is always zero. Each source has an associated seasonal mean concentration of organic matter. The total mass of new allochthonous organic matter that enters the reservoir is the sum of each volume of water entering the reservoir multiplied by the proper mean concentration of carbon for that source.

New allochthonous organic matter entering the reservoir is aged 750 degree-days (°C) before it is available for consumption. When it has aged this amount it is added to the stored carbon available for consumption. Available allochthonous carbon that enters the food chain is a fraction of this stored organic matter, which increases with temperature. The total mass entering the food chain is divided by the lake surface area and length of time step to obtain a loading per surface area per time. Allochthonous loading for a time step (P_a) is computed as:

$$P_a = \frac{C_{avail} b_{clag,0} e^{b_{clag,a} T_1}}{A \Delta t},$$

where C_{avail} is the total mass of carbon available for consumption, T_1 is the temperature of the epilimnion, and Δt is the length of the time step (days).

Total Organic Load (unit 16)

Total primary production (P_T) is the sum of primary and allochthonous production or:

$$P_T = P_1 + P_a.$$

Reservoir oxygen depletion (units 16-18)

For each stratum below the epilimnion in the reservoir profile, a daily oxygen demand is computed as a function of total organic loading and temperature in each of the strata. The maximum rate of depletion in the i'th stratum is:

$$V_{max}=P_T b_{oxy,0} 2^{\frac{T_i-10}{10}-1}.$$

Daily oxygen depletion follows a Michaelis-Menton type of equation,

$$O_{i,d}=O_{i,d-1}-\frac{V_{max}O_{i,d-1}}{O_{i,d-1}+0.75},$$

which is repeated for each day in the time step. The final value is the oxygen concentration of the i'th stratum for the period in question.

Oxygen concentration of the outflow is calculated similarly except the depletion is done for half as many days.

Stream Primary Production (units 32-35)

The rate of plant growth is the product of solar irradiation (Unit 45) on the basin and photosynthetic efficiency. Actual photosynthetic efficiency (E_1) is assumed to be a maximum efficiency (E_m) reduced by several factors: temperature (E_t), nutrient availability (E_n), suspended solids (E_s), particle size (E_p), and riparian shading (E_r). These factors operate independently to reduce the maximum efficiency by a given fraction. The equations for each factor are:

$$E_t = b_{t,0} + b_{t,1} T_1,$$

where T_1 is temperature of the epilimnion in degrees centigrade and E_t is restricted to be between 0 and 1;

$$E_s = \begin{cases} b_{s,0} S^{-b_{s,1}} & \text{if } S > 0 \\ 1.0 & \text{otherwise,} \end{cases}$$

where S is average concentration of suspended solids (mg/liter);

$$E_n = 1 - e^{-b_{n,1} N},$$

where N is the limiting nutrient concentration(mg/liter) -- the lowest of two possible values, [P] and [N]/10.0, and [P] is average total phosphorus (mg/liter), and [N] is average total nitrogen concentration (mg/liter);

$$E_p = 0.05 + 0.25\log_{10}(D_{50new,k,j,t}),$$

where $D_{50new,k,j,t}$ is geometric mean of the substrate particle size in millimeters;

$$E_r = \begin{cases} 1 & if A_{rip} < A_{dry,t} \\ 1 - \dfrac{A_{rip} - A_{dry,t}}{A_{..,t}} & if A_{rip} > A_{dry,t}, \end{cases}$$

where A_{rip} is the area of riparian cover, $A_{dry,t}$ is the area of the dry portion of the channel, and $A_{..,t}$ is the area of the wet part of the channel. This last multiplier only operates during the spring and summer to simulate leaf cover. Photosynthetic efficiency (E_1) is the product of maximum efficiency and the above equations or:

$$E_1 = E_m E_t E_s E_n E_p E_r.$$

Primary productivity is expressed as:

$$P_1 = L_0 E_1 b_{pconv},$$

where P_1 is primary productivity in g C/m^2 /day, L_o is average light intensity in Kcals/m^2 /day at the water surface and b_{pconv} is a conversion coefficient from energy to weight.

Stream allochthonous organic loading (units 34-37)

Allochthonous organic matter enters the stream or stream channel in the form of leaf litter. New litter either falls on the dry part of the channel and is partly stored until a later time or immediately enters the food chain by falling directly on the wetted part of the channel. Stored litter can be washed in the water channel if stream water level rises.

Total mass of carbon falling into the channel is expressed as the product of the respective area and the areal rate of litter loading and the length of the time period. The fraction of the total riparian load that falls directly on the wet portion of the channel is approximated by the fraction of the channel that is occupied by water. The rest of the total load is stored in the dry part of the channel. These two amounts are expressed as:

$$P_{drip}=\left(1-\frac{A_{wet}}{A_{chan}}\right)A_{rip}P_{rip}\Delta t$$

$$P_{wrip}=\frac{A_{wet}}{A_{chan}}A_{rip}P_{rip}\Delta t$$

for the mass of carbon falling on the dry and wet part of the channel respectively. The user supplied parameter P_{rip} is the amount of carbon (g C/m^2/day) falling into the channel and Δt is the length of the time step.

If water levels rise, allocthonous carbon load will increase due to previous carbon storage being washed into the water. The newly inundated area is calculated by the expression:

$$A_{wash,t}=A_{drip,t-1}-A_{drip,t}$$

if water levels have risen between the two time steps. The time subscript is included because these equations depend on the previous time step. Storage is assumed to be uniformly distributed over the dry part of the channel; thus the amount of carbon washed in the channel from previous storage is

$$P_{rwash,t}=A_{wash}*\frac{P_{stor,t-1}}{A_{dry}}$$

where $P_{stor,t-1}$ is the amount of allocthonous carbon in storage during the previous time step.

Allochthonous carbon load is the sum of the newly entered carbon that enters the food chain and the previously stored carbon that is washed into the wet part of the channel. Stored carbon is 75% of the previously stored carbon, less the amount washed into the channel, plus the amount of newly fallen litter that did not enter the wet part of the channel.

MAXIMUM POPULATION PRODUCTION

Initial Population Structure (units 59-64)

Initial population structure is provided for each model site. The population component is a cohort-based model that tracks total numbers ($N_{s,x,t}$) and total weight ($B_{s,x,t}$) of each cohort that occurs in a water body at the end of time-step t. Each cohort is indexed by species (s) and age class (x). The age scheme follows the convention that each individual's birthday is the first of the calendar year. Age zero animals ($N_{s,0,t}$) older than larvae are referred to as juveniles. Some processes operate differently for age zero animals than for the age one and older animals. Age one or older cohorts are sometimes referred to as adults in this description (especially subscripts); they may or may not be capable of reproduction. In addition to the matrix of cohorts, two temporary vectors ($N_{s,yos}$ and $B_{s,yos}$) contain the numbers and biomass of individuals born during the time step and are referred to as larva. Any individual cohort or larval group is referred to generically as a population cell.

Maximum production (units 58-64;66-68)

The maximum growth rate of each population cell is the potential that would occur when conditions are optimum. That growth is reduced by several environmental factors as they vary from optimum. Growth rates under optimum conditions for juveniles and larval fish are P/B ratios. For age 1 and older fish P/B ratios decrease as the mean individual weight of the age class increases. The equations:

$$
\begin{aligned}
G_{opt,s,yos,t} &= \Delta t b_{yospb,s} B_{s,yos,t-1} \\
G_{opt,s,0,t} &= \Delta t b_{juvpb,s} B_{s,0,t-1} \\
G_{opt,s,x,t} &= \Delta t b_{ptob,0} e^{-b_{ptob,1} W_{s,x,t-1}} B_{s,x,t-1} \quad \mathit{for\ all}\ x>0
\end{aligned}
$$

define production for the existing biomass in each population cell when environmental conditions are optimal. Growth is expressed as total biomass gain for the time step in question. The value $W_{s,x,t-1}$ is the mean weight of the age class in the previous time step ($B_{s,x,t-1}/N_{s,x,t-1}$) and Δt is the length of the step.

This maximum P/B is reduced as seven physical factors vary from optimum in a manner similar to instream flow methodology. The algorithm used to compute the reduction follows the basic equation:

$$G_{\max} = G_{opt} \prod_i \mathrm{F}(x_i; x_{i,95}, x_{i,05})$$

where G_{opt} is maximum P/B ratio under optimal conditions defined above and $F(x_i; x_{95}, x_{05})$ are the responses to each environmental factor. Each response is a fraction between 0 and 1. The motivation behind this formulation is similar to instream flow models. Instream flow models replace G_{opt} with habitat area.

