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Technical Completion Report

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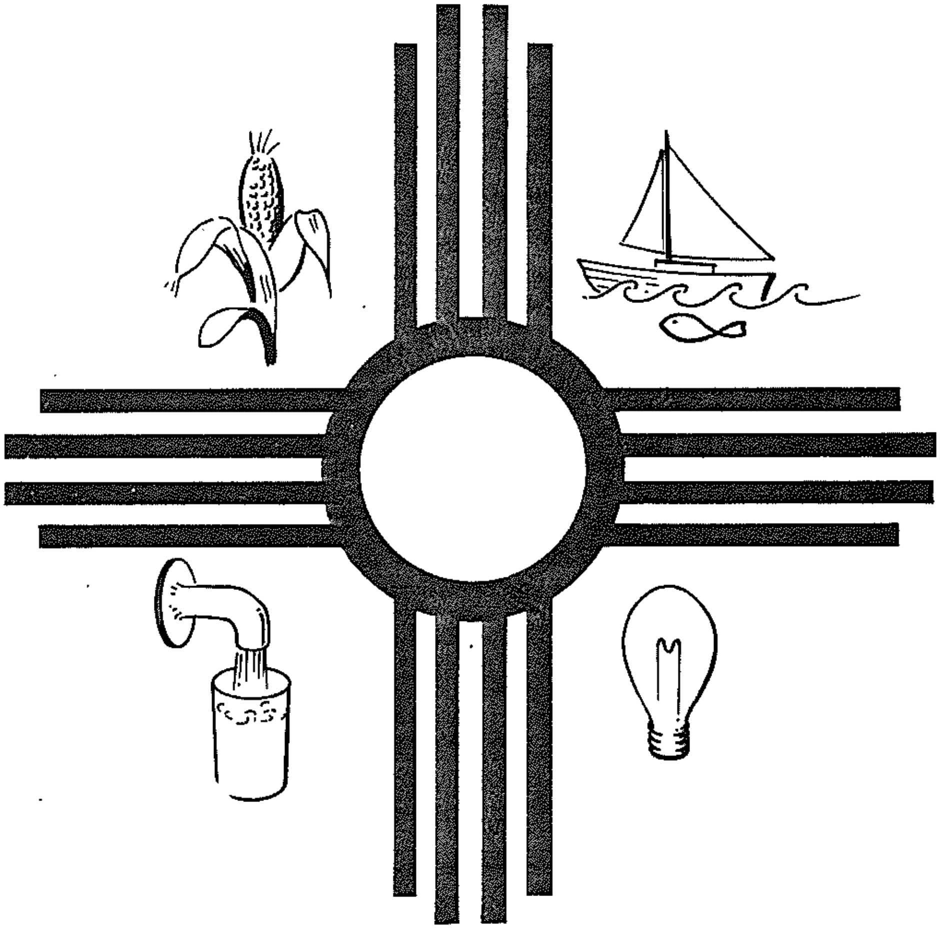

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RIOFISH, A FISHERY MANAGEMENT PLANNING MODEL FOR NEW MEXICO RESERVOIRS

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TABLE OF CONTENTS

PAGE

PAGE

PAGE

LIST OF TABLES

TABLE PAGE

TABLE PAGE

LIST OF FIGURES

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ABSTRACT

This report describes a sportfishery planning model, RIOFISH, developed for use in large New Mexico reservoirs. RIOFISH is a comprehensive planning tool that simulates a fishery planning system including procedural input, the socioecosystem, and outputs pertaining to fishing opportunity and angler benefit. RIOFISH organizes information into simulations of reservoir inventories and can be used to forecast resource and angler response to management strategies applied in different possible planning environments. The model also may be used to facilitate decisions based on anticipated angler benefit and agency management costs. RIOFISH can be used to evaluate which parts of the planning system have the most impact on model outputs and require the greatest resource attention. RIOFISH simulates hydrologic, biologic and socioeconomic interactions in 16 large reservoir fisheries of the Rio Grande and the Canadian, Pecos and San Juan rivers. The model user can modify water levels; reservoir exchange rate; concentrations of nutrients, suspended matter, and organic matter; temperature; solar radiation; fish stocking rate and regulations; fish introduction, removals and mortality effects; and road and boat ramp access. Outputs include simulation of river and reservoir hydrology, water quality, organic loads, fish production and catchable sportfish, catch rates, recreational days, and angler benefits. RIOFISH is run reiteratively, with each subsequent model scenario contrasted with an initial reference run.

PREFACE

Among the top five innovations impacting modern sportfishery management is the internal combustion engine. Computers may also fall in the top five, but less securely. Contemporary planning techniques do not currently fall in the top five. The internal combustion engine has become thoroughly assimilated; the computer has not; and contemporary planning techniques are least accommodated.

Assimilation of and eventual dependency on the internal combustion engine progressed slowly. Fishery managers accepted the adage "get a horse" for nearly three decades after the automobile was invented. But as various forms of the internal combustion engine were developed, management acceptance became inevitable. Total assimilation has occurred despite the deficiencies of the "infernal" combustion engine, which were and remain numerous. The "infernal" combustion engine derived its alias for many reasons, the most recent being environmental concerns. No one, however, seriously considers doing away with it without satisfactory replacement technology. We use the internal combustion engine, as imperfect as it is, because it is better than any other available alternatives. It is indispensable.

More recently in technological history, computers have become indispensable for fiscal management, but much of fishery management remains in an assimilation stage of computer use. Even though computers became routinely used in research, defense and business three to four decades ago, fishery management has just begun to incorporate them into its routines. In thirty more years, computers are likely to become as indispensable as the internal combustion engine. Computers are now becoming adapted into fishery management structures due to the increasing awareness that computer software can greatly increase management efficiency, just as the internal combustion engines did before World War II.

As with engines, the question of what can be done with computers is more relevant than whether or not the present technology is sound. History shows once potential uses become apparent, the drive to provide appropriate technology usually follows. The potential uses of engines became obvious as they were improved and increasingly diversified for various purposes in vehicles, boats and other equipment. The increasing utility of computers is becoming just as obvious. With the right programming software, computers can help managers organize and process information for predictive and communication purposes much more efficiently.

If computer technology has so much potential, why has the assimilation into fishery management been so slow? Software programming and computer operation, much like early engine performance, have disappointed fishery managers more often than not over the past two decades. Manager expectations have often been heightened by computer hardware "hype," as if the computer hardware alone could solve problems. The difficulties in developing useful software were soft-pedaled. Also, fishery management willingness to invest the money, time and effort into appropriate software development was dampened by the demands of existing information processing systems. These systems were usually based in the traditional processes of hatchery management, regulation enforcement and public relations. Little money or expertise remained to do much else. Information gathering and processing became superfluous for institutionalized management activity. Change became routinely difficult but threatening to the established order. Evaluation of progress toward objectives also became meaningless as repeating an existing process itself became a "planning objective." By the 1960s and early 1970s, improvement of sportfishery management had become constrained by management tradition. A contemporary planning system approach (Crowe 1983) was unheard of in state management agencies. The Chafee-Forsythe Act was an important attempt to get states to examine ways to relax tradition-bound management processes through comprehensive planning for a more expansive future.

Many state management agencies recognized that planning ideals were somewhat deflated by lack of information about the resource, resource users, and the agencies themselves. Information was scattered; much was irretrievable or in a useless format. Dependable information was mixed with "noise," which masqueraded successfully as meaningful information. Neither computer hardware nor appropriate software had been developed to better manage data for planning purposes. Continuous eruptions of real and imagined problems diverted attention away from incorporating contemporary planning procedures. The chances for real progress in developing predictive tools for comprehensive planning were slim without some substantial investment in information management, analysis, and synthesis. The advent of personal computers in the late 1970s improved computer hardware accessibility for routine planning. However, inadequate software remained problematic.

The New Mexico Department of Game and Fish (NMGF) recognized this dilemma in 1979 when it funded a study to evaluate the feasibility of developing a mathematical model to create some order out of past confusion. From that feasibility study came conclusions and cautionary recommendations (Cole et al. 1980). The study team concluded that developing a model structure was feasible and could improve: 1) organization of existing and future data; 2) predictive capabilities for assessing management strategy effectiveness; and, 3) communication to help intra- and inter-institutional users of the model. After assessing the NMGF need for a flexible and generally applicable planning tool, the team emphasized planning comprehensiveness rather than site or population specific accuracy and precision. The first objective was to develop an interactive structure that brought together all of the important elements of management habitat, fish biology and recreational economics. This structure would provide a comprehensive working model of a river basin, which could be used to assess management effectiveness through angler benefits prediction. In time, the single-basin model would be refined to develop a greater geographical applicability and greater specifity at sites within each basin to address comprehensive issues .

The NMGF was forewarned that such a model would take many years to reach a stage whereby it could be incorporated into routine department use. All parties involved were made aware through the reporting and proposal process of the complexity and the time required to accomplish the task. All parties agreed to the research and development investments necessary to develop the planning model now called RIOFISH.

RIOFISH is currently at an advanced intermediate stage, ready to be structurally completed as a comprehensive statewide planning tool. It is beginning to be used by NMGF for some of its intended purposes; mostly to help guide information acquisition where important deficits exist. RIOFISH is also becoming a communication focus for NMGF, both internally and externally. The model has met resistance common to most new communication techniques because of newness, initial intrusiveness, and imperfections. But real progress has been made in development and assimilation of this planning tool, particularly within the last year.

Further development and use of comprehensive planning software will progress similarly to previous communications developments. Lag times of decades have been the norm. RIOFISH will, in all probability, end up being an early model of a comprehensive planning software package. It will have served its purpose as it provides a foundation for advancement to something even more effective.

Many people have contributed to the development of RIOFISH. The farsighted dedication of numerous agency, university and other personnel was required to initiate RIOFISH and sustain development. The products of foresight and dedication are now beginning to take useful shape. This report is intended to summarize progress toward RIOFISH structural completion.

INTRODUCTION

RIOFISH Progress

In the late 1970s, following drought and development of a department comprehensive plan, New Mexico Department of Game and Fish (NMGF) personnel were particularly receptive to planning for environmental uncertainties. Water surface area in the largest, most popular, warm-water fishery in the state, Elephant Butte Reservoir, had recently fallen to about 15 percent of its maximum surface area. The drought in the 1970s stimulated growing concern that future water shortages could severely limit angler satisfaction and possibly depress management revenues. A "data" backlog of questionable utility had accumulated on dusty shelves, providing little help for finding solutions.

The NMGF discussed its planning problems with an interdisciplinary research group at New Mexico State University, after a feasibility study in 1979-80. NMGF initiated funding a comprehensive planning model in July 1980. The central issue in agency sportfishery planning was, and continues to be, improved use of department revenues and other resources to improve angler satisfaction. One big obstacle continues to be uncertainty in the planning environment.

Changes in angler numbers and needs, habitats and fish populations are difficult to anticipate. There is not one possible future planning environment, but many. Planning requires choosing among the best strategies to use when any one of the possible alternative futures actually materialized. In 1980, development began on the sportfishery planning system model, RIOFISH, to simulate possible fishery planning environments and their management in New Mexico.

Before the most recent phase of model development began in 1986, a prototype of RIOFISH was completed for the mainstream Rio Grande reservoirs in New Mexico in 1985 (Cole et al. 1987a). Data had been inventoried for modeled waters in separate research projects also, the most important of which were the postal surveys of angler activities at all New Mexico sites (Hatch 1986, for example) and inventories of fish density and biomass changes in surveys of warm-water reservoirs (Cole et al. 1985). These data served to calibrate biological submodels in RIOFISH. Other socioeconomic data were gathered in 1981 to develop and calibrate economic components. Hydrologic data were gathered mostly from existing U.S. Geological Survey (USGS) sources, but also in conjunction with warm-water reservoir studies (Bolin, Ward and Cole 1987). RIOFISH was introduced to the professional world outside New Mexico in symposia publications (Ward et al. 1982 and Cole et al. 1986b). A user manual was first drafted in 1985 and updated in Green-Hammond et al. (1988). Fiore and Ward (1987) described elements of the economics submodel.

This report summarizes model development progress to date. The model description is preceded by a somewhat elaborate discussion of objectives and the planning system concept that is simulated by RIOFISH. This background is emphasized because we have found that potential users have become confused by the model's purpose. The comprehensiveness of RIOFISH is partly responsible for this confusion. RIOFISH can be many different things to different users. We try, therefore, to clearly define primary and secondary modeling objectives. A general overview of model structure is presented. The model outputs and inputs are described as they are accessed by the model user. The model structure is then described along with perceived technical limits. Model calibration and preliminary testing for "reality" are summarized. Model limits are then discussed, with emphasis on the primary purpose of the model.

Planning for Environmental Trends and Uncertainty.

Fishery planning in New Mexico has been thwarted by an uncertain planning environment. A brief description of that planning environment is provided here to help clarify why the model was developed. Data gathered, particularly since 1975, exemplifies some of the trends and planning uncertainty that will influence future New Mexico sportfisheries.

New Mexico's population grew from under 700,000 just after World War II to its present number of 1.5 million. In that same period, the Albuquerque area (Bernalillo County) grew from about 140,000 to nearly 500,000 as the state population shifted from rural to urban. The maximum surface area of reservoir habitat in New Mexico almost doubled between 1938 and 1970, but since 1975 has remained stable. One of the oldest reservoirs, McMillan, has been retired and replaced with a new reservoir, Brantley. Large reservoirs fill at an average rate of about 5 to 10 percent per decade while some smaller reservoirs fill at a rate of over 10 percent per decade. The surface area of New Mexico fishery habitat fluctuates about 5 to 6 times from years of severe statewide drought (e.g., the 1950-1956 drought) to years with high precipitation (e.g., 1982-1988).

Reservoirs are fed by runoff mostly in spring during snowmelt and summer, when rainfall is heaviest. Over the long-term, snowmelt has contributed about 85 percent of the water but less than half of the nutrient and watershed eroded organic matter. Recent wet winters have contributed more than 85 percent of the water to reservoir habitats, but substantially less of the nutrient and organic matter because materials are much more concentrated in intermittent runoff. Summer rainfall and winter snowfall vary independently and randomly from year to year. Since 1979, mainstream runoff has averaged substantially above the long-term average while the intermittent runoff, mostly from summer storms, has been below average (Table 1).

Table 1. Estimated water yeilds (m^3/km^2) for the four main rivers and 16 termporary-runoff watersheds monitored by the U.S. Geological Survey in New Mexico grouped by area.

Area (number)	Water Year 1979	1980	1981	1982	1983	1984	1985	1986	1987	mean	Long-term mean
N. East (5)	5,209	2,060	13,624	10,284	2,568	5,558	4,198	8,415	9,394	6,813	10,787
N. Cent (4)	3,352	1,470	3,731	2,526	2,322	2,080	3,609	2,476	1,380	2,549	3,457
S. East (4)	1,883	1,086	591	625	195	11,155	272	30,408	330	5,172	6,070
N. West (2)	10,802	350	989	2,525	4,993	672	2,039	1,366	2,192	2,880	5,746
Zuni R. (1)	14,954	18,754	611	2,577	15,028	2,530	14,234	362	7,177	8,469	5,920
Mean temp runoff	5,094	2,498	5,866	4,477	2,995	5,274	3,426	11,044	4,086	4,996	6,840
Four Rivers[1]	63,752	46,265	24,066	36,095	49,535	95,375	68,274	59,232	77,609	57,800	37,026

[1]/Canadian (Sanchez), Rio Grande (Otowi), Pecos (Santa Rosa) and San Juan (Archuleta).

Average runoffs integrate large-scale variation, however. In 1986, for example, runoff yields in southeastern intermittent streams exceeded runoff yields in other parts of the state up to nearly 100 times. Southeastern intermittent runoff in 1986 also exceeded runoff in the same stream channels in 1985 and 1987 by roughly 100 times (Table 1). Therefore, local loading of nutrient and organic matter into reservoirs can dramatically vary from year to year or reservoir to reservoir by as much as two orders of magnitude. Statewide estimated reservoir loadings vary from year to year by less than an order of magnitude.

Planning was also complicated by interactions between angler behavior and habitat changes as water levels increased in the 1980s. Based on trends in angler card-survey reports and estimates of fish mass, mean sportfish catch rates in large reservoirs of New Mexico increased nearly 37 percent from the low-water years 1975 and 1978 to high-water years, 1981 and 1986 (Table 2). The reasons for the increased catch rates are complex, because both fish density and fish catchability may have changed. Both habitat fertility and angler effectiveness may have increased since the 1970s. As more anglers use boats, fish-finders, and improved terminal gear, catch rates tend to increase. But trends indicated in Table 2 suggest that catch rates went up from 1978 to 1981 when water levels increased. This suggests that increased fertility from increased tributary loading of nutrient and organic matter played the most important role. Statewide, the average reported daily yield rate per angler increased 12 percent from 1975-78 to 1981-86 in state mail surveys of angler success while the average days fished per angler increased about 8 percent. The average angler harvest rate increased from 10 to about 15 kg yr^{-1} over the 1975-1987 period (based on a 10 day/angler rate and an average of 0.4 kg/fish). Using fish yield as an index to angler satisfaction, anglers benefitted 50 percent more in the high water years compared to the mild drought years. Annual average water surface area about doubled over that period (25,000 to 45,000 ha) in the larger reservoirs.

Table 2. Estimated angler days[1], fish yield and catch rate/day reported in mail surveys for large reservoir[2] and all other waters in New Mexico from 1975-1986.