The seven environmental factors that reduce the optimum P/B ratio are 1) fraction of bottom illuminated, 2) fraction of water volume illuminated, 3) temperature, 4) oxygen, 5) velocity, 6) depth and 7) particle size. The function used is the logistic equation with two parameters, x_{95} and x_{05} which represent the values of the environmental variable that produce a value of 95% and 5% of the optimum P/B, respectively. This function is always decreasing if x_{95} is smaller than x_{05} and always increasing if x_{95} is larger than x_{05}. The temperature response is unimodal, which requires the above function to be applied twice, once for the left side and once for the right side of the mode.

The logistic equation with this parameterization is

$$y=\frac{2.9444(2x-x_{95}-x_{05})}{x_{95}-x_{05}}$$

$$F(x;x_{95},x_{05})=\frac{e^{y}}{1+e^{y}}$$

where 2.9444 is approximately the log of 0.95 divided by 0.05 (ln(19)). An example set of curves is shown in Figure 16 of the main report.

The parameters needed are the values of each specific variable that result in a maximum P/B of 95% and 5% of its optimal value. These are constant for larval and juvenile fish and vary by length for age 1 and older animals. Define these as $b_{pbfct,s,l,i,j}$ where s is the population index, l describes which population class it is (1-- larvae, 2-- juveniles, 3-- adult intercept, 4-- adult slope), i is the habitat factor (1-- fraction bottom illuminated, 2-- volume illuminated, 3-increasing part of temperature, 4--decreasing part of temperature, 5--oxygen concentration, 6--velocity, 7--depth, 8--particle size), and j is the subscript denoting which value of the response curve (5%, 95%). The environmental variables vary within a season by the hydrology time step (semi-monthly), and cells within a cross section. Maximum P/B for the period is the average of equation 1 applied across all portions of the water body and hydrology time-steps within a season weighted by the volume of each water body cell and the length of the time step. In the stream segment a water body cell is the cell k within a section j, the lake segment uses the temperature oxygen profile for the cells.

RIOFISH performs the following algorithm:

$$\mathit{define}:$$

$$\begin{aligned}
&x_{1,j,k,t}=I_{bottom,t},\\
&x_{2,j,k,t}=I_{volume,t},\\
&x_{3,j,k,t}=T_{j,k,t},\\
&x_{4,j,k,t}=T_{j,k,t},\\
&x_{5,j,k,t}=O_{j,k,t},\\
&x_{6,j,k,t}=V_{j,k,t},\\
&x_{7,j,k,t}=D_{j,k,t},\\
&x_{8,j,k,t}=S_{j,k,t},
\end{aligned}$$

$$x_{i,.95}=\begin{cases} b_{pbfcts,s,1,i,.95} & \mathit{if\ larval}\\ b_{pbfcts,s,2,i,.95} & \mathit{if\ juvenile}\\ b_{pbfcts,s,3,i,.95}+b_{pbfcts,s,4,i,.95}L_{s,x} & \mathit{if\ adult}\end{cases}$$

$$x_{i,.05}=\begin{cases} b_{pbfcts,s,1,i,.05} & \mathit{if\ larval}\\ b_{pbfcts,s,2,i,.05} & \mathit{if\ juvenile}\\ b_{pbfcts,s,3,i,.05}+b_{pbfcts,s,4,i,.05}L_{s,x} & \mathit{if\ adult}\end{cases}$$

$$\mathit{then}$$

$$G_{\max,s,x}=\frac{G_{opt}\sum_{t=1}^{n_{npds}}\left[\sum_{j=1}^{n_{sct}}\sum_{k=1}^{n_{cell,j}}\prod_{i=1}^{8}\mathrm{F}\left(X_{i,j,k,t};x_{i,.95},x_{i,.05}\right)V_{j,k,t}\right]\Delta t}{\sum_{t=1}^{6}V_{.\,.,t}\Delta t}$$

to compute maximum production. $W_{s,x}$ is the mean weight of species s and age x, $L_{s,x}$ is the respective length, $V_{.\,.,t}$ is the total volume of the water body and $N_{days,t}$ is the length of the period. The values $x_{i,j,k,t}$ conveniently express the list of habitat factors and are defined in the algorithm.

SECONDARY PRODUCTION

Herbivore Trophic Efficiency (units 16,18,42)

Primary consumer efficiency (E_2) is a function of total carbon loading, epilimnetic temperature, fraction of water column oxygenated, and fraction of water occupied by macrophytes. The equation representing this efficiency is:

$$E_2=F_{OX}(1-f_{macro})\, e^{b_{eff,0}+b_{eff,1}T_1+b_{eff,2}T_1^2+b_{eff,3}P_T}$$

where T_1 is the average temperature of the epilimnion, P_T is total organic load, f_{macro} is the fraction of water volume occupied by macrophytes, and F_{ox} is the fraction (by volume) of the reservoir with oxygen concentration above 1.5 mg/l.

Lake Primary Consumption (units 43-49)

Productivity of the primary consumers is partitioned into four guilds cross classified as suspension feeders vs. deposit feeders and vertebrate vs. invertebrate species. The term "vertebrate" is somewhat of a misnomer because it contains crayfish. It truly represents those populations as well as all true fish populations. The fraction of productivity that are suspension feeders (F_{susp}) is

$$F_{susp}=0.95-e^{-b_{susp}D_{bar}}$$

where D_{bar} is the mean lake depth. The fraction productivity of suspension feeders that are vertebrates is

$$F_{shad}=0.9\left(1-e^{\frac{-b_{shad}P_T}{D_{bar}}}\right)$$

In this equation P_T/D_{bar} expresses total organic loading (primary production plus assimilated allochthonous organic carbon) volumetrically. The fraction of deposit feeders that are vertebrate (F_{carp}) is defined as a constant 0.9.

Using these values, potential productivity of each of the four primary consumer guilds is:

$$\begin{aligned}
P_{shad} &= P_T E_2 F_{susp} F_{shad}\\
P_{zoopl} &= P_T E_2 F_{susp}(1-F_{shad})\\
P_{carp} &= P_T E_2 (1-F_{susp}) F_{carp}\\
P_{ben} &= P_T E_2 (1-F_{susp})(1-F_{carp})
\end{aligned}$$

where $P_{shad}, P_{zoopl}, P_{carp}, P_{ben}$ are production of vertebrate suspension feeders, invertebrate suspension feeders, vertebrate deposit feeders, and invertebrate deposit feeders respectively.

For New Mexico waters, the vertebrate suspension feeding category is thought to represent the productivity of all Gizzard and Threadfin Shad. Using the function for determining maximum production of a population described in the section above, the maximum productivity of both species is known. If P_{shad} exceeds this maximum, the productivities are adjusted so that P_{shad} is at the maximum and P_{zoopl} receives the excess.

Similarly, P_{carp} is compared to the maximum population production of carp and suckers and crayfish. P_{carp} and P_{ben} are adjusted so that the vertebrate bottom feeding category does not exceed the maximum population production

Stream primary consumption (units 43-49)

Model stream primary consumption is similar to the reservoir component except that the fraction of production that suspension feeders obtain is defined as 0 (F_{susp}=0). Allochthonous zooplankton is present in tailwaters due to upstream reservoir outflow.

Zooplankter biomass that is in reservoir outflow is based on the productivity (by volume) of zooplankton occurring in the upstream reservoir divided by a P:B ratio that depends on the same productivity as defined by the equation:

$$B_{zoopl}=\frac{P_{lakez}}{0.15-0.83*P_{lakez}}$$

The numerator is lake productivity (primary production plus assimilable allocthonous carbon) and the denominator represents zooplankton P/B ratio.

Production of allocthonous zooplankton in tailwaters is the multiplication of the concentration of zooplankton in the inflow and the total volume of inflow.

Invertivore Trophic Efficiency (units 46,48,50-56)

Zooplanktivore and benthivore guilds have an efficiency of 40%. This potential only results when maximum production (G_{max}) meets or exceeds this efficiency. Potential productivity (P_{zvore} and P_{bvore}) is the product of this ecological efficiency and the productivity of their respective feeding category:

$$P_{zvore}=.40P_{zoopl}$$
$$P_{bvore}=.40P_{ben}$$

Piscivore Trophic Efficiency and Production

The source of piscivore productivity is the productivity of the four other vertebrate guilds. As with the invertivore guilds, ecological efficiency is 40% between piscivore and invertivore guilds. The pathway between primary vertebrate consumers and piscivores is modified based on vertebrate primary consumer productivity. This modification expressed as a fraction reduction in efficiency and is computed using the equation:

$$F_{fish}=1-b_{fish,0}(P_{shad}+P_{carp})$$

Piscivore production is based on the realized production of the lower trophic levels rather than system production. This value is computed in the section labelled "Realized growth."