	1975	1978	1981	1982	1983	1984	1985	1986
Large Reservoir angler days	594,937	445,800	747,286	796,037	834,352	841,764	970,119	1,163,664
Total angler days	1,572,904	1,584,036	1,876,427	2,071,525	2,000,464	1,853,875	2,205,006	2,249,586
Expected angler increase[3]	1,572,904	1,692,444	1,820,900	1,866,422	1,914,948	1,902,075	1,951,528	2,002,267
% reservoir angling	37.8	28.1	39.8	38.4	41.7	45.4	43.9	51.7
Large reservoir yield	1,632,448	1,155,329	2,775,982	3,213,160	2,605,525	3,335,072	3,555,917	3,872,234
Total state yield	4,505,890	4,314,452	5,870,069	6,513,165	6,031,960	6,017,429	6,328,599	6,803,201
% fish caught in large reservoirs	36.2	26.8	47.3	49.3	43.2	55.4	56.2	56.9
Catch/day in large reservoirs	2.74	2.59	3.71	4.03	3.12	3.96	3.66	3.32
Catch/day in all other waters	2.94	2.77	2.74	2.58	2.93	2.65	2.24	2.69
Days fished/ licensed anglers who fished	10.7	11.1	11.4	11.4	11.6	11.6	12.5	12.5
Reservoir surface area (ha)	18,987	14,721	23,045	22,744	26,642	28,279	33,748	38,638

[1]/Total angler times the mean in number of days fished by each angler.
[2]/Reservoirs include Navajo, Heron, El Vado, Eagler Nest, Bluewater, Abiquiu, Cochiti, Ute, Conchas, Santa Rosa, Sumner, Elephant Butte, Caballo, McMillan (Brantley) and Avalon.
[3]/Based on human population increase in New Mexico.

Mail surveys (Hatch 1986) indicated that catch rates increased substantially in the largest reservoirs (Table 2). Therefore, angler activity evidently shifted from small waters to large reservoirs from 1975 to 1987. The percent of anglers who fished in large reservoirs increased from 40 percent of the state anglers in 1975 to 52 percent in 1986. The fish reported caught in large reservoirs increased from 36 percent of the statewide catch in 1975 to nearly 57 percent in 1986. The switch from small waters to large waters was associated with higher catch rates in the larger waters. Boat ramp access to reservoirs and camping facilities improved over this time period, perhaps encouraging the switch. The increase in angler days was associated in part with increased per capita fishing and partly because of increased state population. There was no evidence that the percentage of anglers in the population changed substantially, thus license sales were well estimated by predicted state population increases.

Planning uncertainty also was associated with statewide potential fish yield, which is a function of two primary variables: total surface area and catchable fish productivity. The actual fish yield from large reservoirs increased about 3.3 times from 1978 to 1986 (Table 2) as surface area increased by 2.6 times and yield per unit area increased by 28 percent. Species composition of the statewide catch did not appear to greatly influence catch rate as expected (Table 3). Cold-water yields did not change much from 1975 to 1986 while warm-water yields increased by 2.3 times. Most of the warm-water yield increase was crappie and white bass, two panfish species usually recognized as less desirable (not angler first choice) than cold-water game fish and warm-water gamefish. Yet the angler effort appeared to shift in response to an increase in catch rate of panfish.

Table 3. Composition of the fish catch reported in mail surveys from 1975-1986 for all New Mexico waters.

	1975	1976	1981	1982	1983	1984	1985	1986
Trout	2,848,551	2,775,560	3,314,855	3,395,291	3,331,795	2,754,972	2,754,294	2,552,843
Salmon	82,724	89,643	62,670	172,005	131,358	266,311	402,216	435,427
Total Cold-Water	2,931,275	2,863,203	3,377,525	3,567,296	3,463,153	3,015,283	3,156,510	2,988,270
Crapie-White Bass	572,980	703,780	1,485,340	1,581,302	1,222,880	1,666,962	2,108,865	2,025,453
Total Warm-Water	1,657,339	1,451,249	2,492,544	2,945,869	2,568,807	3,002,146	3,574,305	3,814,951
Total Fish	4,505,890	4,314,452	5,870,069	6,513,165	6,031,960	6,017,429	6,328,599	6,803,221

Planning Scenario: Worst-Case

The future cannot be determined in a crystal ball. Numerous alternative futures, or planning scenarios are possible. Some are more probable than others. The worst case scenario is always of interest because it sets planning performance limits. A worst-case scenario is described here contrasting alternative futures to provide background for detailed discussions later in the report. Presumably, potential fish yield will decline to 1970 levels or lower when drought years return. One worst-case planning scenario for drought years is described here to provide an example of the planning issues that RIOFISH is designed to analyze.

In 1985, about 250,000 anglers harvested 1.3 million kg of fish from all state waters with an estimated potential yield of 50 kg ha^{-1} yr^{-1} (about 3 million kg). When mild drought years return, we estimate roughly a 35 kg/ha yield potential or a total of 1.0 million kg potential annual harvest, if prevailing management strategies continue. Therefore, the fish supply could fall below angler demand in a mild drought situation, even if the human population remained stable. Drought habitats occurring in the year 2000 may have to serve 25 to 30 percent greater angler demand than occurred in 1985 (1.6 million kg demand in 2000 compared to 1.0 million kg supply). Demand then would substantially exceed supply. With prevailing management, angler impacts in severe drought years could increase total fish mortality by 25 percent or more and require strict regulations to prevent decreased yields. License sales may decline if catch rates and allowable yields decline greatly in severe drought years. If the sales decline is proportional to the imbalance in demand and supply, a 25 percent decrease in department revenues could occur during moderate drought years. If travel costs increase faster than angler income, angler fishing demand could be further thwarted.

The above drought planning scenario is only one of a number of alternative fisheries futures that could emerge in New Mexico over the next decade. Some scenarios are even worse than the example presented, but less probable. Other scenarios are much more optimistic. Table 4 shows three example scenarios. Drought may not return in the next decade. Water transfer demands could increase or decrease as the uncertainties of economics and water law materialize. Angler population growth rate and travel costs also are uncertain variables. Climatic changes that worsen drought conditions may be underway. Changes in the employment environment may reduce or increase average income levels and willingness to travel to fishing sites.

Therefore, the New Mexico Department of Game and Fish cannot simply plan for one fishery future. It must plan for many potential futures in order to act quickly and appropriately as the actual future unfolds. The scenarios in Table 4 reveal several major variables that can impact on the angling rate in any planning scenario chosen. A comprehensive planning model will be inaccurate and irrelevant if major variables are not included. RIOFISH was designed to incorporate such variables. Thus, different future scenarios could be simulated as background for testing the best combination of management strategies for sustaining or increasing benefits in any planning environment that emerges.

Table 4 Three examples of planning scenarios for New Mexico over a 20-year planning horizon.

Scenario I Optimistic	State real per capita income continues to increase as tourism and light industry grow and defense industry remains stable. Real travel costs remain about the same as more fuel efficient vehicles are produced. Droughts do not impede habitat availability. State population growth increases to 35 percent per decade as the economy improves. NMGF more than doubles its revenue base from sources other than licenses. Educational programs stimulate increased per capita angler participation.
Scenario II More Realistic	State real per capita income levels off as the defense industry decline is counterbalanced by other economic growth. Real travel costs increase moderately as taxes are increased to reduce atmospheric quality deterioration. Droughts of moderate intensity occur and reduce habitat availability on the average one out of every four years. State population growth declines to 15 percent per decade NMGF increases its revenue base by 50 percent from sources other than licenses. Educational programs sustain, but do not increase, angler participation rates.
Scenario III Pessimistic	State real per capita income decreases as the defense industry wanes and tourism and light industry are crippled by high fuel taxes. Real travel costs increase greatly with taxes levied to reduce atmospheric quality deterioration. Intense droughts of prolonged duration (perhaps aggravated by green house effect) severely reduce habitats an average of one out of every three years. State population growth declines to near zero growth. NMGF does not increase its revenue base from sources other than licenses. Educational programs suffer funding costs and have little impact on angler participation rates.

The Planning System

The Water-Management Subsystem

Planning systems include planning environments, that include all factors significantly influencing planning systems outputs, such as fish production and angler benefit. Knowledge of the planning environment is crucial for a systems analysis approach to planning. For fisheries, the habitat portion of the planning environment is an elemental consideration. Habitat fluctuation can be anticipated and controlled or mitigated through various management strategies. In New Mexico, as in much of the west where most water resources are privately owned, water may be purchased by public agencies to control its availability.

Alternatively, privately owned water that is stored or routed through public works can be managed to improve recreational benefits as long as existing water rights are not impaired by the recreational use. One of the more potent management strategies perceived by NMGF was improved water-level management in the large reservoirs. Much of the largest river basins in New Mexico, the Rio Grande, Pecos, Canadian and San Juan has been engineered into a water-management system in which water is impounded and routed for irrigation, flood control, municipal and recreational uses. Most of that water management system is administered by the U.S. Army Corp of Engineers and the Bureau of Reclamation, according to laws and rules that respond to water ownership and flood protection needs in New Mexico, other states, and Mexico. Parts of the system are administered by local irrigation districts. The reservoirs and some of the reservoir tailwaters in the system form sportfish habitats and fisheries that are hydrologically, biologically and economically interactive. This water management system forms an important subsystem in the larger sportfishery planning system. Even where NMGF can purchase water for water-level management, or otherwise influence existing water-level management to benefit anglers, the consequences are difficult to predict partly because of uncertainties in the water-management subsystem and partly due to external influences. A management change imposed on one part of the water system may greatly affect other parts of the system both downstream and upstream, but in ways not always intuitively or quantitatively obvious. The hydrologic impacts are most obvious: management of water levels in reservoirs usually results in changed water levels and discharges elsewhere in the system. A request to sustain instream flows in a river segment connecting two reservoirs, for example, will result in some change in water-level behavior in both reservoirs, but the impact varies depending on the volumes in the reservoirs. While instream flow management may have negligible impacts on reservoir fisheries during high-water years, critical fishery impacts may occur in drought years. Because of the system complexity, fishery managers until recently, had little choice other than to manage the parts of the system as if they were independent, or at most, as if the impact of managing one part of the system extended only to adjacent waters.

Recent research has revealed important system dynamics in New Mexico fisheries that were only vaguely suspected in the 1970s. First, anglers migrate among waters as site attractiveness changes. Second, the erosion of watershed organic matter contributes massively to the reservoir bioenergetics that support river-basin fisheries. Both of these observations rest outside the traditional fisheries management perspective. The reproduction and mortality of sportfish often is influenced more by forces outside of a particular reservoir or tailwater than by forces in the reservoir or tailwater. While organic and other material loading fluctuates by as much as an order of magnitude from year to year, fish reproduction follows suit, and anglers change reservoirs in response to changes in fish stocks. The fish mortality also changes as anglers change their fishing habits.

The Social Subsystem

The social subsystem in fishery planning is comprised of the angling community. From the start, the objectives for model development focused on economic measures of angler benefits to evaluate the effectiveness of management by objective. Although other indices to angler satisfaction are included in RIOFISH (e.g., recreational days, fish yield), economic angler benefit is the best single quantitative measure of angler satisfaction derived from the whole fishing experience, including aesthetics, access and amenities associated with the fishery. Benefits terminology is confusing to most fisheries managers; therefore, a brief clarification of the benefits concept follows. The primary objective stated in the 1980 research proposal referred to modeling designed "for delivering the potential economic value of sportfisheries." The "economic value" referred to is the net economic value, commonly called angler benefits, or, more precisely, the consumer's surplus or the net willingness to pay. According to Thomas (1988), "One way to view net willingness to pay or consumer surplus is to consider it a personal income equivalent. While it is not actually cash in hand, it is equivalent to real added income."

For example, if the estimated consumer surplus for fishing by a resident in New Mexico is $200.00 a year, that can be considered equivalent to giving the angler $200.00 in lieu of the opportunity to fish; thus, the angler benefits by $200.00. That $200.00 benefit is the benefit the angler receives from having the opportunity to fish in New Mexico rather than, say, Colorado. Other things being equal, if the angler benefitted more by fishing in Colorado, the angler would be motivated to leave New Mexico and fish in Colorado.

Angler benefit can be increased two ways: by reducing anglers' costs necessary to access fishing and by increasing angler willingness to pay by improving fishing opportunity for given costs. If an angler had to travel farther to fish in Colorado, his cost would probably increase; therefore, the only way he would benefit more would be if the fishing quality in Colorado was high enough to offset the increased cost. Willingness to pay more could be increased by the expectation of catching more or larger fish, better on-site improvements or a more pleasant fishing environment.

Anglers provide revenues for management agencies to increase angler satisfaction or, in economic terms, to increase angler benefits. Thus, the change in the net economic value (consumer surplus) generated by management is a direct quantitative means for measuring the value of improvement in fishing.

The estimation technique used for development of RIOFISH is the travel cost methodology described by Ward and Loomis (1986) and Weithman (1986). It incorporates all present value associated with the fishing experience. Only part of that present value is related to catch rate, sizes and species of fish caught. Many other considerations influence anglers as to whether or not they will fish and, if they fish, where they will do so. One of the most important factors is the travel distance required to catch fish. Other important factors include the accessibility of the fishery, amenities present (campsites, etc.), and environmental comfort (air temperature, shade, aesthetic considerations, crowding). Collectively, the factors that comprise a fishing experience contributes to angler benefits associated with the fishing experience. Thus, the satisfaction gained by anglers from management is increased mostly in two ways: 1) by improved fishing quality (more and larger fish of desirable species, improved access, better facilities, etc.) at existing fishing sites and 2) by improved fishing quality, particularly at sites closer to the anglers. Improvement of fishing satisfaction at existing sites generates a greater willingness to pay for the same travel cost; thus increasing the net willingness to pay. Moving otherwise similar fishing experiences closer to the angler (by stocking closer, for example) reduces angler cost for the same experience and increases angler benefit.

Management by objective as measured by net economic value has one fundamental difference from management by objective as measured by catch rate. Whereas catch rate can be the same for a low number of anglers at a reservoir with low accessibility as for a high number of anglers at a more accessible reservoir, the total benefits will be higher at the more accessible reservoir where there is more angler use. Although total yield of fish may increase proportional to effort, and serve as a better estimate of angler benefit than catch rate, various other aesthetic factors also influence satisfaction and are not indicated by yield alone.

The general principles of cost-effective fisheries management designed to benefit anglers are clear: 1) generally increase angler satisfaction and 2) distribute fisheries to provide angler satisfaction closer to populated areas. The ways available to bring about these management goals are diverse. Fisheries managers traditionally have viewed their role as limited mostly to increasing stocks of catchable fish and improving the distribution of catchable stocks more equitably among anglers. The major tools of management traditionally have been stocking and regulation, and these will continue to be among the most useful management strategies.

If, however, the availability of fish stocks does not limit fishing satisfaction at a site, neither of these strategies will increase benefits; in fact, they may reduce benefit wherever agency revenues are applied to ineffective activities. Instead of investing in useless stocking and regulation, revenue would be more economically directed to reduce the negative impact of factors that impede the full realization of angler satisfaction at a particular site. The availability of suitable camping facilities or improved access are examples of two factors that could influence the added value produced by fishery management decisions.

Angling benefits are usually estimated directly by sampling a population of anglers and determining an angler benefits schedule based mostly on the willingness to travel and the cost of travel. Most past economic models identify human population density and the average distance anglers travel to the site as the two most important factors determining angler visits at a particular site (Weithman and Haas 1982). Human population distribution and travel cost per mile are beyond the control of fisheries managers, and only so much can be done to move aquatic habitats closer to the angling public. But other factors can be greatly influenced by fishery managers. Fishery productivity, accessibility, and habitat attractiveness can be influenced by management. Increasing the management emphasis at sites near anglers is generally advised, but only if non-controllable aesthetic, crowding or other influences do not negate management impact.

A model that attempts to predict angler visitation rates needs to include the most important ingredients for fishing satisfaction. Important factors include the quality and quantity of the fish populations, fish catchability, site accessibility, number of camp sites, boat ramp quality, site fees charged, boat regulations, fish catch regulations, and the availability of substitute fishing sites. With such a model, the primary focus of a fishery planning model will be angler satisfaction, not fish stocks. However, the status of fish stocks is a secondary consideration because it provides information pertaining to the potential for furthering angler satisfaction. RIOFISH is a model that incorporates all ingredients for estimating the change in angler satisfaction resulting from application of management strategies to different, possible, future planning environments.

There is a difference between angler satisfaction and angler opportunity, which sometimes are confused with each other. Increasing opportunity refers to increasing the potential angler satisfaction, such as by increasing fish production. Of course, if anglers do not take advantage of an increased opportunity, their satisfaction is not increased and the money spent to increase the opportunity could have been better spent otherwise. To the extent that increasing opportunities will cost anglers some part of the angler license fee or tax dollars, anglers not benefitting from the increased opportunity will experience angler diminished satisfaction. A complete planning model addresses both opportunity (e.g., fish production) and satisfaction (e.g., angler economic benefit), and allows analysis of the most appropriate ways to develop opportunities for increased satisfaction.

The Agency Subsystem

NMGF fishery managers in the 1970s intuitively sensed that fisheries management of water levels, or any other feature of the water-system planning environment, can have complex and interactive impacts beyond the boundaries of individual sites. Fishery managers suspected that impacts on fisheries at sites outside the managed site could possibly counter positive management gains at any particular site. A clear example is intense investment in an improved fishery at some site when simultaneous but unaccounted changes in water-system management by a water management agency would result in much more attractive fisheries in other sites. Fishery managers needed a quantitative way to track critical interactions and predict the impacts of natural or managed changes on fisheries and angler benefit throughout the state's river basins.