All of the productivities described above (except for stream zooplankton import) are expressed initially as a daily rate per unit area. These values are multiplied by the number of days in the period and the surface area to obtain total production.

CATCH-HARVEST AND TOTAL MORTALITY

Overview

This component simulates a catch, harvest or release fishery. It computes angler success and total mortality. During a time step, anglers apply a certain effort to the fish population. Anglers catch fish at a certain instantaneous rate. A certain fraction of the caught fish are kept or harvested by the anglers and the rest are returned to the fishery. Of those returned, a certain number die because of hooking mortality. These two forms of fishing mortality are identified as harvest mortality and hooking mortality, respectively. Fish additionally die from natural mortality, which is defined functionally as all other forms of mortality not attributable to harvest mortality and hooking mortality (i.e., predation, senility, reproductive stress, disease, and unaccounted illegal harvest). Total mortality is the sum of the natural mortality and the fishing mortality.

Consider first a homogenous fishery. Homogeneity implies that all fish and anglers behave identically. Natural mortality and catch rate are expressed as instantaneous rates M and F and can be any positive value. The probability of retaining a caught fish is denoted π and, as a probability, must be a real number between zero and one. Similarly, the probability of death, given that an animal is caught and released, is denoted by q, which lies between zero and one. The instantaneous force of mortality applied to a population is denoted by Z and is the sum:

$$Z=M+F\pi+F(1-\pi)q$$

where the three terms represent natural, harvest, and hooking mortality respectively.

The probability of each fate occurring is represented by the following idealized equations for a deterministic derivation):

$$\begin{aligned}
Pr[alive] &= e^{-Z} \\
Pr[dead] &= 1-e^{-Z} \\
Pr[natural] &= \frac{M}{Z}Pr[dead] \\
Pr[harvest] &= \frac{F\pi}{Z}Pr[dead] \\
Pr[hooking] &= \frac{F(1-\pi)q}{Z}Pr[dead]
\end{aligned}$$

These probabilities refer to the fate of an individual fish. The expected number of fish in each category is found by multiplying population size by the respective probability. Harvest rate is expressed as number per angler effort and is found by multiplying by population size and dividing by angler effort.

Catch rate includes all animals caught regardless of their ultimate fate. Caught and returned animals may survive and be caught again. The number of times an individual is caught can be derived with the same assumptions used to construct the fate of each animal and is a Poisson random variable with the expected value:

$$E[catch]=\frac{F}{Z}Pr[dead].$$

An individual fish, on average, will be caught E[catch] times during the period in question regardless of its ultimate fate.

Real fisheries demonstrate various degrees of heterogeneity. RIOFISH incorporates heterogeneity by dividing both the fish and the anglers into subgroups; assuming homogeneity within subgroups. What follows is an application of the above theory to a (very large) finite collection of fish categories combined with angler types. The algorithm begins by dividing both angler and fish populations into homogenous categories then applying the above model to each category and finally integrating the classes of mortality and catch into composite data for the other parts of RIOFISH that use these results.

The species by cohort matrix is transformed into a species by length class matrix. The average length of each cohort is given by $L_{s,x}$ and individuals are normally distributed around this mean with a coefficient of variation of one quarter (the same as the juvenile truncation model described later). The density is integrated between the end-points of the length class to obtain the contribution of cohort s,x into length class s,i.

In RIOFISH, length classes are constant between species except for the first length class. The first length class includes those individuals greater than the species-specific minimum catchable size and less than 175 mm. Intermediate length classes are in 25 mm categories starting with 175 to 200 mm and ending with 500 to 525 mm. The last length class is all individuals greater than 525 mm. The midpoints are 150 mm for the first length class distribution, average values for the intermediate distribution, and 600 mm for the last distribution. In RIOFISH, as in harvest regulations, the length classes are actually expressed in inches.

Integration of the cohorts is accomplished by transforming the bounds of the respective length classes to standard normal deviates and subtracting the cumulative distribution of the larger deviate from the smaller. For example; if a particular cohort has a mean length $L_{s,x}$ The fraction of animals between 10 and 11 inches is

$$\Phi\left[4\left(\frac{11}{L_{s,x}/25.4}-1\right)\right]-\Phi\left[4\left(\frac{10}{L_{s,x}/25.4}-1\right)\right].$$

In this equation $\Phi(.)$ represents the cumulative distribution of a standard normal variable and is found by numerical means as with other portions of RIOFISH. $L_{s,x}$ divided by 25.4 provides the mean length of the cohort in inches.

Within a species/length class, animals die in a homogenous fashion. Individuals are removed from the population as a consequence of anglers and so-called natural mortality. The instantaneous rate of natural mortality ($M_{s,i}$) within a length class is proportional to the length of the period and is represented by the equation:

$$M_{s,i}=b_{z,s}\Delta t$$

where Δt is the length of the time step.

Anglers are classified into an arbitrary number of categories based on their behavior. The number of angler types is denoted as $n_{anglers}$. The number of angler categories is five, representing bait, fly, barbless fly, spoon, and barbless spoon categories. Angler types are subscripted with the letter l. A constant fraction divides total angler days (A, obtainable from the economics component) into a total effort for each category of angler types. Fish die from anglers harvesting a caught fish (harvest death) or by hooking damage to a released fish (hooking death).

Modeling the angling process involves determining for each angler type 1) instantaneous catch rate of the animals, 2) the probability than an angler will retain a caught fish, and 3) the probability that an angler accidently kills a fish if the angler releases the fish. These values are to be determined for each angler type, species, and length class.

The instantaneous probability of catching a fish ($F_{l,s,i}$) is proportional angler effort expressed as angler days per surface area. The equation:

$$F_{l,s,i}=b_{ctblty,l,s}\frac{A}{S}p_{anglers,l}$$

provides this value for every angler type l, species s, and length class i. The parameter $b_{ctblty,l,s}$ is the catchability parameter, A is the number of angler days in the period, S is surface area, and $p_{anglers,l}$ is the fraction of anglers of type l. The sum of all $p_{anglers,l}$ must equal 1.

Regulations (unit 74)

The probability that an animal is harvested given that it is caught is the retention probability ($\pi_{l,s,i}$). It depends on the mean length of the length category, the species, gear type, and legal restrictions. Legal restrictions are of two types: length regulations and numeric regulations. Length regulations prevent the angler from keeping fish in particular length categories. All length based regulations must be no more precise than one-inch (25 mm) categories so that the length classes constructed above are either entirely protected or entirely unprotected. Hence retention is defined as zero for those species/length classes protected by a length regulation.

Restrictions on the number of animals caught alter retention across length classes and within a species. The reduction of retention depends on the distribution of catch per angler day if the restriction was not in place. Hence an initial retention probability $\pi^*_{l,s,i}$ is computed, which is the "unconstrained retention" -- the probability of retaining a fish in the absence of numeric regulations. Unconstrained retention is found by the equation:

$$\pi^*_{l,s,i}=\begin{cases}0 & \textit{if protected by length regulations}\\ 1-e^{-b_{rel,l,s}l_{s,i}} & \textit{otherwise.}\end{cases}$$

where $l_{s,i}$ is the midpoint of the length class.

The probability that an animal dies due to hooking mortality, given that it is caught and released ($q_{l,s,i}$), is given by a species/angler specific constant $b_{hook,l,s}$ (i.e. $q_{l,s,i}=b_{hook,l,s}$).

In summary, within a species length class, there is an instantaneous force of natural mortality, and for each angler type, species, and length class there is an instantaneous force of fishing, probability of retaining a caught fish, and probability of killing a released fish denoted by F, π, and q, respectively. If there are legal restrictions on the number harvested, π is initially defined to be the unconstrained retention probability. The next step in the algorithm is to modify retention to account for regulations.

Length-based regulations protect certain sizes of fish and prevent anglers from retaining those individuals. The other type of regulation is a limit on the number of fish harvested within a particular species. The general principle is to determine the harvest per angler day within each angler type, assume a distribution of the catch per angler day, and compute the expected number of fish caught over the number limit. Unconstrained retention is reduced by the fraction of harvest represented by the illegal catch with unconstrained retention. RIOFISH anglers always throw back the part of the catch in excess of the numeric regulation.

Total unconstrained harvest per angler day for a species within an angler category is:

$$H^*_{l,s}=\frac{\sum_{i} N_{s,i}\frac{F_{l,s,i}\pi^*_{l,s,i}}{Z^*_{s,i}}\left(1-e^{-Z^*_{s,i}}\right)}{Ap_{angler,l}}$$

where

$$Z^*_{s,i}=M_s+\sum_{l=1}^{2} F_{l,s,i}\pi^*_{l,s,i}+F_{l,s,i}\left(1-\pi^*_{l,s,i}\right)q_{l,s,i}$$

$N_{s,i}$ is the number of fish of species s and length class i and Z is total force of mortality applied to the category. The first term of the equation describing Z is the contribution of natural mortality, the second term is harvest mortality, and the third is hooking mortality. Harvest mortality and hooking mortality are summed over angler types. Retention probability is already set to 0 for protected length classes in the above equations.

Catch per angler day is assumed to be Poissonly distributed with expected value $H^*_{1,s}$. The expected number of fish that are legally caught is given by the equation:

$$E[H_{l,s,.}] = \sum_{n=0}^{n_{limit,s}} n \frac{e^{-H^*_{l,s,.}} \cdot n^{H^*_{l,s,.}}}{n!} + \sum_{n=n_{limit,s}}^{\infty} n_{limit,s} \frac{e^{-H^*_{l,s,.}} \cdot n^{H^*_{l,s,.}}}{n!} .$$

The first summation represents anglers who (without regulations) caught less than the limit. The second summation represents anglers who would have caught over the limit and are now restricted to harvesting only their limit. This term divided by the unconstrained harvest is the reduction in retention probability. True retention is, therefore,:

$$\pi_{s,l,i} = \frac{E[H_{l,s,.}]}{H^*_{l,s,.}} \pi^*_{l,s,i} .$$

In RIOFISH, there are four types of outputs from this component that are used in other components. The economics component uses catch rate, harvest rate, and mean length of the harvest. The biology component uses the total number dead to determine survivorship and growth into the next time step. It involves summing the expected number dead across all length classes. The expected number of fish that die per cohort is:

$$N_{DEAD,s,x}=\sum_{i} n_{s,x,i}(1-e^{-Z_{s,i}})$$

where $n_{s,x,i}$ is the number of fish from cohort s,x that is in length class i and $Z_{s,i}$ is the total realized force of mortality on species s in length class j.

The economic model requires the number harvested and caught. The number harvested is described above and catch rate is done as before with substitution of the true retention probability (after numeric regulations are incorporated) instead of the unconstricted retention probability. The mean size of the harvested fish is a mean of the length classes harvested weighted by the probability of that species/length class being harvested.

GROWTH AND SURVIVAL

Realized growth (units 58,64,66-68)

The amount of realized production each population cell obtains from each guild is in proportion to the maximum growth rate a population receives and constrained to be equal to the system productivity for all but the piscivore guilds. An individual population cell is allowed to "feed" across several guilds and this is controlled by a set of partitioning coefficients $b_{comp,s,l,g}$ these coefficients differ among lifestage (l), species group (s), and feeding guild (g). Feeding guilds are the 5 fish (including crayfish) guilds represented in the system production component. Growth derived from each guild is summed across all possible fish guilds to obtain the realized production for that population cell. The equation

$$G_i = \sum_g \frac{b_{comp,s,l,g} G_{\max,i}}{\sum_i b_{comp,s,l,g} G_{\max,i}} P_g,$$

where P_j are four of the five fish system productions (P_{zvore}, P_{bvore}, P_{carp}, P_{shad}) described above and indexed by j and each population cell is indexed generically as i and $b_{comp,s,l,g}$ is the parameter associated with the i'th population cell.

In this calculation, actual growth can exceed the population cell's maximum growth when system productivity is larger than the previously computed maximum production. The denominator represents growth when all population cells are at their computed maximum. When system production exceeds the sum of population maximums, the equation is modified so that an individual's population cell maximum growth is not exceeded. The denominator of the above equation is examined and, if it is smaller than its corresponding system productivity, growth for a particular population cell within the feeding guild is set at maximum. To account for this condition, the above equation is modified to the following algorithm:

$$F_g=\max\left(1,\frac{P_g}{\sum_i b_{comp,s,1,g}G_{\max,i}}\right)$$

$$G_i=\sum_g b_{comp,s,1,g}G_{\max,i}F_g.$$

This is equation is applied to the four guilds mentioned and a value is obtained for growth in each guild. These are summed across species for the base values for piscivore production. Piscivore production (P_{pisc}) is the 40% efficiency of the realized production of the benthivore and zooplanktivore guild plus the 40% conversion efficiency modified by Carp and shad maximum productivity. The equation:

$$P_{pisc}=.40(G_{.,zvore}+G_{.,bvore})+.40F_{fish}(G_{.,shad}+G_{.,carp})$$

represents the systems production of piscivores used in this component of the model if $G_{.,x}$ is the representation of the sum of realized productions within guilds and across species. Realized production is then computed similarly to the other guilds.

Survivorship and Growth of Age 0 and Older (units 69-70)

The change in numbers and biomass is based on total mortality and growth. Mortality of the population cells are determined from the previous section. The output of that routine expresses death as the total number removed. This is re-expressed as an instantaneous rate of mortality $Z_{s,x}$. Larval fish are recruited into the juvenile age class at the end of the period. The equations are:

$$N_{s,0,t}=N_{s,0,t-1}e^{-Z_{s,0,t}\Delta t}+N_{yos,s,t}$$

$$B_{s,0,t}=B_{s,0,t-1}e^{-Z_{s,0,t}\Delta t}+\frac{G_{s,0,t}}{Z_{s,0,t}\Delta t}(1-e^{-Z_{s,0,t}\Delta t})+B_{yos,s,t}$$

and

$$N_{s,x,t}=N_{s,x,t-1}e^{-Z_{s,x,t}\Delta t}$$

$$B_{s,x,t}=B_{s,x,t-1}e^{-Z_{s,x,t}\Delta t}+\frac{G_{s,x,t}}{Z_{s,x,t}}\Delta t(1-e^{-Z_{s,x,t}\Delta t})$$

where Δt is the length of the time step. Mortality ($Z_{s,x,t}$) is computed in the angler catch-harvest component of the model.

From these two quantities, mean weight and mean length of each population cell can be computed. The average length is defined as the length of an individual with mean weight $W_{s,x,t}S=SB^{*}_{s,x,t}/N^{*}_{s,x,t}$. The relationship of weight to length follows the typical power function

$$W_{s,x,t}=b_{wtlen,0,s}L_{s,x,t}^{b_{wtlen,1,s}}$$

where Ls,x,t is the length of an individual of species s with weight $W_{s,x,t}$. The values for mean weight and mean length are not superscripted since other sources of mortality do not affect these values.

There are two other sources of mortality which affect the modeled populations. The oxygen and temperature profile through time is scanned and compared to three constraints for each population; minimum temperature, maximum temperature, and minimum oxygen content. If for any one time step there does not exist a stratum or stream cell that is within these constraints, all but a (small) fraction ($b_{s,refuge}$) of the population will die. This is done during the middle of each season.

Stocking (unit 77)

The model user can also manipulate the populations by stocking fish. Stocking for any time step t occurs at the end of the time step. The total weight and numbers of stocked fish are added to the population immediately after the computations done in unit 38. To identify which particular population cell the fish are added to, stocked animals are classified as three types.

Small fry stocked at time t ($N_{s,fry,t}$) are considered to be the same as newly recruited juveniles. Because mean weight of fry are

$b_{wtyos,s}b_{rec,s}$, only the total numbers can be given. The total weight of fry stocked is $B_{s,fry,t}S = SN_{s,fry,t}b_{wtyos,s}b_{rec,s}$.

The last two classes represent juvenile and adult fish. The user, in addition to numbers, supplies an average length for the stocked fish. The weight-length regression described above is used to determine the total weight of the animals. Fingerlings are considered to be juveniles and are added in age class 0. Catchable fish are added to the first adult category (age class S1).

Reproduction (units 79-82)

The number of eggs that females lay is a power function of the mean weight of each cohort, whose mean individual size is greater than a defined weight at maturity. The function for total number of eggs for species s at time t is:

$$N_{eggs,s,t} = \sum_{x: W_{s,x} > b_{mat,s}} b_{seas,s,t} b_{sex,s} N_{s,x,t-1} b_{fec,0,s} W_{s,x}^{b_{fec,1,s}}$$

where $W_{s,x}$ is the mean weight of an individual of the s'th species and x'th age class i.e., $W_{s,x} = B_{s,x}/N_{s,x}$. The summation only involves those age classes that have a mean weight greater than the weight at maturity ($b_{mat,s}$). The parameter $b_{seas,s,t}$ specifies the fraction of females that spawn during the season associated with t and the parameter $b_{sex,s}$ is the sex ratio of the population.