Comprehensive fish and wildlife planning was initiated in NMGF nearly simultaneously with the mild drought of the 1970s. Through federal funding sources, state game and fish agencies were encouraged to develop comprehensive plans to improve the efficiency and cost-effectiveness of their decision making. These planning exercises were frustrated by inadequate data, an imperfect understanding of the planning process, and inadequate measures of angler benefit. The concept of "management by objective" to benefit recreationists particularly frustrated agencies. The process of estimating how much angler benefits could be generated by management, in advance of actual management, also was poorly understood. Few good quantitative planning tools were available in the 1970s to help forecast the angler benefits to be derived from management by objective. Without better indices, fish catch rate and total yield greatly determined estimates of angler benefit. But this approach to estimating angler benefits was not always easily related to costs.

Cost-benefit planning was often perceived to be an unattainable ideal. Even where the planning environment remained nearly stable, such planning activity was viewed with skepticism because of inadequate understanding of the environmental process. In the arid west, where planning environments were instable, the concept of planning was often thought to be overly optimistic, if not hopeless. Yet among the biggest fishery problems that faced NMGF were planning problems related to forecasting resource use rates and department revenues. NMGF recognized the best hope for sustaining recreational benefits and departmental revenues was to develop appropriate planning tools that would accurately predict benefits from management strategies applied to constantly shifting planning environments.

In 1979, NMGF funded a feasibility study of the prospects for developing river-basin models that could be interactively manipulated to predict economic benefit and impact. The study indicated that river basin models could be developed, and their ultimate utility depended on departmental acceptance as much as structural adequacy. The main recommendation of the feasibility study was to first generate a prototype model of the Rio Grande, developed from USGS data and, if the prototype proved promising, expand the model to the remaining river basins and watersheds.

A five-year project was initiated in 1980 to develop the prototype model of the Rio Grande; it was completed in late 1985 (Cole et al. 1987a). The model was named RIOFISH in 1985 when a user's manual was first drafted for the model (Green-Hammond et al. 1988). Because the prototype was completed as planned and its potential utility looked bright, the second phase of RIOFISH development began in late 1985.

The Comprehensive Planning System

Simulation of a complete planning system integrates the resource (the water management subsystem), the resource users (the social subsystem) and the management agency activity (the agency subsystem). The greatest value of RIOFISH rests in the integrated simulation such that complex and large-scale interactions can be examined with regard to agency management activity. Although subsystems can be pulled from the model to examine specific aspects and minor interactions, there are often more precise models available for such purposes (however, they are usually not user friendly and have limited management application as a consequence). One intent of RIOFISH development has been to create a comprehensive structure, which can be used in sensitivity analysis to direct continued refinement of the model parts. Those components of the model that have the greatest impact on output of dimensions usually need the greatest resource attention. Except for cost assessment, which is the responsibility of the management agency, RIOFISH simulates all aspects of large reservoir planning systems needed to estimate benefits and costs for alternative futures and contingency planning.

RIOFISH OBJECTIVES AND PLANNING FOCUS

Project Objectives

The primary objective of the initial modeling project in 1980 was:

> "To organize and develop a mathematical model of the Rio Grande in New Mexico for delivering the potential economic value of the sportfisheries and other water recreational activities related to present and future water usage."

The objective and subobjectives were limited to model structural development; the proposal neither addressed verification nor specific management applications. Angler use inventories of fisheries (NMGF mail surveys, e.g., Hatch 1986) and six reservoir habitats and their fisheries (Cole et al. 1985) were conducted in parallel studies designed to simultaneously provide greater insight into effectiveness of New Mexico fishery management in warm-water reservoirs, and to calibrate the model. The completed prototype model was viewed as a promising management tool by NMGF and a second phase of development was begun in 1986 to develop a model structure for all large reservoirs in the mainstream rivers of New Mexico. This report describes the product of the second phase of development.

The basic objective of the second research phase was much the same as the first, but the new project objective read:

> "To link, integrate, refine, and apply hydrological, biological, and economical submodels into a more accurate working model with greater emphasis on watershed processes, and apply the model to sport-fisheries management in major watersheds in New Mexico (e.g., Rio Grande, San Juan, Pecos, Canadian, and Gila)."

Operational Objectives

The project's major operational objectives identified and attained since 1986 were:

1) Simulate management responsiveness of river flows, water levels and material loadings based on USGS data and other data sources, including increased emphasis on watershed processes, over the water year period 1975 through 1987 (or whenever accurate USGS data were made available).

2) Over the same period, 1975 to 1987, simulate management responsiveness of fish-food production dynamics and dynamics of important sport and forage fish populations in major mainstream reservoirs including Heron, El Vado, Abiquiu, Cochiti, Elephant Butte, Caballo, Eaglenest, Conchas, Ute, Santa Rosa, Sumner, McMillan-Brantley, Avalon, and Navajo reservoirs.

3) Simulate reservoir management responsiveness of fish-food production and fish production, and biomass dynamics in cold-water and warm-water sportfish in the reservoir tailwaters of the main rivers.

4) Simulate angler fishing recreational days of activity, fish catch rate, angler impact on fisheries, and angler economic benefits and expenditure (regional income) for the mainstream reservoirs, including the effect of site substitution impacts on angler behavior.

5) Enable model-user modification of important hydrologic, biologic, and sociologic variables to simulate the impacts of management strategies on river-basin fisheries.

6) Interact with other researchers to provide a user-friendly model operable with desk-top, IBM-PC compatible and Data General Computer systems.

7) Document the model structure.

Objective Priorities

The primary purpose intended for RIOFISH is comprehensive planning with emphasis on decision making based on estimated angler benefits and costs. Comprehensive planning implies inclusion of all relevant habitats over all relevant planning-horizon time frames and all probable futures. Therefore, the emphasis in model development was to build a geographically and temporally adaptable model allowing simultaneous analysis of management strategies at many sites within basins and in all important basins. Also a priority was building a model that would allow flexible scenario development for analysis of management strategies interaction with the different planning environments that could emerge over the years. The model structure and uses were to be limited by modeling technology and natural processes, but not by legal agreements (e.g., water-use compacts) or traditional operational modes. Estimation accuracy of total state-wide benefit was judged to be more critical than precision in developing the initial structure. Development accuracy relied mostly on including all factors having a major impact on fish and angler behavior, including impacts not normally considered the traditional purview of fishery management, such as watershed and economic processes.

Within this comprehensive context of model development, it became obvious early in structural development that angler activity was collectively responsive to total sportfish availability and much less responsive to specific combinations of gamefish and panfish within the total catchable biomass. Therefore, individual fish population dynamics were not emphasized for simulations of comprehensive impacts on benefits minus costs.

Heuristic emphasis was placed on developing reasonable approximations of population structures in the context of aquatic communities. Fishery manager model users could then learn how parameters representing various fishery statistics (e.g., fecundity, mortality, minimum reproductive size), and how prediction of various fisheries indices (e.g., morphoedaphic index;

length of growing season index), compared to model dynamics. The development of accuracy and precision in individual population dynamics was recognized from the beginning to be limited by inadequate data. The philosophy was to make the best approximation possible in the context of overall model development so that sensitivity analysis would reveal which information deficits were most critical.

Planning Models Used in Fisheries Management

Recognition of Planning Needs

The need for simulating entire fisheries planning systems, including habitat, fish populations and resource users, has been recognized for well over a decade (Paulik 1969, Lackey 1975, Schaff 1975, and Fletcher 1977), coincidental with federal encouragement of state agency planning. Development and implementation of such comprehensive management planning models has progressed slowly, particularly where uncertain environments and resource interactions dominate policy decisions. Sportfisheries management agencies in the western states are faced with managing large areas with widely dispersed, fluctuating aquatic habitats and rapidly growing angler populations. The agencies are responsible for assessing sportfishery supply, determining angler demand, and managing disparities between supply and demand. The concept of sustained fishery yield remains a strong management commitment, despite limited management revenues and an uncertain habitat base in drought-prone regions.

It is, therefore, no accident that some of the more advanced analyses of game and fish planning systems have been conducted in western states (Crowe 1983). Yet comprehensive planning models have had only limited application. The New Mexico Department of Game and Fish initiated development of RIOFISH in 1980 (Cole et al. 1987a), with the intent of developing a comprehensive tool to analyze the biologic and economic impacts of planning decisions on modeled reservoir ecosystems. Unlike most existing models, which focus on specific issues, RIOFISH was designed to address a wide variety of planning issues. NMGF realized intuitively that no single issue would dominate their planning decisions and many issues were interactive. They elected to have a model structure developed that would reflect issue interactiveness and be flexibly responsive to their needs while recognizing that specific applications (at a site or with a specific strategy in mind) would be less accurate than a model designed especially for that purpose. A model was needed that would provide insight into interactions between management strategy and environment rather than a cookbook to direct specific activities. NMGF wanted a model to stimulate agency thinking rather than one that replaced agency thinking. Effective use of RIOFISH requires careful thought.

Limitations of Existing Models

Although numerous models have been developed to analyze sportfisheries (Taylor 1981, Stewart et al. 1983, Rice and Cochran 1984, Engstrom-Heg and Engstrom-Heg 1984, Sclater et al. 1985, Zagar and Orth 1986, Evans and Dempson 1986), most sportfishery models were designed for specific management or research purposes. Fewer sportfishery models have been designed for broad management planning purposes (Taylor 1981). Fewer management models still are ecosystem-based models (Park, Groden, and Desormeau, 1979). Until recently (Cole et al. 1987a), neither ecosystem-based nor population models were used to estimate economic benefits derived from sportfishery management activity. Few if any of these fishery models have been routinely incorporated into fishery comprehensive planning because they too narrowly focus on specific issues.

The elements of sportfishery planning systems are highly dynamic, socially interactive, and rooted in habitat-ecosystem processes. Habitats are modified, stocking rates and regulations are changed, new species are introduced, other species are controlled, and anglers continuously shift preferences, efforts, and fishing effectiveness. One decision often generates a wave of changes that require other decisions. Models that assume constant or stochastically varying ecological or social environments allow little entry for manager control (e.g., to introduce species), and are not suitable for comprehensive analyses of agency planning systems (Schaff 1975). Most sportfisheries models have emphasized small subsystems of the planning system and concentrated on precise simulation of those subsystems (e.g., Zagar and Orth 1986, Stewart et al. 1983, Bennett, Maughen and Jester 1985). Despite valuable use of such models for research purposes or specific planning issues, they have had limited broad-spectrum planning use because of limited model comprehensiveness. Some of the most promising models allow user access to the model to apply certain management alternatives (Engstrom-Heg and Engstrom-Heg 1984, Taylor 1981). But until these user accessible models incorporate measures of economic benefit, both benefit-cost analysis and estimation of net angler economic benefit will be precluded. Thus, a decision has to be made in advance that a modeled management strategy is the most cost-effective approach before these specialized models can become useful. A comprehensive planning model, like RIOFISH, is a tool that can be used to help determine which specific management strategy or research models are worth pursuing further.

Defining the Planning System to be Modeled

Management by Objectives

We defined the planning system to be modeled by RIOFISH much as Crowe (1983) described it. At the heart of the planning system approach is the concept of management by objective. To implement this concept, some inventory knowledge of the fishery is required. During inventory, program managers identify amounts and distributions of fish resources, resource use, and benefits derived from the fishery. Ideally, the management agency continuously inventories the supply of the resource, the user demand for the resource, and the value attached to the resource. But exhaustive inventory is prohibitively expensive. Planning models offer a cost-effective alternative.

A preliminary strategic plan is developed from the agency mission statement, inventory data and management goals. To pursue goals effectively, quantifiable objectives must be defined and strategies must be outlined to reach the objectives. Quantification of appropriate objectives may be the most critical step in the planning system. An example of a quantifiable objective is: "Increase average angler recreational days at warm-water reservoirs by 20 percent over the next five years." To develop and achieve realistic objectives, management strategies must be proposed to solve problems that impede objective accomplishment.

Figure 1 illustrates how an example series of sportfishery program objectives focusing on benefits may be attained through a series of project strategies. Common strategies for increasing fishing benefits focus on increasing the availability of fish stocks and include stocking, enforcing regulations, improving habitat and increasing access. In a fully developed plan, site specific strategies are defined. The intended output from Figure 1 is increased fish availability. However, the objectives (increased benefits) will be attained only if anglers make use of the improved fishery. In a traditional management system, only inputs (management costs) and processes are measured; whether or not those who were intended to benefit actually did so is not documented. In a planning system approach, the outputs and benefits also are measured to estimate objective accomplishment and to document the effectiveness of management. Processes become strategies only when they are directed at measurable objective accomplishment. RIOFISH and other comprehensive planning models simulate benefits derived from the management process, thus simulating a planning system.

SPORTFISH PROGRAM			
TRADITIONAL		PLANNING SYSTEM	
INPUTS →	PROCESS →	OUTPUT →	BENEFITS
Physical Plant	Stocked Fish	Fish Available	Fish Harvest
Personnel Time	Law Enforce	Fish Avaliable	Recreation Days
Equipment Dollars	Habitat Improved	Fish Avaliable	Angler Benefit
	Access Gain	Fish Avaliable	Merchant Benefit

Figure 1. Examples of traditional and planning system elements as conceived by Crowe (1983). The traditional approach focuses on input costs and processes, whereas the planning system approach focuses on outputs and benefits. Four commonly encountered management activities are used as examples.

Accounting for Uncertainty in the Future

Where stable habitats and angler populations occur, management by objective is simplified because there is a high probability that the future planning environment will remain like the past planning environment. Where habitats, fish populations, and angler efforts fluctuate, numerous alternative futures are possible. In such situations, strategies need to be applied to fisheries that occupy the different possible planning scenarios to attain objectives uniquely appropriate for each planning environment. The failure to create various planning scenarios, representing a range of probable futures, is one of the most common causes for planning failure.

An example will serve to illustrate. Over the next decade, a hypothetical agency in a western state is faced with: a human population growth expectancy between 10 and 30 percent per decade, an expected angler percentage of the population between 15 and 25 percent, an average habitat availability (surface area) between 10,000 and 40,000 hectares, hatchery production unable to expand substantially, and real (inflation corrected) travel cost expected to increase by 10 to 50 percent. From these stated conditions, a series of probable alternative futures can be developed. For this example, low water, high angler population growth rate, and moderate travel cost increase represents a possible future.

One goal of the fish management agency is to sustain or increase public fishery benefits; therefore, the management objectives are framed to increase recreational days of fishing in proportion to the expected human population growth. If high water habitats and low population growth materialize, the strategic objectives will be obtained without effort, because there is no challenge to accomplishment. Under such conditions, the strategic objectives are "empty" objectives, and better and more challenging objectives should be found. In contrast, when high population growth and low-water habitats coincide, it may be impossible for the agency to increase fishing benefits in proportion to population growth. Then the strategic objective to substantially increase benefits would be futile, given limited revenues. A more realistic strategic objective for a severe drought planning environment is the mitigation of expected decreases in benefits.

For this hypothetical agency, each planning environment scenario needs its own appropriate objectives and strategies ready for application when one of the alternative fisheries futures actually materializes. The number of scenarios chosen should not be unmanageable. Between six and eight scenarios may be reasonable. RIOFISH facilitates the testing of proposed management strategies against various planning scenarios deemed possible by NMGF. With such tests, more realistic strategic objectives can be determined. The planning horizon chosen by an agency is also important. Five-year planning horizons are commonly chosen when defining an operational plan. But, many of the most impactive planning strategies influence much more distant futures. A new reservoir, for example, should last well over several decades. Fish species introductions may be permanent. Artificial fish habitats, new access to existing sites, and many other structural changes have long-term impacts. Public habitat management agencies, such as the U.S. Forest Service, have 20- to 50-year plans that influence state agency operations. Even the distributions of law enforcement and stocked fish tend to assume patterns resistant to change within a five-year planning horizon. Therefore, programs based on five-year planning horizons often lag behind the management needs that materialize. Fifteen- to 20-year planning horizons are minimal strategic planning time frames, and 30- to 50-year planning horizons may be better. As long as the department determines the conditions likely to exist at the future time horizon chosen, RIOFISH can be used for any time horizon.

Management strategies are realized through application of the operational plan, which allocates revenues to those project procedures identified in the annual budget. Many more objectives can be proposed than afforded in an agency with limited revenues and authority to increase resource availability. Only a fraction of the projects can be funded. Priority projects usually are identified by contrasting project benefits with management costs, political attractiveness, and special-interest claims. Without adequate means for estimating benefits, project prioritization relies greatly on intuition and political influence.

Sportfishery management based on a planning system can use a model of the planning system like RIOFISH to simulate and analyze relationships among management processes, resource outputs, and user benefits in advance of agency operational planning (Figure 2). For a typical sportfishery program, the primary management processes are stocking, setting and enforcing regulations, habitat improvement, introduction and control of fish populations, improved resource access and improved angler amenities (e.g., toilets, campsites). The planning system model, RIOFISH, simulates the fishery outputs and benefits generated from the processes applied by the model user. Fishery program managers, using RIOFISH, can add benefit-cost analyses to the political and special interest considerations, as long as the managers estimate management costs.

The ideal comprehensive planning model should include enough of the planning system to incorporate all important elements substantially influencing prediction of resource-user response to management activities. One of the best uses of a planning system model, like RIOFISH, is evaluation of project strategy priorities through benefit-cost analyses. A series of proposed projects can be separately or simultaneously entered into the model to determine which sportfishery projects generate the most benefits for their costs and which combination of strategies produces the maximum overall sportfishery program benefits.

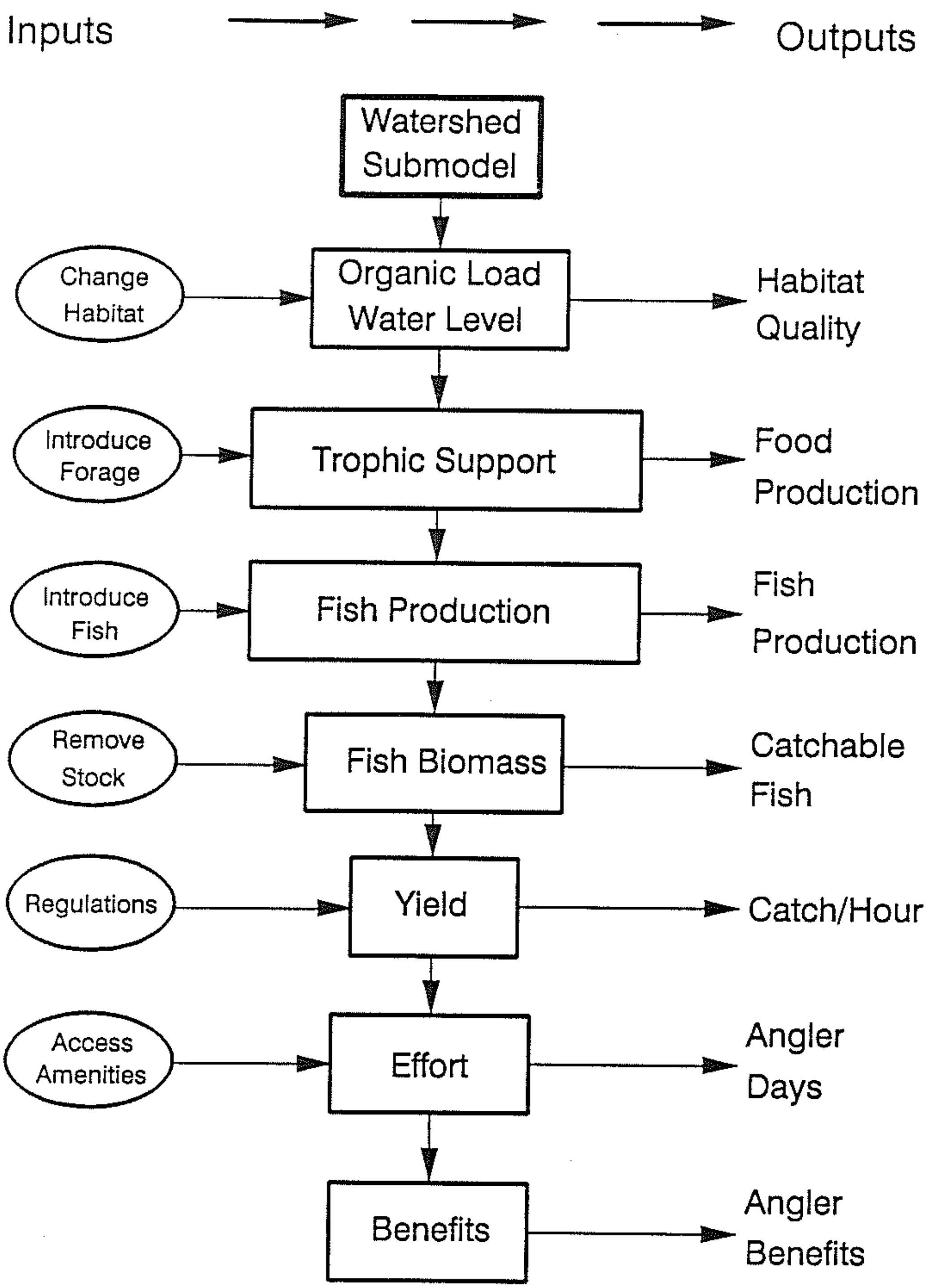

Figure 2. RIOFISH simulates a planning system from input process (management strategy) through planning environment to outputs including benefits. The planning environment includes river basin hydrology, biologic environment and angler environment.

An appropriately designed planning model can be used to analyze the effects of a changing planning environment on the cost effectiveness of program objectives. All critical environmental elements need to be incorporated in the model to analyze environmental impacts. With respect to RIOFISH, changeable environmental elements that greatly influence sportfishery project prioritization in New Mexico are increasing human population numbers, urbanization, severe climatic changes, and changes in travel costs. Using RIOFISH, fishery managers can forecast the effectiveness of alternative management procedures against an array of different environmental conditions, thereby developing different management scenarios.

RIOFISH IN 1989 -- A GENERAL OVERVIEW

Model Structure

This section and the next two sections describe the RIOFISH model. This section is intended to give the reader a broad perspective of model design and utility. The next section shows inputs and outputs for the model. Finally, the construction of the model is described in detail and structural limitations discussed. We believe it is helpful for most readers to review first what the model can provide before the model's construction is reviewed in detail.

RIOFISH simulates a planning environment that includes river-basin habitats, their aquatic communities, the sportfisheries, angler effort, angler impacts and angler benefits. The model first inventories sportfishery habitats and ecosystems. RIOFISH is confined to the main rivers and reservoirs. Smaller tributary streams and reservoirs sites are not included; about half of the state's fishing activity remains outside RIOFISH boundaries.

RIOFISH runs a series of simulations comparing the effect of user-altered planning environments with a reference planning environment. The reference planning environment is a modeled approximation for the 13 water years, 1975 through 1987. The reference simulation is not an exact reproduction of what existed from 1975 to 1985 due to insufficient information for that period. The model represents a facsimile of what <u>could</u> have existed.

An appropriate test for model performance is one that compares the degree of change introduced into the reference scenario by a proposed management scenario with a real-world response (with similar underlying conditions) to a real-world application of management strategy. The model would not fail the test, for example, if the modeled response to stocking of the reference reservoir increased fish catchable biomass by 20 percent, and the observed real-world response was 25 ± 10 percent increased biomass. Also, if the biomass in the initial reference year was 100 kg/ha and the observed (tested) biomass in the lake was 200 kg/ha, the model succeeded in simulating relative change in real-world biomass.

RIOFISH answers the general question "if...what would happen if...?" If reference conditions occurred, what would happen if management strategy scenarios were applied? In more specific terms: - if the Heron Lake fishery existed as defined in the reference scenario (hydrology, biology, management history and use rate), what would happen if fish had been stocked differently? The model can be used to anticipate impacts of natural events as well as management strategies. If average Santa Rosa Lake levels existed as defined in the reference scenario, what would have happened if a severe drought condition had occurred instead?

Once estimates of fish density are introduced into RIOFISH, the 1975-1987 hydrologic record of four major river basins in New Mexico is simulated, including flows of phosphorus and nitrogen nutrient, total suspended matter, and suspended organic matter. In the model, the river basins are subdivided into reservoir segments, each of which can be examined alone or in combination with other reservoirs. Reservoirs in four mainstream river basins are simulated in this version; the Rio Grande, Canadian, Pecos, and San Juan. The hydrologic submodels operate on the basis of semi-monthly mean-flow dynamics. Ecosystem and management processes are simulated to estimate aquatic community and sportfishery outputs on a seasonal and annual basis. Concentrations of nutrients and suspended matter are simulated in each water segment through use of loading-concentration submodels (e.g., Chapra and Reckhow 1979, Bolin, Ward and Cole 1987). In addition to inputs of solar energy and air temperature, primary production is determined from the reservoir exchange rate, water level, and nutrient and suspended matter generated by the hydrology submodels (Figure 3).

Allochthonous organic loading (organic loading from sources outside the aquatic ecosystem) from the watershed is added to the organic loading from primary production to form

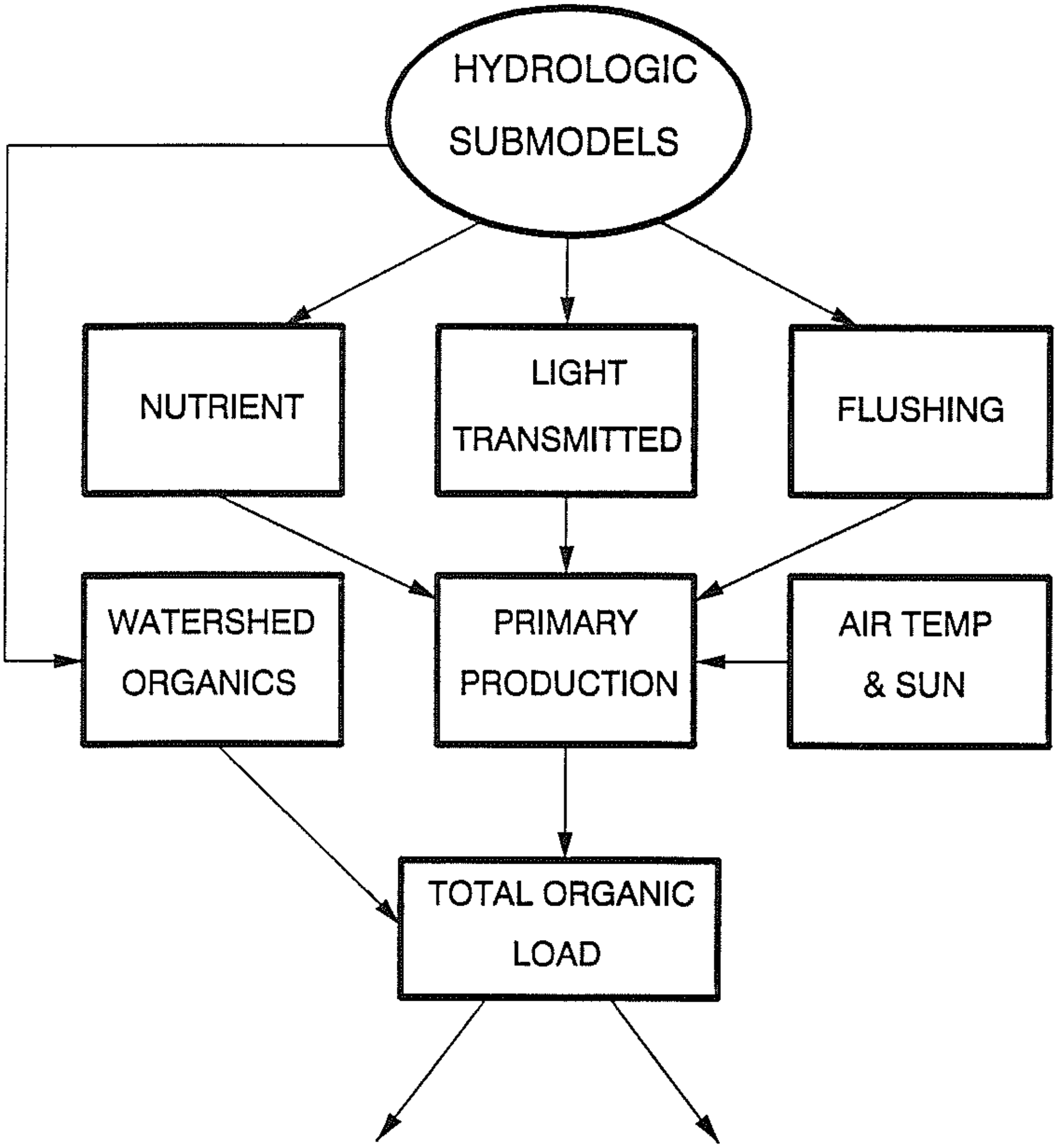

Figure 3. The RIOFISH planning environment incorporates hydrologic and climatic processes that generate organic loading to reservoirs.

the trophic base for estimating fishery outputs, sportfish production, and fish biomass. Allochthonous organic loads are not immediately available for consumer processing until it is made palatable by micro-organisms. A seasonally determined delay to allow for colonization of organic matter by bacterial and fungal decomposers is included. Thus, much organic material that enters in the fall will not be processed until the following spring and summer. An initial estimate of fish density, derived from field surveys or "best" guess, must be entered into the model to obtain outputs different from a "default" estimate included in the model.

The sportfishery benefits estimated by the model include angler recreation days, angler yield, and economic benefits to anglers. Sportfish biomass (via catch rates) and water levels contribute to the determination of angler fishing effort (Figure 4). But other factors also are involved, including proximity of the water segment to concentrations of human populations, site access (roads and boat ramps), facilities, and the availability of alternative sites.

Although total angler catch (yield) is a function of fish biomass, water size, and fish catchability, the most important determinants of angler fishing effort usually are human population density and proximity to the site, much as Weithman and Haas (1982) reported. Therefore, angler fishing effort can, in reality and in RIOFISH, exceed the capacity of a water body to sustain fish yield over several years. A feedback loop exists in the model that simulates angler impact on 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.

Model User Control

RIOFISH allows the angler benefits derived from a diversity of proposed project strategies to be analyzed in advance of actual project selection. Projects can be prioritized by contrasting expected costs with the model-predicted benefits from proposed projects. Different combinations of proposed projects can be examined to estimate which projects should contribute

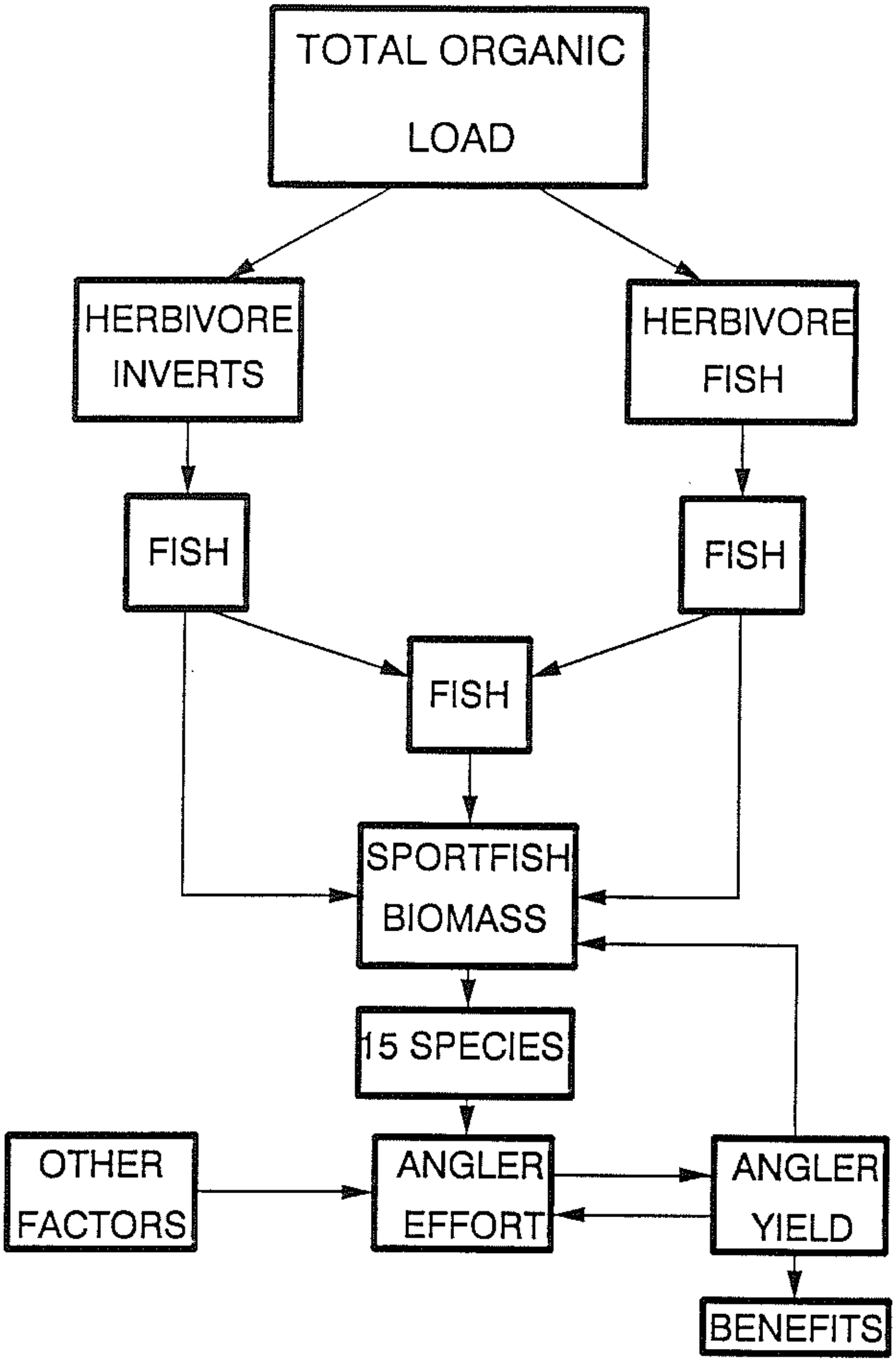

Figure 4. Organic loading is the trophic foundation of RIOFISH that greatly determines the sportfish production and angler yield rate. Total angler activity is influenced by the distribution and density of human population, access to the fishery and other fishing related factors.

most to angler net benefit after all project costs are subtracted from the model estimated gross angler benefit. RIOFISH does not estimate project costs; the model user must do so.

The model can be operated in sequences of up to 5 years for the 13-year period from 1975 through 1987. The final fishery condition generated in a 5th year can be used to initialize the next sequence. In this manner, the whole 13 years may be simulated. Thus, as water levels fluctuate and human populations change, the long-term benefits of the proposed projects emerge. Resource inventories change as the environment changes, simulating real-world conditions. Because many projects have long-term consequences, and management strategies are usually applied over 3- to 5-year periods, the angler opportunities and benefits derived usually should be estimated over a period longer than the next budget year. The design of the model is such that the responses averaged over longer term simulations are more representative of average real world conditions than specific responses are representative of specific annual events.

Examples of project strategies that can be analyzed with RIOFISH include treating for nutrient reduction, fertilizing reservoirs, modifying water-level changes during spawning periods, stocking fish, introducing new species, removing nuisance species, setting harvest regulations, and adding or deleting boat ramps, site-use fees, or state park facilities. Using RIOFISH, managers can analyze the potential for objective accomplishment in advance of actual budget allocation during operational planning.