Egg Survivorship (83-85)

The survivorship of the spawn ($S_{spawn,s,t}$) is a linear function of water level fluctuation or

$$S_{spawn,s,t}=b_{wlfl,0,s}+b_{wlfl,1,s}\Delta E_t$$

where ΔE_t is the difference between the maximum water level elevation and the minimum water level elevation during the period t. This function is constrained to be between zero and one. The number of eggs times this survivorship is the number of larval fish at the beginning of the time period. The mean weight of the $S_{spawn,t,s}$ is given as a parameter $b_{wtyos,s}$.

Larval Growth and Survivorship (units 85-86,58,66-68)

Survivorship of larval fish to the juvenile age class is that value that results in a specified growth rate. It is a solution of the equation

$$b_{rec,s}=1+\frac{G_{yos,s,t}}{zB_{yos,s,t}}(1-e^{-z})$$

with respect to z. This equation has no closed solution for z. Therefore, a numeric algorithm has to be used to find z. This z (say, $Z_{yos,s}$), when put in the survivorship and growth equations explained below, results in an individual growth rate

$b_{rec,s}$. The number of larval fish at the end of the period is the product

$$N_{yos,s,t}=N_{eggs,t}S_{spawn,s,t}e^{-Z_{yos,s,t}}$$

The biomass of the $N_{s,yos,t}$ $(B_{s,yos,t})$ is the product

$$B_{yos,s,t}=N_{yos,s,t}b_{wtyos,s}b_{rec,s}$$

because the growth weight and the initial weight are the constants $b_{rec,s}$ and $b_{wtyos,s}$.

Recruitment to Age 1 (unit 71)

At the end of the calendar year juveniles below a certain size die. The mean weight of juvenile fish is assumed to be distributed normally around a mean weight $(W_{s,0} = B_{s,0,t}/N_{s,0,t})$ with a coefficient of variation of 25%. The fraction of animals surviving is

$$P_{s,0,t}=1-\Phi\left[\frac{b_{wtjuv,s}-W_{s,0,t}}{0.25W_{s,0,t}}\right]$$

where $W_{s,0}$ is the mean weight of the juvenile fish immediately before the end of the calendar year and $b_{wtjuv,s}$ is the minimum weight an individual must be to survive the winter.

The function Φ() is the standard normal cumulative distribution. The average weight of the surviving fish is the expectation of weight over all individuals greater than the minimum weight, which is

$$B_{s,0,t'} = B_{s,0,t}\left[P_{s,0,t} + \frac{1}{4\sqrt{2\pi}} e^{-\frac{1}{2}\frac{b_{wtjuv,s} - W_{s,0,t}}{0,25W_{s,0,t}}}\right].$$

In this equation, the subscript t′ denotes the instant after truncation takes place and $p_{s,0,t}$ is defined in the above equation.

GLOSSARY OF TERMS

Δt	Length of time step
$\pi_{l,s,i}$	Retention probability
A	Number of angler days
$A_{..}$	Total area of stream segment
A_{dry}	Area of dry part of channel
$A_{k,j}$	Area of stream cell k within stream section j
A_{rip}	Area of reach under riparian influence
A_{wet}	Area of wet part of reach
$B_{s,x}$	Biomasss of species s and age class x
$B_{yos,s}$	Biomass of the larval species s
B_{zoopl}	Biomass of imported zooplankton in tailwaters
C_{avail}	Allochthonous carbon available for consumption
D	Julian day
D_1	Depth at 1% light penetration
$D_{50new,k,j}$	Particle size for stream cell k within stream section j
D_{bar}	Mean depth of water body
E	Elevation
E_1	Photosynthetic efficiency
E_m	Maximum photosynthetic efficiency
E_n	Nutrient reduction in photosynthetic efficiency
E_p	Reduction in photosynthetic efficiency due to particle size
E_r	Reduction in photosynthetic efficiency due to riparian shading
E_s	Suspended solid reduction in photosythnetic efficiency

E_t	Water temperature reduction in photosynthetic efficiency
E_x	Flushing rate reduction in photosynthetic efficiency
F_{carp}	Fraction bottom feeders that are in population model
$F_{l,s,i}$	Instantaneous catch coefficient for l'th type of angler and species s
F_{ox}	Fraction by volume of water body with oxygen concentration above 1.5 mg/l.
F_{shad}	Fraction of suspension feeders that are shad
F_{susp}	Fraction of primary consumers that are suspension feeders
G_i	Realized production of population cell i
$G_{max,s,x,t}$	Maximum possible growth for species s and age x
$G_{opt,s,x,t}$	Optimal growth of species s, age x at time step t
I_{bot}	Fraction of bottom illuminated
I_{vol}	Fraction of water volume illuminated
L	Length of reach
L_0	Light intensity at water surface
$L_{s,x}$	Mean length of individuals of species s and age class x
M_s	Natural mortality of species s
N	Limiting nutrient concentration
$n_{anglers}$	Number of different angler types
$N_{dead,s,x}$	Number of species s, age class x that die during the period
N_{strata}	Number of lake oxygen temperature strata
$N_{s,x}$	Number of individuals of species s and age class x

$N_{yos,s0}$	Number of larval fish of species s
O_0	Oxygen concentration at beginning of reach
O_i	Oxygen concentration of i'th strata
O_{in}	Oxygen concentration of inflow
$O_{k,j}$	Oxygen concentration of stream cell k within section j
O_{sat}	Oxygen concentration at 100% saturation
P_a	Allochthonous carbon actually consumed
P_{ben}	Production of bottom feeding invertebrates
P_{bvore}	Production of benthivores
P_{carp}	Production of bottom feeding vertebrates
P_l	Primary productivity
P_{lakez}	Production (by volume) of upstream zooplankton
P_{pisc}	Production of piscivores
P_{shad}	Production of suspension feeding vertebrates
P_T	Total organic load
P_{zoopl}	Production of suspension feeding invertebrates
P_{zvore}	Production of invertevores
$q_{l,s,i}$	Hooking mortality
S	Suspended solid concentration
S	Surface area of water body
T_0	Temperature of stream at beginning of reach
T_a	Ambient air temperature
T_i	Temperature of i'th strata
T_{in}	Temperature of inflowing water
$T_{k,j}$	Temperature of stream cell k within stream section j
V_i	Volume of i'th strata ($i=1,2,..N_{strata}$)

$V_{k,j}$	Volume of stream cell k within stream section j
V_{out}	Volume of outflow
$W_{s,x}$	Mean weight of the $N_{s,x}$
X	Flushing rate
$Y_{max,k,j}$	Maximum depth of stream cell k within section j
$Y_{min,k,j}$	Minimum depth of stream cell k within section j

ECONOMICS COMPONENT MATHEMATICS

This section documents the specification of the equations used in the formulation of the demand and benefits model used in RIOFISH.

INDICES:

Index	Name of index	Assigned members
i	Fishing site	Appendix B includes all 132 NM fishing waters
j	NM zone-of-origin	9 Zones: SE, South, NE, North, SW, West, NW, East, and Central. NM counties included in each zone are shown in Appendix C.
k	Site quality indicator	Appendix D includes all 19 individual indicators
h	Site-Zone quality indicator	Appendix D includes all 19 individual indicators
t	Calendar season	Winter, Spring, Summer, Fall; For selected years*
L	Demographic Variable	Appendix E includes the description of all 7 demographic variables. Appendix F includes values for demographic variables by zone.

* Model estimated is based on seven seasons, Spring 1988-1989. Total and marginal benefits are based on any single year.

PARAMETERS

Parameter for kth site specific quality variable

γ_k Site quality/zone index interaction parameter obtained from transformation of OLS estimation of the CES demand system. Complete description of quality indicators in Appendix D.

(1)	Access	0.031676	(.-)*
(2)	Average weight fish kept	0.30157	(1.540)
(3)	# Boat Ramps	11.4006	(11.818)
(4)	# Developed Campsites	0.71367	(2.970)
(5)	Drinking Water (0-1)	1.24678	(0.959)
(6)	# Fish/day kept	6.39353	(6.729)
(7)	# Fish/day caught	0.23974	(1.934)
(8)	Macrophyte density (0-10)	-0.0015838	(.-)
(9)	Precipitation at site	-10.7702	(-16.681)
(10)	Modern Toilets at site	3.92583	(9.412)
(11)	Surface area of water in acres	1.42234	(10.531)
(12)	Tailwater fishing (0-1 dummy)	0.015838	(.-)
(13)	Temperature at site	-10.1787	(-3.935)
(14)	Water turbidity	-0.0015838	(.-)

γ_h Parameter for hth general geographic quality variable.