Model Outputs

A series of modeled outputs are provided that represent an inventory of the resources and benefits derived from resource use. Information about the habitat condition is provided in a series of outputs about water quality, habitat quantity, and fish food production. This information is useful for diagnosing trends and assuring that yields are sustained indefinitely.

Other output reflects the status of the sportfish resource including fish productivity, the catchable fish biomass and, more specifically if desired, the density, biomass and yields of each fish species by age class. This information provides the manager with diagnostic outputs that may help explain the benefits observed and give insight into how to alter project strategies to improve angler benefits or to encourage greater angler efforts.

Benefits may be estimated in various ways with RIOFISH: by the model-estimated fish yield, angler recreational activity (recreational days), and sportfishery net economic value (angler benefits). The yield (harvest) provides information about actual fish meat taken by anglers. The potential yield is an estimate of unused resources. For example, it may signal an under used resource due to inadequate fishing skills that may be improved through education. Under use may also indicate the resource is too costly for anglers to access.

The amount of fishing recreational activity indicates angler satisfaction. More anglers fish more frequently when the experience is satisfying. Unlike economic benefits, which are difficult to verify, recreational activity can be easily measured.

Angler economic benefit is the cost savings to anglers provided by management. If all cost savings are reinvested in more fishing trips, recreational activity and benefits should be closely related. However, if the cost savings are invested elsewhere, the relationship of benefits to angler activity diminishes. Angler benefit is an estimate of the difference between the anglers' overall willingness to pay for fishing and their actual fishing costs. Ultimate management for the angler would provide free fishing with no angler expense.

Such ultimate management would, however, eliminate economic impact, that is, the benefits to those who provide goods and services to anglers. Thus angler expenditure, sometimes incorrectly used as a measure of the benefits to anglers, is actually a benefit to those people whose income depends on angler demands. The relative emphasis an agency assigns to economic impact and angler benefit depends on agency mission and revenue sources available to the department.

Example Plan Uses of RIOFISH

Scenario Development and Forecasting

Table 5 illustrates how RIOFISH predicted fishing opportunities change with an extreme water level management process. The process was applied at reservoirs in the Rio Grande basin that receive variable water runoff from drought-prone watersheds. Four-year averages were used to represent response. A series of forecasting scenarios is examined representing two water conditions different from the low (1975-78) and changing conditions (1978-81). Outputs were predicted to change with changes in water level, but not necessarily as intuition would predict. RIOFISH predicts that the control of water level would boost opportunity, despite no regulation or stocking in certain lakes under certain conditions. Thus, water-level control should be examined further, particularly with respect to upstream and downstream effects and the control costs. Subsequent scenarios could be developed to refine the best water-level management.

Despite the opportunity predicted from water-level control, there may be costly impediments to actual strategy implementations that lie outside the simulation process. The model user cannot forget these costs. RIOFISH does not provide estimates of management costs. The model user has to estimate costs to derive the net benefit (gross benefit less cost). Also, legal constraints must be recognized by the user; they are not incorporated into the model. The costs of water-level management may be excessively large or institutionally infeasible (water agreements must be maintained), even though angler opportunity from such management is predicted to be high.

In establishing priorities for project development, the administrators responsible for determining budget allocation among all projects should be involved in all aspects of model use

Table 5. An example of a planning scenario use of RIOFISH to estimate fishing opportunity changes at several reservoirs at low and changing water levels. The results indicate the effect of water level stabilization for the low water run (1975-78), the changing water run (1978-81). Volumes were held constant and constrasted to the reference run without stocking or regulation.

	Reservoir mean value over four years		
Year/Parameter	Heron	Cochiti	Caballo
1975-78 (low water)			
Catchable sportfish (kg/ha)	-23.0[1]	+46.7	-42.0
Fish production (kg/ha/yr)			
Pan fish	+ 0.1	+ 1.4	-26.9
Game fish	-12.1	+16.8	-19.0
Carp-sucker	+ 7.5	+94.1	+123.6
Catch rate/hr	- 0.20	+ 0.18	- 0.15
1978-81 (changing water)			
Catchable sportfish (kg/ha)	- 3.6	-32.6	+66.6
Fish production (kg/ha/yr)			
Pan fish	+ 0.1	-10.3	- 4.7
Game fish	- 2.2	-13.6	+44.2
Carp-sucker	+ 9.9	- 8.2	+149
Catch rate/hr	+ 0.5	- 0.5	- 0.2

[1]/For example, holding water levels constant at Heron Lake did not offset stocking and regulations under the 1975-78 conditions and the run comparison indicated that catchable stocks would decrease an average of 23.0 kg/ha over the four years.

for operational planning purposes. Those administrators need to know the costs of all options to make a reasonable decision. Those managers who conduct field inventory and evaluation of objective attainment need to integrate their field work with model use and verification; field work is needed particularly to evaluate simulation predictions for the most costly projects and for projects with the most doubtful simulations.

A common management technique is to stock reservoirs with fingerling fish to replace lost fish recruitment from water-level fluctuation or other impacts. Also, length and numerical limits are often applied to better distribute the catch of scarce adult stocks among anglers wherever scarce stocks of adult fish limit reproduction, recruitment and fish population maintenance. The effects of stocking and regulation, as they were practiced over the period of record, were examined and results are presented in Table 6. Generally, RIOFISH predicts that cessation of stocking and regulation would depress catchable stocks and sportfish production over the four-year period, but it may not necessarily reduce catch rate. This apparent inconsistency results because all fish are not equally harvestable. The next step in model use should be to examine the effects of different stocking and regulations when water levels are low.

An increased estimated angler impact at Cochiti Reservoir, would eventually depress fishing opportunity (Table 7). This scenario compares the effect of using a totally compensatory fishing mortality submodel (when fishing mortality exactly replaces natural mortality and total mortality does not change) and a totally additive mortality submodel (when all fishing mortality is added to natural mortality and natural mortality increases). In all water-level conditions in the reservoirs, the fisheries will fail to provide as much opportunity when the fishing mortality is additive. The differences indicate the importance of correctly estimating fishing mortality effects.

Table 6. An example of impact of angler opportunity of stocking and regulation at one reservoir in New Mexico for low (1975-78), changing (1978-81), and high (1984-87) water levels. The results indicate the net change between the reference runs with stocking and regulation and the alternative of not stocking and regulating.

	Reservoir mean value over four years		
Year/Parameter	Heron	Cochiti	Caballo
1975-78			
Catchable sportfish (kg/ha)	+ 1.8	+13.0	-36.3
Production (kg/ha/yr)			
Pan fish	--	+ 0.1	- 1.6
Sport fish	+14.0	+53.6	+30.2
Carp and suckers	- 0.3	- 0.8	- 0.1
Catch rate/hr	- 0.25	+ 0.35	- 0.68
1978-81			
Catchable sportfish (kg/ha)	+12.5	+101.7	+17.45
Production (kg/ha/yr)			
Pan fish	--	- 0.1	- 0.2
Sport fish	+24.6	+151.7	+40.1
Carp and suckers	- 0.7	- 0.8	+ 9.6
Catch rate/hr	+ 0.13	+ 0.43	+ 0.1
1984-87			
Catchable sportfish (kg/ha)	+ 9.0	+21.2	+13.5
Production (kg/ha/yr)			
Pan fish	--	+ 0.38	- 0.63
Sport fish	+24.0	+25.4	+ 9.0
Carp and suckers	- 0.9	+ 3.0	--
Catch rate/hr	- 0.04	+ 0.17	- 0.49

Table 7. An example of the impact of angler fishing mortality on fishing opportunity for several reservoirs. The results indicate the net change between the reference runs with compensatory mortality[1] and the management-strategy run with fishing mortality altered to an additive mortality.[2] Runs were stocked and regulated as they were historically.

	Reservoir mean value over four years		
Year/Parameter	Heron	Cochiti	Caballo
<u>1975-78 (low water)</u>			
Catchable sportfish (kg/ha)	- 9.4[3]	- 5.8	-53.6
Fish production (kg/ha/yr)			
Pan fish	--	- 1.6	- 0.2
Game fish	- 3.9	- 3.6	-30.0
Carp and suckers	- 0.1	- 3.4	- 0.07
Catch rate/hr	+ 0.01	- 0.02	- 0.07
<u>1978-81 (changing level)</u>			
Catchable sportfish (kg/ha)	+23.7	-121.2	-34.4
Fish production (kg/ha/yr)			
Pan fish	--	- 3.8	-12.7
Game fish	-28.9	-156.8	-49.0
Carp and suckers	- 0.6	- 8.5	-13.1
Catch rate/hr	- 0.27	- 0.49	- 0.12
<u>1984-87 (high water)</u>			
Catchable sportfish (kg/ha)	-11.6	- 8.2	-26.4
Fish production (kg/ha/yr)			
Pan fish	--	- 0.4	- 1.1
Game fish	- 0.6	- 3.2	-13.1
Carp and suckers	- 0.2	- 3.1	- 5.0
Catch rate/hr	- 0.28	- 0.03	- 0.05

---

[1]/In compensatory mortality, fish mortality exactly replaces natural mortality.

[2]/In additive mortality, fish mortality is added to natural mortality.

[3]/Mean catchable sportfish, for example, decreased by 9.4 kg/ha when the totally additive fishing mortality was used instead of totally compensatory mortality.

Predicted annual variation in outputs can be examined in RIOFISH (Table 8). Within a five-year period, any one management policy can have consistent to variable year-to-year effects. Multiple-year mean values may be more realistically contrasted because most policies are difficult to alter annually. Also, estimation precision is reduced on an annual basis. Even so, anticipation of dramatic shifts in opportunity may signal a need for mitigative action during similar years or at least forewarn management that exceptional circumstances can occur within the operational planning horizon. More detailed examination of fish population outputs provided by RIOFISH may reveal the underlying model conditions responsible for such shifts.

The model can be used to simulate the hydrology of next year's fisheries. There are two methods to do this. In both methods, the most recent updating of flows and operational conditions must be gathered from USGS and water management agencies. In the first method, the closest approximation to a sequence of years like the last several years is chosen from the record. The last year of the sequence is considered next year's condition. One would choose 1980-84 for example, if, by midwinter, runoff conditions look like those of the monitored last year, 1984. The outputs for 1984 modeled conditions then serve as a simulation. If a run-off estimate is available for next year, the hydrology of the 1984 modeled year can be modified to match.

The second method requires additional steps. Basically, all of the sequence in the 1980-84 example is hydrologically modified to mimic the most recent years on record, in this example, 1985-89. The last year, 1989 is simulated from the extension of the 1985-88 period.

Inventory

The model can be used to estimate inventories of fishery habitats, fish populations, and catch rates. Inventories of angler use rates and success are relatively cost-effective when compiled from mail or telephone surveys. However, fewer surveys need to be conducted once

Table 8. An example of annual variation in fishing opportunity generated from a management strategy applied to the reference scenario in several New Mexico reservoirs.

	Heron	Cochiti	Caballo
Catchable fish (kg/ha)			
1984	+ 0.5	+ 2.2	+ 0.0
1985	+ 2.8	+ 1.7	+21.7
1986	+12.0	+27.7	+16.4
1987	+23.5	+20.1	+35.1
Panfish Production (kg/ha/yr)			
1984	--	0.0	0.0
1985	--	0.0	- 0.1
1986	--	- 0.2	- 0.2
1987	--	0.0	- 2.3
Sportfish Production (kg/ha/yr)			
1984	+ 7.8	+ 4.5	+ 0.0
1985	+17.7	+13.0	+ 1.6
1986	+25.9	+43.9	+ 9.7
1987	+44.5	+27.7	+24.9
Carp & Sucker Production (kg/ha/yr)			
1984	0.0	- 0.1	0.0
1985	- 0.2	0.0	0.0
1986	- 0.4	- 0.1	0.0
1987	- 1.1	+ 0.1	0.1
Catch Rate (fish caught/hr)			
1984	+ 0.84	+ 0.01	- 0.05
1985	0.00	+ 0.05	- 0.44
1986	+ 0.32	+ 0.36	- 0.43
1987	+ 0.40	+ 0.16	- 1.05

relationships among habitats, human populations and fisheries are well represented in a model, and the simulations are reasonably accurate (i.e., as precise and accurate as direct surveys). Instead of annual surveys, biannual or triennial surveys may be justified, releasing funds for other planning strategies.

Fishery population surveys are more expensive to conduct than angler surveys by telephone or mail. As with most agencies, NMGF is able to make statistically valid annual surveys of only a small fraction of the state's waters. A decade or more may be needed to sample all important fisheries effectively. RIOFISH can be used to extend the fishery inventory by simply estimating this year's populations from an extension of the last few years of simulation. As field inventory estimates increasingly resemble the modeled estimates, managers can increase their reliance on the model estimates at sites with no field inventories. Field inventories can also be used to help refine the model through improved coefficient calibration to fit specific conditions at those sites. An inventory example (Table 9) is provided for 1987 in the mainstream reservoirs.

Issue Management

The New Mexico Department of Game and Fish is lobbied by concerned anglers to "do something" about a long history of fishery problems including low catch rates, declining habitat quality, inadequate access, inadequate regulations, massive fish kills, and nuisance weeds. Especially when inventories and departmental intuition are in agreement, an analysis of the problem is in order and cost-effective solutions should be applied, whenever possible. Four examples of management issues are provided below with descriptions of how RIOFISH may be used to analyze impacts and help make management decisions.

The Water Loss Issue: A recent water master decision could have directed an average of 36,000 acre-feet a year of water from New Mexico to Texas. Depending on water-runoff

Table 9. A model simulated inventory of 1987 mainstream reservoir characteristics generated as output from RIOFISH, following a five-year model run.

Lake	Mean Surface Area (Acres)	Catchable Sportfish[1] Kg/hectare	Panfish & Sportfish Production Kg/ha/year
Rio Grande			
Heron	5,637	197	46
El Vado	2,597	500	38
Abiquiu	3,424	342	135
Cochiti	1,207	663	598
Elephant Butte	27,403	648	104
Caballo	4,657	296	79
Canadian			
Eagle Nest	1,870	218	44
Conchas	6,637	979	185
Ute	1,906	2,137	544
Pecos			
Santa Rosa	795	2,111	475
Sumner	1,290	1,334	218
McMillan	4,047	136	52
Avalon	687	204	58
San Juan			
Navajo	14,178	82	36

[1]/includes carp and suckers.

rates, and when and where the water is delivered (stored in Texas reservoirs for example), the impact on Pecos river reservoirs could have had small to catastrophic fisheries effects. RIOFISH can be used to analyze the various water transfer proposals to determine their relative impacts on angler benefits. For the Texas example, the least harmful situation would have existed if all water transferred to Texas were stored in the New Mexico Pecos reservoirs as it has been in the past. In a scenario with intermediate impact, Texas could have requested that all water be stored in Brantley Reservoir, the closest New Mexico reservoir to Texas users. That would result in massive relocations of water southward in the basin but the water would remain in New Mexico. In the worst case scenario, all of the water would have been transferred out-of-state to Texas storage facilities.

As the decision turned out, New Mexico water users paid to keep the water in New Mexico. But for similar cases, RIOFISH can be used to help settle final water distribution arrangements to the extent fisheries concerns are considered. The economic benefits are most helpful in this instance. Once the distribution is decided, a series of fishery management strategies may be tested to estimate the best way to mitigate negative impacts on angler benefits or local economies.

<u>Lake Fertility Issue</u>: Although high water years are associated with high overall fish yields from many reservoirs, Navajo Lake may be exceptional. Anglers have complained about low catch rates and slow-growing fish. One proposal is to fertilize Navajo Lake to generate greater zooplankton production and to stimulate fish growth. Another proposal is to stock more fry and fingerlings of various species. Combinations of proposals can be analyzed and costs contrasted with the benefits predicted. Excessively high management costs for all alternatives may indicate a need to provide substitute fisheries by concentrating greater management effort on more manageable local waters.

The Declining Habitat Issue: Numerous small reservoirs across the state are filling with sediments and suffer from severe oxygen depletion that limits potential fish yield. Anglers in various locations have requested improvement by deepening or other means. Dredging greater depth is expensive and may not improve catch rate much, whereas destratification and bottom aeration are much more cost effective and more likely to increase catch rates. The biological part of RIOFISH can be disconnected in the Fortran version (non-user-friendly) of the model and used to analyze the impacts of dredging and destratification. Input data required include: area-depth-volume curves for dredged and undredged lake basins, estimates of draw down rates if any; initial fish biomass; and, estimated inputs of water, suspended matter, nutrient, organic matter, air temperature, solar energy and angler days of activity (from card survey estimates). A status quo condition with stocking and regulations is simulated without dredging or destratification, and a management strategy implementation is run for comparison. The net changes in sportfish productivity, catchable fish mass, and yield rates of fish are the primary measures of procedural impacts. For this purpose, the model has to be used with the help of the model developers; it cannot be done by the manager alone.

The Introduction of Forage Fish Issue: A number of small, warm-water lakes in New Mexico are eutrophied (nutrient enriched and oxygen depleted in bottom waters) and have poor predator-prey ratios. Complaints about low catch rates and nuisance algal growths may be jointly managed by introductions of herbivorous threadfin shad. Given similar input data to that described in the previous section, modeled lakes can be stocked annually with threadfin shad and regulated so as to protect larger predators more effectively in the Fortran version of the model. Estimated responses in angler catch rates and fish productivity can be used to make decisions. This use of the model has to be done with the model developers; it cannot be done by the manager alone.

The New Reservoir Issue: Recently, several new reservoirs have been considered for construction. Reservoir potential production and yield can be estimated with RIOFISH in advance of construction. This use of the model must be done cooperatively with the modeling team.