(1)	Large cold stream	6.15732	(0.934)
(2)	Lake on national forest	27.7068	(3.468)
(3)	Kokanee salmon at lake	22.8850	(3.556)
(4)	Mid-elevation lake (4000'- 7000')	26.6705	(3.442)

σ Elasticity of substitution among pairs of sites, $\sigma > 0$.

1.63139	**(18.909)**

α_L Parameter estimates used in the specification of the composite zone index. Complete description of zone variables in Appendix E.

(1)	**PERHISP**	**-0.423182**	**(-6.153)**
(2)	**PERAGE65**	**1.674945**	**(6.473)**
(3)	**PERUNIV**	**1.072249**	**(16.339)**
(4)	**PERSFWC**	**-1.297639**	**(-3.012)**
(5)	**PERMCNC**	**-2.174851**	**(-4.059)**
(6)	**PERMCWC**	**3.310306**	**(5.578)**
(7)	**PERSMNC**	**0.538718**	**(5.113)**

*Student t-ratios in parentheses. T-ratios are not defined when parameter entered as a restriction. All t-ratios of quality indicator and price to reference quality indicator and price.

VARIABLES

X_{ijt}	predicted trips to the ith site from jth zone for the tth season.
P_{ijt}	(round trip miles x travel cost/mile + entry fee); travel cost includes an opportunity cost of time valued at 1/2 the zone average hourly wage.
M_{jt}	total fishing expenditure per angler from jth zone-of-origin, tth season $= \sum_i P_{ijt}X_{ijt}$. Appendix G includes values for 9 zones, 7 seasons.
Q_{ikt}	individual site facility variables of the ith site kth quality indicator for the tth season.
G_{ijht}	geographical site class variables of the ith site hth quality indicator for the jth zone and tth season.
D_{Ljt}	individual Lth demographic variable of jth zone for the tth season, $0 < D_{Ljt} < 1$.
Z_{jt}	composite demographic zone index of jth zone, tth season, a multiplicative combination of zone demographic variables shown in Appendix C, $0 < Z_{jt} < 1$. Values for 9 zones shown in Appendix H.
β_{ijt}	function of individual quality indicators and zone index that enters angler preference ordering for the ith site, jth zone, for the tth season.
A_{it}	administratively closed site variable for the ith closed site, for the tth season. $A_{it}=1$ when site is open. $A_{it}=0$ when site is closed.

CALIBRATION FACTORS

ϵ_k minimum value assigned to kth site variable to assure correct model behavior when variable = 0.

$\epsilon_k = 0$	{critical variables: Q_1, Q_7, Q_{11}} for which demand goes to zero as variable goes to zero
$\epsilon_k = 1$	{all non-critical variables: Q_2, Q_3, Q_4, Q_5, Q_6, Q_8, Q_9, Q_{10}, Q_{12}, Q_{13}, Q_{15}}

ϵ_h hth variable epsilon.

$\epsilon_h = 1$	{geographic vars.: G_1, G_2, G_3, G_4}

EQUATIONS

Rational choice theory is used as the framework for specifying angler demand and benefits. This framework allows for the specification of a demand system for predicting fishing trips to each fishing site and then deriving a benefits measure based on the parameters obtained from those demands. Demand equations are consistent with utility theory and a fishing budget constraint.

Direct Satisfaction Index

The direct fishing satisfaction index is based on a CES preference ordering and has the form:

$$(1) \qquad U_{jt} = [\sum_i (\beta_{ijt} X_{ijt})^{\rho}]^{1/\rho}, \qquad \rho \le 1$$

Demand System

A system of demands predicts fishing trips per jth zone angler to each ith site for the tth season. Angler demands are based on the assumption that the angler acts as if maximizing the satisfaction index subject to the limited budget, $\mathbf{M_{jt}}$. The result of that maximization produces the following system of demands:

$$(2) \qquad X_{ijt} = \frac{M_{jt}\, \beta_{ijt}^{\sigma-1}\, P_{ijt}^{-\sigma}}{\sum_i \beta_{ijt}^{\sigma-1}\, P_{ijt}^{1-\sigma}}, \qquad \sigma > 0$$

where,

$$(3) \qquad \beta_{ijt} = A_{it} \prod_k (Q_{ikt} + \epsilon_k)^{\gamma_k (100 Z_{jt})} \prod_h (G_{ijht} + \epsilon_h)^{\gamma_h (100 Z_{jt})}$$

where Z_{jt}, the multiplicative zone index, is defined as the following:

$$Z_{jt} = \prod_{L} (D_{Ljt})^{\alpha_L}, \qquad 0 < D_{Ljt} \le 1 \tag{4}$$

The demand system $\mathbf{X}_{ijt}$ defined in (2) is derived from the assumption that the angler maximizes (1) subject to the fishing expenditure constraint:

$$M_{jt} = \sum_{i} P_{ijt} X_{ijt} \tag{5}$$

Indirect Satisfaction Index

The indirect fishing satisfaction function is obtained from substituting the equilibrium demand system in (2) into the direct satisfaction index (1). It results in the following:

$$U^{\circ}_{jt} = M_{jt} \,/\, C^{\circ}_{jt} \tag{6}$$

where,

$$C^{\circ}_{jt} = \Big(\sum_{i} \beta^{\circ}_{ijt}{}^{\sigma-1} P^{\circ}_{ijt}{}^{1-\sigma}\Big)^{1/(1-\sigma)} \tag{7}$$

where the (°) superscript in (6) and (7) indicates pre-policy prices and quality attributes.

Expenditure Function

The indirect satisfaction index can be used to solve for the expenditure function. It explains the angler's minimum total fishing expenditure required under post-policy levels of $\mathbf{P}_{ij}$, $\mathbf{Q}_{ikt}$, to achieve the same fishing satisfaction index as under pre-policy satisfaction, $\mathbf{U}_{jt}{}^{\circ}$. The expenditure function is obtained by inverting the indirect satisfaction index (6) and solving for expenditure as a function of satisfaction. This results in:

$$E^{\circ}_{jt} = U^{\circ}_{jt} \Big(\sum_{i} \beta_{ijt}{}^{\sigma-1} P_{ijt}{}^{1-\sigma}\Big)^{1/(1-\sigma)} \tag{8}$$

where, E_{jt}° is interpreted as the minimum expenditure to sustain pre-policy angler welfare at post-policy conditions.

Benefits

Benefits per angler measure the angler's welfare change resulting from a new policy relative to pre-policy conditions. We use the compensating variation (*CV*), measured as:

$$(9)\quad CV_{jt} = M_{jt} - E_{jt}^{o}$$

Total benefits from a policy change at the jth zone of the tth season are found by multiplying per capita benefits by angler population as:

$$(10)\quad Benefits_{jt} = (CV_{jt})(POP_{jt})$$

where POP_{jt} (see Appendix I) is the estimated angler population in the jth zone in the tth season. Population varies by year but not by season within a year. Total statewide benefits from a policy change are found by summing (10) over zones of angler origin and the relevant time periods as follows:

$$(11)\quad Benefits = \sum_{j}\sum_{t} Benefits_{jt}$$

Marginal Benefits of A Quality Change

Marginal benefit per angler of an improvement in a site quality indicator is calculated as the change in CV_{jt} with respect to a single quality indicator, Q_{ikt}. The marginal benefit per angler of the kth quality indicator at the ith site, jth zone in tth season is specified in the following way:

$$(12)\quad MBQ_{ijkt} = \frac{\partial CV_{jt}}{\partial Q_{ikt}}$$

where the term, $\frac{\partial CV_{jt}}{\partial Q_{ikt}}$, is the change in the total benefits with respect to an individual quality indicator (see Appendix D).

The term $\frac{\partial CV_{jt}}{\partial Q_{ikt}}$ is obtained by differentiating (9) with respect to Q_{ikt}, which is:

$$(13)\quad MBQ_{ijkt} = M_{jt} P_{ijt}^{1-\sigma} \gamma_k Z_{jt} Q_{ikt}^{-1} (\beta_{ijt})^{\sigma-1} \frac{(C_{jt})^{\sigma}}{C_{jt}^{o}}$$

where C_{jt}, is defined in (7).