Heuristic Analysis of Fishery "Statistics" and Indices

Numerous indicators are used by fishery managers including proportional stock densities, predator-prey ratios, the morphoedaphic index, growth rates, estimated catch rates (total yield rates), and fish young-of-year recruitment. The relationship of these indices to aquatic communities is not always intuitively obvious. RIOFISH can be used to analyze how these various indices reflect modeled aquatic community dynamics and provide insight into real community dynamics. For example, does variation in catch rate necessarily indicate the variation in the fish populations present and the satisfaction of anglers as indicated by recreational days or benefits measured? What types of population performance and catch rates do the proportional stock density index predict in modeled populations? Is the yield predicted by the morphoedaphic index also predicted by the model, and what modeled conditions appear to make the morphoedaphic index nonpredictive? Many widely used indices of fish population dynamics can be applied to the modeled fish communities and provide insight into what the indices may or may not mean in real-world situations.

Sensitivity Analysis

Managers and researchers can use RIOFISH to examine the impact of uncertain estimations on model performance. RIOFISH can be a powerful tool for analyzing research needs. The various inputs in the model are simulated with different levels of statistical certainty. Whereas, for example, solar radiation is fairly accurately estimated, nutrient concentrations are less certain. Whereas reservoir exchange rates and depths are closely approximated, concentrations of allochthonous organics and total suspended matter are much less certain. Whereas the fecundity/size and size and maturity relationships of fish species are quite well documented for many species, the relationships between egg survival and water-level fluctuation are much less certainly known. Initial fish biomass may range from high certainty in a censured population to low certainty in some survey situations. These and numerous other input variables can be analyzed to determine the impact they have on model simulations. Those coefficients that are both uncertain and have high impacts on model simulation outcome are top priority research topics. Uncertain but low-impact variables are of lower priority.

Using sportfish productivity and catch rate as output variables, RIOFISH reveals that it is sensitive to poor estimates of allochthonous total suspended and organic matter, and relatively insensitive to nutrient loadings that are likely to occur. It also indicates that after the second year of a model run, the model output is relatively insensitive to inaccurate estimates of initial fish density. This result indicates a need to emphasize research that enables more accurate estimates of allochthonous loadings. Under the conditions of water-level fluctuation that occur in the test reservoirs, the water-level fluctuation variable appears to be less important as an effector of fish recruitment than is the organic loading estimator. Low spawning success from water-level fluctuation still leads to high fisheries recruitment of young fish when food (based on organic loads) is plentiful. Even stable water levels can generate fish classes with low abundance when organic loading is low.

RIOFISH STRUCTURE AND OPERATION

The following section describes outputs and inputs as provided on actual monitor displays. Ideally, the reader will operate the model while reading this section.

Setting Up Reference Simulations

Basins and Timeframe

The user-friendly version of RIOFISH provides outputs for the Rio Grande, Canadian, Pecos and San Juan rivers. The four basins cannot be run on RIOFISH simultaneously. The user must first choose a basin for simulation (Table 10). For each basin, a reference simulation may be made for water years 1975 (October 1974) through 1987 (October 1987), in which simulated conditions are approximations of historic hydrologic conditions.

Introduction to Menu System

In the first of four menus, a series of nine menu options is provided to examine reference simulations (Table 11). The first option provides information about the menu system. The four menus: 1) display the references simulation ("historic") data, 2) set up a scenario for model run, 3) execute the run, and 4) examine run results in detail. The first menu has a help option (option 2), which provides a brief description of menu purpose and what each option provides. Because RIOFISH is frequently updated, the third menu option identifies the version of the model.

The fourth menu option is a map (Figure 5). As with any monitor display, the user has the choice of printing or not printing the map. The map includes all model-relevant basin segments, in this case the Rio Grande. Reaches between reservoirs are defined by the location of the reservoirs, or by location USGS monitoring stations. Reaches above or below reservoirs

Table 10. Once RIOFISH is called up, the first screen provides a copyright statement, the date, general composition of the RIOFISH version, relevant bulletins, and an initial menu. The menu allows the user to choose a river system (Printed as screen appears).

```
/-------------------------------------------------------------\

               APL*PLUS PC APPLICATION DEVELOPMENT SYSTEM

:-------------------------------------------------------------:

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registered  trademark  and  service  mark  of  STSC,  Inc.
\-------------------------------------------------------------/

  3 MONSTER SAVED 11/20/1989 15:06:33
****** SUMMER 1989 VERSION OF RIO FISH MODEL ******


RIOGRANDE, CANADIAN, PECOS AND SAN JUAN RIVER SYSTEMS
         24 FISH SPECIES IN RESERVOIRS
         WATER YEARS 1975 THROUGH 1987

SOME CHANGES HAVE BEEN MADE IN THE LAKE BIOLOGY MODEL
THE ECONOMICS MODEL IS NEW, COVERS ALL LAKES, AND IS MUCH MORE
POWERFUL

WHICH RIVER SYSTEM?

 1  RIO GRANDE
 2  CANADIAN
 3  PECOS
 4  SAN JUAN
```
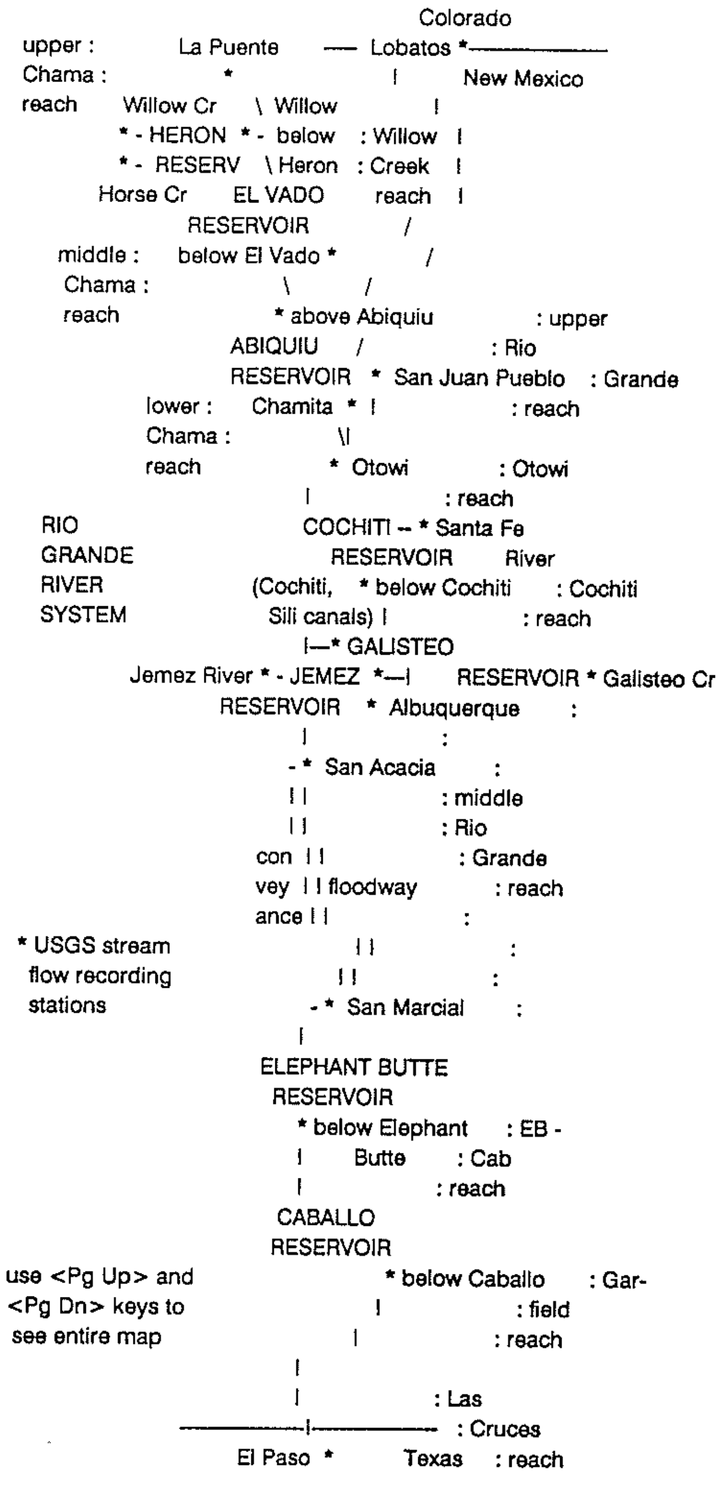

Table 11. The level I beginning menu offers the model user initial choices for simulating waters within the basin already identified (Printed as screen appears).

```
MENU:        BEGINNING
LEVEL:       1
CALLED BY:   STARTUP FUNCTION
OBJECTIVE:   INTRODUCE MENU SYSTEM, EXAMINE HISTORICAL DATA BASE

          1 HELP INFORMATION ON THE MENU SYSTEM
          2 HELP INFORMATION ON THIS MENU
          3 VERSION OF THE MODEL


          4 LOOK AT THE MAP
          5 PLOT USGS MEASURED IN AND OUT FLOWS AND OTHER DATA
            FOR ANY RESERVOIR

          6 PLOT USGS MEASURED FLOW DATA FOR ANY STREAM
          7 MAKE HARD COPY OF REQUESTED PRINTOUTS NOW

          8 PROCEED TO MENU FOR SETTING UP A SCENARIO


          9 QUIT

PLEASE CHOOSE (1 2 3 4 5 6 7 8 9) ===>
```



```
                                    Colorado
 upper :       La Puente   —— Lobatos *————————
 Chama :           *              |     New Mexico
 reach    Willow Cr  \ Willow        |
          * - HERON * - below  : Willow |
          * - RESERV  \ Heron : Creek  |
        Horse Cr    EL VADO     reach  |
                RESERVOIR          /
     middle :  below El Vado *       /
     Chama :            \     /
     reach             * above Abiquiu        : upper
                   ABIQUIU    /          : Rio
                   RESERVOIR   * San Juan Pueblo  : Grande
            lower :  Chamita  * |           : reach
            Chama :          \|
            reach           * Otowi        : Otowi
                          |          : reach
   RIO                    COCHITI -- * Santa Fe
   GRANDE                   RESERVOIR     River
   RIVER             (Cochiti, * below Cochiti  : Cochiti
   SYSTEM              Sili canals) |        : reach
                          |—* GALISTEO
           Jemez River * - JEMEZ *—|  RESERVOIR * Galisteo Cr
                  RESERVOIR    * Albuquerque     :
                          |          :
                        - * San Acacia    :
                         | |         : middle
                         | |         : Rio
                      con | |          : Grande
                      vey | | floodway    : reach
                      ance | |          :
 * USGS stream                | |          :
  flow recording             | |          :
  stations                - * San Marcial   :
                         |
                      ELEPHANT BUTTE
                       RESERVOIR
                         * below Elephant  : EB -
                         |    Butte    : Cab
                         |           : reach
                        CABALLO
                       RESERVOIR
use <Pg Up> and                  * below Caballo  : Gar-
<Pg Dn> keys to                 |           : field
 see entire map               |           : reach
                         |
                         |           : Las
               ———————————|—————————— : Cruces
                    El Paso *     Texas   : reach
```

Figure 5. The map provided for the Rio Grande Basin when that output is requested from RIOFISH. Similar maps are provided for each of the basins (Printed as screen appears).

are defined by USGS stations alone. The basin reservoirs simulated in RIOFISH include:

1) Rio Grande Basin - Heron, El Vado, Abiquiu, Cochiti, Jemez, Galisteo, Elephant Butte and Caballo.

2) Canadian Basin - Eagle Nest, Conchas, Ute.

3) Pecos - Santa Rosa, Sumner, McMillan (Brantley), Avalon.

4) San Juan - Navajo.

The fifth option allows the user to plot hydrologic information for any one to all of the reservoirs at half-month intervals (14 to 15.5 days). The information that can be plotted graphically (an example is Figure 6) includes evaporation, rainfall, volume (acre-ft), inflows from up to three sources, including one general watershed source, and outflows through up to 3 outlets. Because the plot axis is a constant size, the maximum and minimum dimensions vary for each plot. These plots provide the pattern of flows, whether erratic, stable, or seasonal. Most information for the simulations producing these plots is provided from USGS and U.S. Weather Service records. Watershed inputs are approximated (by difference from) a mass balance examination of water budgets in each reservoir. The watershed estimates are preliminary and the most uncertain of the hydrologic information provided. All of the graphic outputs can be provided by year, for up to a five-year period starting in 1975 and ending in 1987. The user also has the option (Option 6) of plotting, half-monthly, any flow data for USGS-monitored stream segments in the Basin as well as sum estimates of unmonitored watershed flows (including negative estimates from mass balance determination).

The seventh menu option allows the user to print any of the previous transactions.

The eighth option routes the model user to the next menu. The user may also quit here (ninth option). If option 8 is chosen, the first of two Level 2 menus (Table 12) appears.

```
COCHITI  MODEL RESULTS

OTOWI                  (INTO COC) M
353.8      TO 8353.1   BY 275.84

CALCULATED AREA IN ACRES          A
1005       TO 1804     BY 27.552

    MIN                         MAX
OCT :  MA          :              :
 79 :  MA          :              :
NOV :   A M        :              :
 79 :   A M        :              :
DEC :   A M        :              :
 79 :   AM         :              :
JAN :-M-A----------:--------------:
 80 :  MA          :              :
FEB :  MA          :              :
 80 :   A          :              :
MAR :   A          :              :
 80 :   A          :              :
APR :    A         :              :
 80 :            AM:              :
MAY :              :      A       :
 80 :              :     A  M     :
JUN :              :         MA   :
 80 :    A         :  M           :
JUL :   A      M   :              :
 80 :   A          :              :
AUG :   A          :              :
 80 : M A          :              :
SEP :  MA          :              :
 80 : M A          :              :
OCT : M A          :              :
 80 : M A          :              :
NOV :   AM         :              :
 80 :   AM         :              :
DEC :   AM         :              :
 80 :    A         :              :
JAN :--MA----------:--------------:
 81 : M A          :              :
FEB : M A          :              :
 81 :  M A         :              :
MAR :  MA          :              :
 81 : M  A         :              :
APR : M A          :              :
 81 :  MA          :              :
MAY :   MA         :              :
 81 :  MA          :              :
JUN :  MA          :              :
 81 :   A          :              :
JUL : M A          :              :
 81 :   A          :              :
AUG :  MA          :              :
 81 : M A          :              :
SEP : M A          :              :
 81 :M  A          :              :
```

```
SUSPENDED SEDIMENTS IN MG/L       S
0.17       TO 1035.2     BY 35.69

PHOSPHORUS IN MG/L                P
8E³3       TO 0.104      BY 3.3103E

    MIN                         MAX
OCT : S           P:              :
 79 : S           P:              :
NOV : S           P:              :
 79 : P            :              :
DEC : SP           :              :
 79 : S      P     :              :
JAN :-S------------:P-------------:
 80 : S            :P             :
FEB : S            :       P      :
 80 : S            :  P           :
MAR : S            : P            :
 80 : SP           :              :
APR : S      P     :              :
 80 :  S           :     P        :
MAY :     S        :          P   :
 80 :      S       :          P   :
JUN :     S        :     P        :
 80 :    S        P:              :
JUL :             PS              :
 80 :  S           :      P       :
AUG :  S           P              :
 80 :  S          P:              :
SEP : S            : P            :
 80 : S            :    P         :
OCT : S     P      :              :
 80 : S      P     :              :
NOV : S      P     :              :
 80 : S P          :              :
DEC : S    P       :              :
 80 : S        P   :              :
JAN :-S------------:--P-----------:
 81 : S            :     P        :
FEB : S            : P            :
 81 : S           P:              :
MAR : S        P   :              :
 81 : S            :P             :
APR : S            :   P          :
 81 : S            P              :
MAY : S            :       P      :
 81 :S      P      :              :
JUN : S        P   :              :
 81 : S           P:              :
JUL : S            :            P :
 81 : S     P      :              :
AUG : S            :        P     :
 81 : S            :   P          :
SEP : S            :        P     :
 81 : S            :     P        :
```

Figure 6. An example graphic display showing inflow volume and reservoir surface area (left) and the total phosphorus and suspended solids concentrations (right). The entire five-year run was cut for figure presentation (Printed as seen on the screen).

Table 12. The level 2 scenario menu provides the opportunity to choose a reservoir or reservoirs for simulation (option 3). Alternatively the user may look at the top of the map or return to the beginning menu (Printed as seen on the screen).

```
MENU:       SCENARIO
LEVEL:      2
CALLED BY: BEGINNING MENU
OBJECTIVE: SET INPUT CONDITIONS DEFINING THE SCENARIO FOR A MODEL
           RUN

         1 HELP INFORMATION ON THIS MENU

         2 LOOK AT THE MAP
         3 SEE / RESET RESERVOIRS, YEARS FOR THIS SIMULATION


         9 RETURN TO BEGINNING (DATA BASE) MENU

PLEASE CHOOSE (1 2 3 9) ===>
```

The second menu display of Level 2 provides a help option (Option 1), a look at the map for geographical reference (Option 2), a review or opportunity to reset inputs (option 3), and a return to the Level 1 menu (Option 9) (Table 12). Option 3 must be chosen to make any modifications or review output other than the map. The user is given the choice of reservoirs to simulate (from one to all in any combination) and which water years (from 1975 to 1987) to simulate in 1- to 5-year sequences. The model can be used to simulate the entire 13-year sequence if fish density outputs from the end of each 5-year run are used as fish density inputs for the next 5-year run. The fish density distributions among age groups is reset to the original each time a five-year sequence is started. The original represents a stable distribution based on the total mortality rate.