Aggregate marginal benefits over all anglers at the ith site, jth zone, in tth season are found by multiplying per capita marginal benefits in (13) by angler population as:

$$(14)\quad MBQ_{ijkt} = (MBQ_{ijkt})\ (POP_{jt})$$

where POP_{jt} (see Appendix I) is the estimated angler population in the jth zone in the tth season. Total annual statewide marginal benefits per quality indicator per site for a given time interval (e.g., a water year) from a policy change are found by summing (14) over zones and the relevant time periods:

$$(15)\quad MBQ_{ik} = \sum_{j} \sum_{t} MBQ_{ijkt}$$

Angler Days

Per capita angler days at the ith site, jth zone, in the tth season are found by multiplying per capita angler trips (2) by the average number of days an angler fishes at a site per fishing trip as:

(16)

$$DAYS_{ijt} = (X_{ijt})\ (DAYTRIP_{ijt})$$

where **DAYTRIP**$_{ijt}$ is the estimated average days per fishing trip at the ith site from the jth zone in the tth season.

Aggregate angler days over all anglers at the ith site, jth zone, in tth season are found by multiplying per capita angler days (16) by angler population as:

$$\textbf{(17)}\quad DAYS_{ijt} = (DAYS_{ijt})\,(POP_{jt})$$

where **POP**$_{jt}$ is the estimated angler population in the jth zone in the tth season (see Appendix I). Total annual statewide angler days per site for a given time interval (e.g., a water year) are found by summing (17) over zones and the relevant time periods:

$$\textbf{(18)}\quad DAYS_i = \sum_j \sum_t DAYS_{ijt}$$

Total annual statewide angler days across all sites are found by summing (18) over all sites:

$$\textbf{(19)}\quad DAYS = \sum_i DAYS_i$$

Table A4. New Mexico Fishing Waters

SITE NO	SITE NAME
1	ABIQUIU RESERVOIR
2	ALBUQUERQUE DRAIN
3	ALTO LAKES
4	ANIMAS RIVER
5	AVALON LAKE
6	BATAAN LAKE
7	BEAR CANYON RESERVOIR
8	BELEN DRAIN
9	BILL EVANS LAKE
10	BLACK RIVER
11	BLUEWATER CREEK
12	BLUEWATER LAKE
13	BONITO CREEK
14	BONITO CREEK-NF
15	BONITO CREEK-SF
16	BONITO LAKE
17	BOSQUE REDONDO
18	BOTTOMLESS LAKE
19	BRANTLEY LAKE
20	BRAZOS RIVER
21	BURN LAKE
22	CABALLO RESERVOIR
23	CABRESTO CREEK
24	CABRESTO LAKE
25	CANADIAN RIVER1-NORTH
26	CANADIAN RIVER2-NORTH
27	CANADIAN RIVER3-CENTRAL
28	CANADIAN RIVER4-EAST
29	CANJILON LAKES
30	CARLSBAD LAKE
31	CEBOLLA RIVER
32	CHAMA RIVER1-NORTH
33	CHAMA RIVER2-CENTRAL
34	CHAMA RIVER3-SOUTH
35	CHAPARRAL PARK LAKE
36	CHARETTE LAKE LOWER
37	CHARETTE LAKE UPPER
38	CHICOSA LAKE
39	CIMARRON RIVER1-WEST
40	CIMARRON RIVER2-EAST
41	CLAYTON LAKE
42	COCHITI LAKE
43	CONCHAS LAKE
44	COSTILLA RIVER
45	COYOTE CREEK
46	EAGLE NEST LAKE
47	EL VADO RESERVOIR
48	ELEPHANT BUTTE
49	EMBUDO CREEK
50	ESCONDIDA LAKE
51	FENTON LAKE
52	GALISTEO RESERVOIR
53	GALLINAS RIVER
54	GILA RIVER1-NORTH
55	GILA RIVER2-SOUTH
56	GILA RIVER3-WF
57	GREEN ACRES LAKE
58	GREEN MEADOW LAKE
59	GRINDSTONE LAKE
60	GUADALUPE RIVER
61	HERON RESERVOIR
62	HOLLOMAN LAKE
63	HONDO RIVER
64	HOPEWELL LAKE
65	ISLETA LAKE
66	JACKSON LAKE
67	JEMEZ RESERVOIR
68	JEMEZ RIVER1-MAIN
69	JEMEZ RIVER2-EF
70	LAKE ALICE
71	LAKE FARMINGTON
72	LAKE MALOYA
73	LAKE ROBERTS
74	LAKE SUMNER
75	LAKE VAN
76	LOS ALAMOS LAKE
77	LOS PINOS RIVER
78	LOST LAKE
79	MAXWELL LAKE 13
80	MAXWELL LAKE 14
81	MCALLISTER LAKE
82	MCGAFFEY LAKE
83	MIAMI LAKE
84	MIMBRES RIVER
85	MONASTERY LAKE
86	MORA RIVER
87	MORA-PECOS RIVER
88	MORGAN LAKE
89	MURPHY RESERVOIR
90	NAVAJO RESERVOIR
91	PECOS RIVER1-NORTH
92	PECOS RIVER2-NORTH
93	PECOS RIVER3-CENTRAL
94	PECOS RIVER4-CENTRAL
95	PECOS RIVER5-SOUTH
96	PECOS RIVER6-SOUTH
97	PENASCO RIVER
98	QUEMADO LAKE
99	RAMAH LAKE
100	RED BLUFF LAKE
101	RED RIVER
102	RIO DE LAS VACAS
103	RIO GRANDE1-NORTH
104	RIO GRANDE2-NORTH
105	RIO GRANDE3-CENTRAL
106	RIO GRANDE4-CENTRAL
107	RIO GRANDE5-SOUTH
108	RIO GRANDE6-SOUTH
109	RIO GRANDE7-SOUTH
110	RIO LA CASA
111	RIO PUEBLO
112	RIO VALLECITOS
113	RITO DEL PADRE
114	RUIDOSO RIVER
115	SAN ANTONIO RIVER
116	SAN GREGORIO LAKE
117	SAN JUAN RIVER1-WEST
118	SAN JUAN RIVER2-EAST
119	SANTA BARBARA CREEK
120	SANTA CRUZ RESERVOIR
121	SANTA FE LAKE
122	SANTA FE RIVER
123	SANTA ROSA LAKE
124	SIX MILE DAM LAKE
125	SNOW LAKE
126	SPRINGER LAKE
127	STORRIE RESERVOIR
128	STUBBLEFIELD LAKE
129	TINGLEY AQUATIC PARK
130	TULAROSA CREEK
131	UTE RESERVOIR
132	WILLOW LAKE

Table A5. Angler Zones-of-Origin Composed of New Mexico Counties

Zone[1]	County No.[2]	NM County[3]
C	1	Bernalillo County
C	15	Lincoln County
C	29	Socorro County
C	31	Torrance County
C	33	Valencia County
E	6	Curry County
E	7	DeBaca County
E	11	Guadalupe County
E	21	Quay County
E	23	Roosevelt County
N	16	Los Alamos County
N	22	Rio Arriba County
N	24	Sandoval County
N	27	Santa Fe County
N	30	Taos County
NE	5	Colfax County
NE	12	Harding County
NE	19	Mora County
NE	26	San Miguel County
NE	32	Union County
NW	18	McKinley County
NW	25	San Juan County
S	8	Dona Ana County
S	20	Otero County
S	28	Sierra County
SE	3	Chaves County
SE	9	Eddy County
SE	14	Lea County
SW	10	Grant County
SW	13	Hidalgo County
SW	17	Luna County
W	2	Catron County
W	4	Cibola County

[1] 9 zones

[2] Alphabetized counties are assigned the numbers 1-33 in ascending order

[3] 33 counties

Table A6. Site Facility Parameter Estimates Obtained From OLS Estimation of Log Transformed CES Demand System,

$$ln \frac{[f_{ijt}]}{[f_{Ijt}]} = (\sigma - 1) \; [[\sum_{h} \; \alpha h Z_{jt} \; \gamma_K \; Z_{jt} \; ln \frac{[Q_{ikt}]}{[Q_{Ikt}]}] + \sum_{K} (1-\sigma) \; ln \frac{[G_{ijt}]}{[G_{Ijht}]}]$$

where f_{ijt} is the ratio of expenditures on the ith site jth zone of origin tth season to expenditure at the reference site jth zone and tth season. The Ith reference site, Elephant Butte Reservoir, is located in south central New Mexico.