After the sites and time frames have been chosen, the Level 2 menu provides several new options (Table 13), including: Option 4) resetting all linkage (between submodels) values to the start-up values (default values), if any have been previously changed in the model run; Option 5) reviewing or resetting any hydrologic variables or inputs; Option 6) reviewing or resetting any biological variables or inputs; Option 7) reviewing or resetting any economic variables and inputs; and Option 8) proceeding to the next menu level, which runs the model. If the intent is to make an historic simulation, only the review capability of the menus option is used before proceeding to run the model using Option 8.

Option 8 provides access to a series of model run choices in the Level 3 menu (Table 14): Option 1) a help option briefly describing each option; Option 2) a run with hydrological, biological and economic models linked; Option 3) a run with hydrological and biological submodels linked; Option 4) a run with biological and economic submodels linked; Option 5) the hydrological submodel alone; Option 6) the biological submodel alone; Option 7) the economic submodel alone; and Option 8) a return to the scenario development

Table 13. Level 2 menu options include reviewing and resetting of hydrologic, biologic, and economic parameters (Printed as seen on the screen).

```
MENU:       SCENARIO
LEVEL:      2
CALLED BY: BEGINNING MENU
OBJECTIVE: SET INPUT CONDITIONS DEFINING THE SCENARIO FOR A MODEL
RUN

         1 HELP INFORMATION ON THIS MENU

         2 LOOK AT THE MAP
         3 SEE / RESET RESERVOIRS, YEARS FOR THIS SIMULATION
         4 RESET ALL LINKAGES TO SESSION STARTUP VALUES

         5 SEE/RESET/CHANGE HYDROLOGIC VARIABLES AND INPUTS
         6 SEE/RESET/CHANGE BIOLOGICAL VARIABLES AND INPUTS
         7 SEE/RESET/CHANGE ECONOMIC VARIABLES AND INPUTS

         8 PROCEED TO MENU FOR RUNNING THE MODEL
         9 RETURN TO BEGINNING (DATA BASE) MENU

PLEASE CHOOSE (1 2 3 4 5 6 7 8 9) ===>
```

Table 14. The level 3 model run menu called up by option 3 in the scenario menu (level 2) allows the user to run several combinations of submodels or each submodel singly. If a scenario already has been run, the user may proceed from this menu to examining results or the user can return to the level 2 scenario menu (Printed as seen on the screen).

```
MENU:       MODEL.RUN
LEVEL:      3
CALLED BY:  SCENARIO MENU
OBJECTIVE:  RUN ALL OR PART OF THE MODEL BASED ON SELECTED SCENARIO


          1 HELP INFORMATION ON THIS MENU

          2 RUN HYDROLOGICAL, BIOLOGICAL, AND ECONOMIC MODELS
            LINKED

          3 RUN HYDROLOGICAL AND BIOLOGICAL MODELS, LINKED
          4 RUN BIOLOGICAL AND ECONOMIC MODELS, LINKED


          5 RUN HYDROLOGICAL SUBMODEL ALONE
          6 RUN BIOLOGICAL SUBMODEL ALONE
          7 RUN ECONOMIC SUBMODEL ALONE

          8 RETURN TO SCENARIO DEVELOPMENT MENU
          9 PROCEED TO MENU FOR EXAMINING RESULTS IN DETAIL

PLEASE CHOOSE (1 2 3 4 5 6 7 8 9) ===>
```

menu (previous menu). The choices provided for running the model are designed for economy in model use. Running time is a function of model comprehensiveness. Whereas a run of the hydrology model only for one year at one site takes seconds on a PC, a run of all three submodels linked for all waters in the Rio Grande Basin for a full five years may take more than an hour on a PC. These time estimates are approximate, depending on the hardware used.

The choice of model run must be sensible and related to run purpose as well as time economy. The user must be aware of the interactiveness that exists among submodels. For example, if a simulation run is made in which the user is trying to predict the outcome of a management strategy on, biomass of catchable fish, he or she must recognize that changes in the intensity of angler use (determined partly by the economic submodel) could play an important role in determining the catchable biomass over a sequence of several years. But, if the fishery manager is interested in better understanding the interactions of fish population parameters in the model, he or she may elect to assume some historical background level of fishing intensity without using the economics submodel. Because of the interactiveness of submodels, it is probably best for a new model user who is concerned about predicting full responses to management strategies, to run all three submodels together. Then RIOFISH can be run in various combinations of submodels to determine the extent of submodel interaction effect on output and the suitability of single submodel simulations.

First-time RIOFISH users often do not understand that the reference simulation for habitat conditions that existed in 1975-87 is a benchmark run for a series of subsequent comparative simulations. New users often expect that the reference simulation is in itself a meaningful simulation exercise instead of the first in a series of simulations, which is to be compared to simulations of altered conditions. The change in output from the reference to the altered condition is the measure of impact on the planning system. Because the reference simulation is a benchmark for comparison, the relevant outputs need to be stored on paper, either through printed output or through user recording of the specific information that is displayed.

Once the model has been run, the user proceeds to the Level 4 menu (Table 15), which provides outputs from the run.

Output Descriptions

Output choices are numerous and sometimes overwhelming for RIOFISH users. The outputs come in two levels of detail, a summary output and much more detailed output for those wanting more specific information from each submodel. The summary output is useful for general planning purposes including prediction of resource or angler responses to application of various management strategies.

The detailed output is most useful for heuristic investigation of specific population parametric interactions with management strategies. Most of the dynamics of the detailed output have relatively little impact on the general outputs.

General Outputs for Reference Run

Option 2 from the Level 4 (Table 15) provides the most general output (Table 16). As always, the user has the choice of printing the output, if desired. The general output first provides elemental hydrological, biological and economic information for the sites and years indicated. Table 16 is an example output for one lake (Cochiti Lake) over several years (1980-1984). The output simulated for each year provides: 1) minimum mean and maximum reservoir elevations, 2) minimum mean and maximum lake volume, 3) minimum mean and maximum lake area, 4) the average lake exchange rate (annual discharge divided by mean volume), 5) an estimate of the biomass of total catchable-size fish and, 6) the percentage of all fish in the catchable stock, the total angler days spent, and the total fish catch per hour.

Table 15. The Level 4 results menu allows the user to examine results from a summary or general output options or from more detailed results of the different submodels or to return to the scenario model (Printed as seen on the screen).

```
MENU:        RESULTS
LEVEL:       4
CALLED BY: MODEL.RUN MENU
OBJECTIVE: EXAMINE ADDITIONAL INFORMATION FROM MODEL RESULTS

           1 HELP INFORMATION ON THIS MENU

           2 SCENARIO DESCRIPTION AND BASIC OUTPUT, LABEL PRINTOUT

           3 EXAMINE HYDROLOGICAL MODEL RESULTS IN DETAIL


           4 EXAMINE FISH POPULATION RESULTS IN DETAIL
           5 EXAMINE RESERVOIR, STREAM PRODUCTION RESULTS IN DETAIL


           6 EXAMINE ECONOMIC MODEL RESULTS, ANGLER DAYS AND
           BENEFITS
           7 EXAMINE ECONOMIC MODEL TRIPS, INPUTS IN DETAIL

           8 MAKE HARD COPY OF REQUESTED PRINTOUTS NOW
           9 RETURN TO MENU FOR SETTING UP A SCENARIO
          10 QUIT

PLEASE CHOOSE (1 2 3 4 5 6 7 8 9 10) ===>
```

Table 16. The general output option in the Level 4 results menu provides a broad spectrum of relevant outputs for the user to evaluate the effects of management strategies by comparing the reference output with the output in a subsequent management strategy run (Printed as seen on the screen).

```
*****************     COCHITI                     1980         1981         1982         1983         1984

      LAKE ELEVATION - MAXIMUM                  5347.1       5330.0       5329.1       5344.0       5349.5
           (feet)    - AVERAGE                  5331.2       5329.1       5325.6       5328.5       5330.5
           (feet)    - MINIMUM                  5328.5       5328.7       5323.5       5324.9       5328.5

         LAKE VOLUME - MAXIMUM                   71412        47532        46537        66442        75621
          (acre-ft)  - AVERAGE                   49382        46602        42907        46263        48386
          (acre-ft)  - MINIMUM                   45958        46111        40696        42114        45896

           LAKE AREA - MAXIMUM                    1684         1109         1079         1576         1804
            (acres)  - AVERAGE                    1153         1082         1031         1102         1130
            (acres)  - MINIMUM                    1070         1072         1005         1019         1069

         AVERAGE EXCHANGE RATE                    29.6         11.8         25.7         31.9         27.5


CATCHABLE PAN,GAME FISH(kg/ha)                    87.0        134.0        246.0        240.0        247.0
   CATCHABLE o/o OF TOTAL FISH                    10.1         10.6         17.3         21.3         20.0
             TOTAL ANGLER DAYS                   38327        42079        37102        36627        36090
               FISH CATCH/HOUR                    0.37         0.79         0.68         0.69         0.96

  PRIM PROD + ALLOC (gC/m2/yr)                  1480.3       1309.5       1344.2       1704.5       1704.7
      BENTHOS PRODN (kg/ha/yr)                   855.3        691.5        729.4        959.3        869.5
  ZOOPLANKTON PRODN (kg/ha/yr)                 18933.7      15884.8      17196.0      20962.2      19631.1

MAXIMUM POTENTIAL FISH PRODUCTION:
    CARP,CRAY PRODN (kg/ha/yr)                   142.3        145.4        177.2        145.6        165.0
         SHAD PRODN (kg/ha/yr)                     0.0          0.0          0.0          0.0          0.0
  BENTH.CONS. PRODN (kg/ha/yr)                   146.9        117.2        128.0        157.6        140.9
  ZOOPL.CONS. PRODN (kg/ha/yr)                  3184.1       2629.0       2936.9       3396.6       3072.4
   FISH CONS. PRODN (kg/ha/yr)                   590.5        499.7        563.4        610.9        535.4

ACTUAL OR REALIZED FISH PRODUCTION OF CATCHABLE SIZE FISH:
     PAN FISH PRODN (kg/ha/yr)                    14.2         24.3         28.4         23.0         22.4
    GAME FISH PRODN (kg/ha/yr)                    57.9        148.3        194.1        118.6        132.3
 CARP, SUCKER PRODN (kg/ha/yr)                   121.0        181.8        165.4        129.2        163.3

*************** SYSTEM WIDE                       1980         1981         1982         1983         1984

    STATEWIDE BENEFITS, $1000s                 -27,743          -23          825       34,709       88,926
```

Also provided are simulations of production (mass generated per unit area per unit time). The primary production and allochthonous organic load represent the combined habitat loading of organic food bases for sportfish forage organisms. The rate of organic loading fundamentally determines fish production in RIOFISH. Primary production includes a simulation of all photosynthetic production in the reservoir. Allochthonous organic load includes organic matter imported into the aquatic community from all watershed sources beyond the lake perimeter in intermittent watershed and mainstream inflows.

The benthos production refers to small invertebrate production on the bottom comprised mostly of oligochaetes and dipteran larvae. The zooplankton production includes all invertebrate zooplankton, mostly microcrustaceans and rotifers. Potential fish production is summarized by trophic group in two categories of fish. The first group feeds on plants and detritus in the water column (shad). The second group feeds on detritus and plants on the bottom (carp, crayfish) and several categories of carnivorous fish (benthos consumers, zooplankton consumers, and fish consumers). These categories include different life stages and species. For example, zooplankton feeding fish include all larval fish, portions of juvenile fish (less than one year old), and few older fish. This potential is obtained only if all habitats are occupied by the feeding groups.

There is also a category of actual sportfish production. This is subcategorized into 1) gamefish (blackbass, trout, walleye, salmon, striped bass, catfish), 2) panfish (white bass, crappie, sunfish, bullheads), and 3) carp and suckers. It includes production of the catchable size fish for each category in all habitats, but does not include production of subcatchables. Sportfish production will fall below potential when all habitats are not occupied by fish. Partly for that reason, the actual sportfish production is always less than the potential.

If the economic submodel had been run, gross economic benefits contributed to the state would be reported at this point.

More detailed output for hydrology is also provided in Table 17. The initial volume, maximum physically possible volume and minimum physically possible volume are provided for each year and lake requested. The possible extremes in the model are not affected by any legal restrictions that may be in effect. Such restrictions need to be known by the model user and implemented in the model if necessary.

The modeled main inflow and outflow variables can be altered for a management scenario. Flows can be reviewed or changed monthly to determine if some previous changes have been made. A multiplier indicates whether flow rates have been modified simply by multiplying by a factor greater than 1.0 to increase whatever estimated historical flow existed, or less than 1.0 to depress estimated historic flows. The general response to a proposed stream diversion or an anticipated drought condition could be examined, for example, by multiplying by an appropriate fraction each month. A constant value is also displayed. A zero value means the actual "historic" flow rates are in effect. A positive number would indicate that historic flow rates had been replaced with scenario flow rates. For example, if the historic value for October in the first month displayed was 10,000 cfs and was in effect, the display value would be 0. If the value displayed was instead 11,000 cfs, then a change had been made previously from the historic flow rate. Thus, model users have two sources of information to examine hydrologic model conditions: 1) a multiplier value which, if different from 0, indicates that some multiple of the historic flow rates is in effect, and 2) an actual flow rate value, which, if different from 0, indicates some altered flow rate has been introduced in previous model runs.

Table 17. The general output provides information on the hydrologic status of the reservoirs, including whether the default or alternative scenarios were chosen. If an alternative was chosen, the multiplier values or constants would have been changed in the outflow the the inflow (Printed as seen on the screen).

```
* * * * * * * * * * * * * * * * COCHITI  * * * * * * * * * * * * * * * *

INITIAL VOLUME (acre-ft)    46880
MINIMUM VOLUME (acre-ft), January to December,
40000 40000 40000 40000 40000 40000 40000 40000 40000 40000 40000 40000
MAXIMUM VOLUME (acre-ft), January to December,
505700 505700 505700 505700 505700 505700 505700 505700 505700 505700 505700 505700 MAIN INFLOW

                                   MULTIPLIER
        J     F     M     A     M     J     J     A     S     O     N     D
1979                                                         1.00  1.00  1.00
1980  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1981  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1982  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1983  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1984  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
                                    CONSTANT
        J     F     M     A     M     J     J     A     S     O     N     D
1979                                                          0     0     0
1980    0     0     0     0     0     0     0     0     0     0     0     0
1981    0     0     0     0     0     0     0     0     0     0     0     0
1982    0     0     0     0     0     0     0     0     0     0     0     0
1983    0     0     0     0     0     0     0     0     0     0     0     0
1984    0     0     0     0     0     0     0     0     0     0     0     0

MAIN OUTFLOW
                                   MULTIPLIER
        J     F     M     A     M     J     J     A     S     O     N     D
1979                                                         1.00  1.00  1.00
1980  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1981  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1982  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1983  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
1984  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00
                                    CONSTANT
        J     F     M     A     M     J     J     A     S     O     N     D
1979                                                          0     0     0
1980    0     0     0     0     0     0     0     0     0     0     0     0
1981    0     0     0     0     0     0     0     0     0     0     0     0
1982    0     0     0     0     0     0     0     0     0     0     0     0
1983    0     0     0     0     0     0     0     0     0     0     0     0
1984    0     0     0     0     0     0     0     0     0     0     0     0
```

The model does not automatically include stocking and regulation history (Tables 18 and 19). The user can easily introduce historic stocking by choosing a menu item from option 3 of Level 2 (Table 20) and it will be displayed in general output as indicated in Table 18. If past scenarios have changed any fish parameters from the default values used in the model, that information also will be provided from the RIOFISH run as shown in Table 19. When a reference simulation is run with the intent of including past stocking and regulation, the model operator has to remember to insert historic regulations and stocking into the model run in advance of the run. If the lake had been previously stocked in model scenarios for the year identified, a record of the stocking will be provided as in Table 18. Also, any fish regulations that had been applied in previous scenarios are identified.

Detailed Reports - Hydrology

The hydrologic outputs can be examined graphically in detail via Option 2 of Level 4 for patterns including three different inflows (monitored mainflow, a monitored secondary inflow and the consolidated unmonitored watershed inflows); lake volume; lake area; lake elevation; concentrations of suspended solids, total phosphorus and total nitrogen; and water residence time in days. Choices are offered as shown in Table 21. The graphic outputs have fixed scales with variable dimensions on the scales, depending on location and year. They are best used to define patterns rather than to precisely recover simulated data (Figure 6 shows examples).