Variable no. (k)	Quality Indicator (Q_{ikt})	Units	Parameter estimate (γ_k)	Student t ratio
1	Access	Percent of shoreline accessible within a 1/4 mile walk from vehicle	0.031676	(-)[1]
2	Average weight kept	Average weight of harvested fish (grams); game fish weighted twice pan fish	0.30157	(-)
3	Boat Ramps	Number of concrete boat ramps at a site	11.4006	(11.818)
4	Developed Campsites	Number of developed campsites within 10 miles of site	0.71367	(2.970)
5	Drinking Water	0-1 dummy; 1 = drinking water available at site	1.24678	(0.959)
6	Fish/day kept	Fish no. harvested per day; game fish weighted twice pan fish	6.39353	(6.729)
7	Fish/day caught	Fish no. caught per day; game fish weighted twice pan fish	0.23974	(1.934)
8	Macrophyte	Water plant vegetation, rated by fishery managers from 0 (none) to 10 (highest density)	-0.0015838	(-)
9	Precipitation	Seasonal precipitation at site, inches	-10.7702	(-16.681)
10	Modern Toilet Access	Number of modern toilets within 10 miles of site	3.92583	(9.412)
11	Surface Area	Average surface acres of water at site, by season	1.42234	(10.531)
12	Tailwater	Number of river miles below a dam that have good fishing	0.015838	(-)
13	Tempsite	Site temperature by season	-10.1787	(-3.935)
14	Turbidity	Water turbidity rated by fishery manages, 0 (none) to 10 (muddy)	-0.0015838	(-)

Variables no. (h)	Quality Indicator (Q_{ikt})	Units	Parameter estimate (γ_h	Student^{t} ratio
1	Cold River	Large cold stream fishing site	6.15732	(0.934)
2	Forest Lake	Nearest lake within the boundaries of a National Forest to a city with population of 50,000	27.7068	(3.468)
3	Kokanee Lake	Lakes that support Kokanee Salmon and have surface area less than 10,000 surface acres	22.8850	(3.556)
4	Mid-Elevation Lake	Lakes with elevation between 4000 feet and 7000 feet and have 1 or 2 boat ramps	26.6705	(3.442)

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[1] Student t-ratios not defined, when parameter entered as a restriction. All t-ratios based on log-ratios of actual quality to reference quality.

Table A7. Demographic Variables and Regression Equation that Predicts Zone Index, Z_{jt}, as a Multiplicative Function of Individual Demographic Variables,

$$Z_{jt}=\prod_{L}(D_{Ljt})^{\alpha_L}.$$

Variable number (L)	**Demographic Variable (D_{Ljt})**	**Units**	**Parameter estimate (α_L)**	**Student t ratio**	**Approx. $p > \|t\|$**
1	**PERHISP**	Percentage of total persons per zone that are of Hispanic origin.	-0.423182	(-6.153)	0.0001
2	**PERAGE65**	Percentage of total persons per zone that are 65 years of age or older.	1.674945	(6.473)	0.0001
3	**PERUNIV**	Percentage of total persons per zone that are 25 years of age or younger and have a bachelor's degree.	1.072249	(16.339)	0.0001
4	**PERSFWC**	Percentage of total households per zone that are single female with children.	-1.297639	(-3.012)	0.0026
5	**PERMCNC**	Percentage of total households per zone that are married couples without children.	-2.174851	(-4.059)	0.0001
6	**PERMCWC**	Percentage of total households per zone that are married couples with children.	3.310306	(5.578)	0.0001
7	**PERSMNC**	Percentage of total households per zone that are single male without children.	0.538718	(5.113)	0.0001

Table A8. New Mexico Demographic Data, 1990 Census of Population and Housing.[1]

Zone No	Zone Abbrev.	Total Persons	Total Households	PERHISPA	PERUNIV[2]	PERAGE65	PERSFWC	PERMCWC	PERMCNC	PERSMNC
1	C	560,080	214,428	0.38	0.09	0.11	0.08	0.26	0.26	0.02
2	E	76,140	27,775	0.30	0.05	0.13	0.08	0.30	0.29	0.01
3	N	237,845	86,133	0.46	0.10	0.10	0.08	0.30	0.26	0.01
4	NE	48,043	17,190	0.67	0.05	0.14	0.09	0.29	0.26	0.02
5	NW	152,291	45,328	0.13	0.04	0.07	0.12	0.38	0.21	0.01
6	S	197,350	67,612	0.46	0.07	0.10	0.08	0.32	0.27	0.01
7	SE	162,219	57,367	0.34	0.05	0.13	0.08	0.32	0.29	0.01
8	SW	51,744	18,574	0.50	0.05	0.16	0.08	0.29	0.30	0.01
9	W	26,357	8,302	0.34	0.04	0.09	0.11	0.34	0.24	0.02

[1] Census of Population and Housing, 1990: Summary Tape File 1 on CD-ROM New Mexico [STF 1A] / prepared by the Bureau of the Census. --Washington: The Bureau, 1991.

Census of Population and Housing, 1990: Summary Tape File 1 on CD-ROM Technical Documentation / prepared by the Bureau of the Census. --Washington: The Bureau, 1991.

[2] Census of Population and Housing, 1990: Summary Tape File 3 on CD-ROM New Mexico [STF 3A] / prepared by the Bureau of the Census. --Washington: The Bureau, 1991.

Table A9. Total Fishing Expenditure Per Angler, M_{jt} ($).

		New Mexico Angler Zone-of-Origin								
Season	**Season No.**	**C**	**E**	**N**	**NE**	**NW**	**S**	**SE**	**SW**	**W**
Spring 1988	2	44.21	44.09	29.13	18.78	28.92	32.84	32.37	16.21	89.75
Summer 1988	3	33.09	21.08	21.28	25.76	24.64	33.82	33.81	18.22	18.20
Fall 1988	4	10.91	9.83	4.82	1.45	10.21	5.78	4.56	13.67	1.33
Winter 1989	5	8.72	5.26	5.62	0.72	10.24	4.48	10.53	10.84	1.24
Spring 1989	6	38.43	32.95	46.83	24.39	31.18	29.54	34.27	25.25	15.04
Summer 1989	7	28.71	18.40	20.63	23.02	14.50	21.85	19.03	9.72	13.27
Fall 1989	8	8.24	0.40	4.92	1.46	4.06	4.82	2.04	0.35	1.33

Table A10. Zone Index by Angler-Zone-of-Origin

Zone No.	Angler Zone-of-Origin	Zone Index, Z_{jt}[1]
1	Central	0.19713
2	East	0.13379
3	North	0.19184
4	Northeast	0.15235
5	Northwest	0.13871
6	South	0.14927
7	Southeast	0.15711
8	Southwest	0.12671
9	West	0.11841

[1] Actual zone index value x 100.

Table A11. Estimated NM Angler Population, POP_{jt} .

Zone No.	Angler Zone-of-Origin	Population, POP_{jt}[1]
1	Central	81,640
2	East	12,597
3	North	26,440
4	Northeast	9,006
5	Northwest	19,756
6	South	20,378
7	Southeast	20,566
8	Southwest	7,265
9	West	4,466

[1] Values based on a percentage of total population, 1989.

Table A12. New Mexico Median Income Per County, 1990 New Mexico Census[1]

Zone No.	Angler Zone-of-Origin	Income[2] ($)
1	Central	21,051
2	East	20,723
3	North	19,743
4	Northeast	24,714
5	Northwest	18,542
6	South	23,316
7	Southeast	20,967
8	Southwest	18,583
9	West	21,270

[1] Census of Population and Housing, 1990: Summary Tape File 3 on CD-ROM New Mexico [STF 3A] / prepared by the Bureau of the Census. -- Washington: The Bureau, 1991.

[2] 1989 New Mexico median income per county aggregated into 9 angler zones-of-origin, then divided by number of counties in zone. Final result is the average median income per angler zone-of-origin for 1989.

Table A13. Consumer Price Index (CPI), Base Period 1982-1984[1]

Year	CPI[2]	% Change[3]
1974	49.3	11.0
1975	53.8	9.1
1976	56.9	5.8
1977	60.6	6.5
1978	65.2	7.6
1979	72.6	11.3
1980	82.4	13.5
1981	90.9	10.3
1982	96.5	6.2
1983	99.6	3.2
1984	103.9	4.3
1985	107.6	3.6
1986	109.6	1.9
1987	113.6	3.6
1988	118.3	4.1
1989	124.0	4.8
1990	130.7	5.4
1991	136.2	4.2
1992	140.3	3.0
1993	144.5	3.0

[1] U.S. Department of Labor, Bureau of Labor Statistics. UNM Databank, Ms. Karma Shore. Phone: 505-277-6626, Fax: 505-277-7066

[2] U.S. city average all items index for urban consumers (CPI-U).

[3] Inflation rate for year ending.