Detailed Reports - Biology

The model provides detailed output for individual fish species via Option 4 in Level 4 by age and size class as recruited as juveniles and older in late summer (Table 22). The total angler catch per hour for each length class of species is estimated (Table 23). For each age class by species, outputs also are provided for the number per ha in length classes in late summer

Table 18. If the historic stocking was inserted in the model, the general output will reflect the stocking. Any alternative stocking scenario will also be reported here (Printed as seen on the screen).

```
STOCKING COCHITI  WATER YEAR(S) 1980

SPECIES                 CLASS                NUMBER        LENGTH (MM)        SEASON      HALF
 8 RAINBOW TRT          FINGERLING             93,000       25.0              SPR 80      1st
 8 RAINBOW TRT          CATCHABLE              21,200      200.0              SPR 80      2nd
 6 CATFISH              FINGERLING            116,000       90.0              SPR 80      2nd
 1 LARGEM BASS          FINGERLING            100,000       45.0              SPR 80      2nd
12 SMALLM BASS          FINGERLING            118,500       40.0              SPR 80      2nd
 3 WALLEYE              FRY                 1,000,000        0.0              SPR 80      1st
 2 WHITE BASS           CATCHABLE                 527      250.0              SPR 80      2nd

STOCKING COCHITI  WATER YEAR(S) 1981
SPECIES                 CLASS                NUMBER        LENGTH (MM)        SEASON      HALF
 8 RAINBOW TRT          FINGERLING             57,600       25.0              SPR 81      1st
 8 RAINBOW TRT          CATCHABLE                 680      200.0              SPR 81      2nd
 6 CATFISH              FINGERLING             18,200      125.0              SPR 81      2nd
 3 WALLEYE              FRY                 1,050,000        0.0              SPR 81      1st

STOCKING COCHITI  WATER YEAR(S) 1982
SPECIES                 CLASS                NUMBER        LENGTH (MM)        SEASON      HALF
12 SMALLM BASS          FINGERLING             66,000       50.0              SPR 82      2nd
 8 RAINBOW TRT          FINGERLING              4,600      125.0              SPR 82      2nd
 8 RAINBOW TRT          CATCHABLE              13,000      200.0              SPR 82      2nd
 3 WALLEYE              FRY                   500,000        0.0              SPR 82      1st

STOCKING COCHITI  WATER YEAR(S) 1983
SPECIES                 CLASS                NUMBER        LENGTH (MM)        SEASON      HALF
 6 CATFISH              FINGERLING             67,100      100.0              SPR 83      2nd
 3 WALLEYE              FRY                   500,000        0.0              SPR 83      1st

STOCKING COCHITI  WATER YEAR(S) 1984
SPECIES                 CLASS                NUMBER        LENGTH (MM)        SEASON      HALF
 8 RAINBOW TRT          CATCHABLE              15,700      200.0              SPR 84      2nd
 6 CATFISH              FINGERLING            114,000       50.0              SPR 84      2nd
 2 WHITE BASS           FINGERLING                 90      125.0              SPR 84      2nd
 3 WALLEYE              FRY                   900,000        0.0              SPR 84      1st
```

Table 19. If the historic regulations were inserted in the model, the general output will reflect the regulations. Any alternative scenario will also be reported here (Printed as seen on the screen).

```
 REGULATIONS   COCHITI   1980
    SPECIES  MIN SIZE(MM) MAX SIZE(MM) SLOT MIN  MAX(MM)  CREEL LIM
 1 LARGEM BASS    305.0
 2 WHITE BASS                                       40
 3 WALLEYE                                          12
 5 CRAPPIE                                          40
 6 CATFISH                                          15
 7 N. PIKE                                          12
 8 RAINBOW TRT                                       8
 9 BROWN TROUT                                       8
10 KOKANEE SAL                                       8
11 LAKE TROUT                                        8
12 SMALLM BASS    305.0
13 STRIPE BASS                                       4

REGULATIONS   COCHITI   1981
    SPECIES  MIN SIZE(MM) MAX SIZE(MM) SLOT MIN  MAX(MM)  CREEL LIM
 1 LARGEM BASS    305.0
 2 WHITE BASS                                       40
 3 WALLEYE                                          12
 5 CRAPPIE                                          40
 6 CATFISH                                          15
 7 N. PIKE                                          12
 8 RAINBOW TRT                                       8
 9 BROWN TROUT                                       8
10 KOKANEE SAL                                       8
11 LAKE TROUT                                        8
12 SMALLM BASS    305.0
13 STRIPE BASS                                       4

REGULATIONS   COCHITI   1982
    SPECIES  MIN SIZE(MM) MAX SIZE(MM) SLOT MIN  MAX(MM)  CREEL LIM
 1 LARGEM BASS    305.0
 2 WHITE BASS                                       40
 3 WALLEYE                                          12
 5 CRAPPIE                                          40
 6 CATFISH                                          15
 7 N. PIKE                                          12
 8 RAINBOW TRT                                       8
 9 BROWN TROUT                                       8
10 KOKANEE SAL                                       8
11 LAKE TROUT                                        8
12 SMALLM BASS    305.0
13 STRIPE BASS                                       4
```

Table 20. Options available to modify the reference run for creation of altered planning environments (e.g., drought) or management strategies.

```
CHOOSE ONE OF THE FOLLOWING TO CHECK, RESET OR CHANGE.
(ANY OPTION CAN BE REPEATED AS OFTEN AS NECESSARY.)

   1   UPSTREAM REACH ENVIRONMENT, NUTRIENTS, CARBON
       (NOT IMPLEMENTED THIS VERSION)

   2  RESET STOCKING, REGULATIONS, INITIAL FISH, AND ENVIRONMENT,
       NUTRIENTS, AND CARBON TO SESSION STARTUP DEFAULT SETTINGS
       (N,P,SS WILL BE DIFFERENT FROM ANY HYDRO RUN RESULTS)
   3   INSERT ACTUAL STOCKING RECORDS, REGULATIONS FOR RESERVOIRS
       IF AVAILABLE
   4   SEE/ MODIFY INITIAL FISH POPULATIONS IN RESERVOIRS
   5   SEE/ MODIFY REGULATIONS FOR RESERVOIRS
   6   SEE/ MODIFY STOCKING FOR RESERVOIRS
   7   SEE/ MODIFY RESERVOIR ENVIRONMENT, NUTRIENTS, CARBON

   8   RESET FISH SPECIES PARAMETERS TO ORIGINAL MODEL VALUES
   9   SEE/ MODIFY FISH SPECIES PARAMETER VALUES

   Q     RETURN TO MAIN SCENARIO SET UP MENU


 1, 2, 3, 4, 5, 6, 7, 8, OR 9, (OR Q):
```

Table 21. The detailed hydrologic output provides 13 hydrologic choices that may be graphically displayed as in Figure 6 (Printed as seen on the screen).

```
BASIN IS COCHITI
Which part of the output information do you want to look at?

    1 main inflow               7 volume
    2 second inflow             8 area
    3 third inflow              9 elevation

    4 main outflow             10 suspended sediments
    5 second outflow           11 phosphorus
    6 third outflow            12 nitrogen
                               13 water residence time

Enter up to four choices, 1 to 13:
```

Table 22. Size and age provided for detailed fish population outputs (Printed as seen on the screen.

```
FOR ONE SPECIES IN A SINGLE RESERVOIR:

BY SIZE CLASS
 1: DENSITY BY SIZE CLASS   (NUMBERS PER HECTARE IN LATE SUMMER)
 2: YIELD BY SIZE CLASS   (AVERAGE CATCH/HOUR)

 4: TOTAL FISHING EFFORT   (TOTAL ANGLER DAYS)

BY AGE CLASS
 5: BIOMASS BY AGE CLASS   (KG/HA IN LATE SUMMER)
 6: DENSITY BY AGE CLASS (NUMBERS/HA IN LATE SUMMER)
 7: AVERAGE LENGTH BY AGE CLASS  (AVERAGE MM IN LATE SUMMER)
 8: MORTALITY BY AGE CLASS   (LN FINAL NUMBER/INITIAL NUMBER)
 9: GROWTH BY AGE CLASS (KG/HA IN LATE SUMMER)

FOR ALL SPECIES (AGE OR SIZE CLASSES SUMMED) IN A SINGLE RESERVOIR:
 10: NUMBERS PER HECTARE
 11: KG/HECTARE
 12: HARVEST PER ANGLER DAY
 13: FINAL VOLUME, FISH DENSITIES FOR INITIALIZING NEXT YEAR

WHICH TABLE OR TABLES?
```

Table 23. Detailed output for Cochiti Lake crappie (an example species) includes number/ha and average catch/hr by length intervals (Printed as seen on the screen).

```
NUMBERS PER HECTARE IN LATE SUMMER
LENGTH (MM)      1979     1980     1981     1982      1983     1984

  0.0  76.2             360.98   664.80   574.20    427.76   141.67
 76.2 152.4      94.13   47.30   179.02   441.15    207.67   205.83
152.4 228.6      69.96   23.52    23.49    12.30              21.04
228.6 304.8      22.90   17.50    17.49     6.13      8.68     2.77
304.8 381.0               5.70     5.71     6.02      2.82     2.71
381.0

     AREA IN HA    441       435      435     413       436      453


3 INS = 76.2 MM; 6 INS = 152.4 MM; 12 INS = 304.8 MM

COCHITI        5 CRAPPIE

AVERAGE CATCH/HOUR
LENGTH (MM)    1980    1981   1982    1983   1984
   0.0  76.2
  76.2 152.4
 152.4 228.6   0.009   0.002                 0.003
 228.6 304.8   0.007   0.003  0.001   0.001
 304.8 381.0   0.002   0.001          0.001
 381.0

3 INS = 76.2 MM; 6 INS = 152.4 MM; 12 INS = 304.8 MM
```

(Table 23). The biomass per ha and total lake biomass are provided (Table 24). The annual mortality rates and an average length by age class is provided (Table 25) for all species combined. The numbers and biomass per hectare and for the entire lake are provided (Table 26 and 27). The population growth (of survivors plus those that died) by age class and in total for the lake are estimated (Table 28). Population growth is equivalent to production by age class.

Contrasting density and biomass outputs is useful for separating the effects of water level from other effects on fish density per area and concentration of biomass per area. The fish densities at the final lake volume in the run are also provided (Table 29). The final density estimate can be used to initiate a subsequent series of years, although the distribution of numbers among age classes will revert to the original distribution. Harvest rate for all species is also provided as in Table 30.

The outputs shown in Tables 26 and 27 include up to 24 species and totals for all sportfish including: panfish, carp and sucker and all other species. The 24 species include commonly occurring species in New Mexico and certain species being considered for introduction. Some uncommon species are lumped with other species (e.g., spotted bass is lumped with largemouth bass). Crayfish is included as a fish species.

The detailed fish outputs are sensitive to the initial population density and distribution of sizes first introduced in the model. Because sampling intensity at practical levels rarely allows a truly accurate estimate of the initial fish size distribution, a fundamental assumption of size distribution is made for the model based on the population total natural mortality rate. The user may change this initial size distribution, however.

In reality, the model can never recreate the actual structure present in the reservoirs from 1975-1987, except by accident. There is no record accurate enough to create or to verify

Table 24. Detailed output for Cochiti Lake crappie (an example species) includes the biomass/ha and total biomass in the lake estimated for each age class (Printed as seen on the screen).

```
COCHITI        5 CRAPPIE

BIOMASS KG/HA IN LATE SUMMER
AGE CLASS 1979       1980       1981       1982       1983       1984
    0     0.94       0.99       1.83       0.75       0.17       0.19
    1     2.55       1.32       1.48       2.21       0.67       0.23
    2     2.89       2.78       1.65       1.75       1.90       0.92
    3     2.45       2.48       2.41       1.53       1.45       2.47
    4     1.63       1.75       1.75       1.69       1.00       1.66
    5     0.91       1.05       1.10       1.10       0.93       0.72
    6     0.45       0.56       0.62       0.65       0.58       0.55
    7     0.22       0.28       0.33       0.36       0.33       0.32
    8     0.11       0.14       0.16       0.19       0.18       0.18
    9     0.05       0.07       0.08       0.09       0.09       0.09
   10     0.03       0.03       0.04       0.05       0.05       0.05
   11     0.01       0.02       0.02       0.02       0.02       0.02
   12     0.01       0.01       0.01       0.01       0.01       0.01
   13                                      0.01       0.01       0.01
   14


AREA IN HA     441   435        435        413        436        453

TOTAL KG BIOMASS FOR ENTIRE LAKE, LATE SUMMER
AGE CLASS 1979       1980       1981       1982       1983       1984
    0      415        432        796        310         72         84
    1     1126        576        646        912        290        106
    2     1276       1212        719        724        830        417
    3     1082       1079       1051        631        633       1121
    4      721        760        763        696        436        753
    5      400        458        477        455        405        329
    6      199        245        271        269        251        247
    7       98        122        142        148        144        144
    8       49         60         70         77         78         79
    9       24         30         35         38         40         42
   10       12         15         17         19         20         22
   11        6          7          9          9         10         11
   12        3          4          4          5          5          5
   13        2          2          2          2          2          3
   14        1          1          1          1          1          2
```

Table 25. Detailed output for Cochiti Lake crappie (an example species) includes the average length and the mortality rate in each age class (Printed as seen on the screen).

```
COCHITI         5 CRAPPIE

AVERAGE LENGTH IN MM IN LATE SUMMER
AGE CLASS       1979      1980      1981      1982      1983      1984
     0          100       67        67        53        49        67
     1          170       138       94        87        65        70
     2          220       217       184       122       105       90
     3          260       260       258       220       145       143
     4          285       290       290       282       244       191
     5          295       308       312       307       296       278
     6          295       315       325       324       318       316
     7          295       315       331       336       332       332
     8          295       315       330       340       342       344
     9          295       316       331       340       347       352
    10          295       315       330       339       345       353
    11          295       315       330       339       345       354
    12          295       311       326       334       339       348
    13          295       303       323       332       337       345
    14          295       266       271       277       279       291

COCHITI         5 CRAPPIE

MORTALITY RATE  (LN FINAL NUM/INITIAL NUM)
AGE CLASS        1980        1981        1982        1983        1984
     0
     1
     2           -0.70       -0.70       -0.70       -0.70       -0.70
     3           -0.70       -0.70       -0.70       -0.70       -0.70
     4           -0.70       -0.70       -0.70       -0.70       -0.70
     5           -0.70       -0.70       -0.70       -0.70       -0.70
     6           -0.70       -0.70       -0.70       -0.70       -0.70
     7           -0.70       -0.70       -0.70       -0.70       -0.70
     8           -0.70       -0.70       -0.70       -0.70       -0.70
     9           -0.71       -0.71       -0.71       -0.71       -0.71
    10           -0.69       -0.69       -0.69       -0.69       -0.68
    11           -0.69       -0.69       -0.69       -0.69       -0.69
    12           -0.64       -0.64       -0.64       -0.64       -0.64
    13           -0.59       -0.69       -0.69       -0.69       -0.69
    14           -0.22
```

Table 26. Detailed output for all species summarizes number/hectare and total numbers in the entire Cochiti Lake in later summer (Printed as seen on the screen).

```
 COCHITI
   TOTAL NUMBERS PER HECTARE
                   1979      1980      1981      1982      1983      1984
  1 LARGEM BASS    10.6     193.7     160.6     134.8      74.4      41.7
  2 WHITE BASS    130.0     157.5     194.7     282.3     242.3     215.4
  3 WALLEYE        24.0      35.7      69.1      98.6      98.2      84.7
  4 SUNFISH       228.7     200.1     208.2     166.6      94.1      59.5
  5 CRAPPIE       187.0     455.0     890.5    1039.8     646.9     374.0
  6 CATFISH        33.7     281.7     186.6     167.6     310.5     445.0
  7 N. PIKE         4.8       4.7       4.3       4.4       3.8       3.2
  8 RAINBOW TRT    43.6     204.3     188.5     125.9      56.4      51.7
  9 BROWN TROUT
 10 KOKANEE SAL
 11 LAKE TROUT
 12 SMALLM BASS    33.9     246.8     151.0     235.3     110.9      58.3
 13 STRIPE BASS
 14 LNGNOSE GAR
 15 BULLHEAD
 16 YELLW PERCH
 17 CARP,SUCKER   507.6     489.3     552.4     643.3     570.5     527.0
 18 WHITE SUCKR   236.0     143.5    1563.2    1980.6    1060.0     611.5
 19 GIZZARD SHD
 20 THREADFN SH
 21 GOLDEN SHIN
 22 CYPRINIDS     132.5     130.0     336.8     223.0     112.1      80.0
 23 SMELT
 24 CRAYFISH     1873.7     387.6     103.4      37.1      10.7       3.1

     AREA IN HA     441       435       435       413       436       453

 TOTAL NUMBERS FOR ENTIRE LAKE
                   1979      1980      1981      1982      1983      1984
  1 LARGEM BASS    4674     84316     69901     55648     32423     18902
  2 WHITE BASS    57323     68566     84749    116593    105565     97690
  3 WALLEYE       10588     15524     30075     40702     42783     38402
  4 SUNFISH      100879     87096     90606     68792     40971     27000
  5 CRAPPIE       82467    198033    387573    429388    281822    169597
  6 CATFISH       14846    122621     81233     69214    135245    201792
  7 N. PIKE        2112      2031      1881      1833      1657      1467
  8 RAINBOW TRT   19212     88907     82018     51988     24557     23440
  9 BROWN TROUT
 10 KOKANEE SAL
 11 LAKE TROUT
 12 SMALLM BASS   14963    107428     65740     97149     48306     26443
 13 STRIPE BASS
 14 LNGNOSE GAR
 15 BULLHEAD
 16 YELLW PERCH
 17 CARP,SUCKER  223867    212972    240413    265642    248519    238948
 18 WHITE SUCKR  104072     62440    680323    817885    461767    277268
 19 GIZZARD SHD
 20 THREADFN SH
 21 GOLDEN SHIN
 22 CYPRINIDS     58446     56576    146562     92109     48816     36294
 23 SMELT
 24 CRAYFISH     826386    168714     45001     15328      4669      1405

ALL SPORT FISH    66395    420827    330848    316534    284971    310446
  ALL PAN FISH   240669    353695    562928    614773    428358    294287
 CARP, SUCKERS   327939    275412    920736   1083527    710286    516216
ALL OTHER FISH   884832    225290    191563    107437     53485     37699
ALL FISH TOTAL  1519835   1275224   2006075   2122271   1477100   1158648
```

Table 27. Detailed output for all species summarizes the biomass/ha and the total biomass in the entire Cochiti Lake in late summer (Printed as seen on the screen).

```
COCHITI

  TOTAL WEIGHT KG/HA
                     1979      1980      1981      1982      1983      1984
 1 LARGEM BASS       10.4       7.5       8.6       5.9       3.5       3.3
 2 WHITE BASS        16.0      18.6      23.9      32.8      35.1      34.1
 3 WALLEYE           17.6      23.0      28.2      41.4      41.8      45.9
 4 SUNFISH            4.5       2.6       2.2       1.3       0.7       0.7
 5 CRAPPIE           12.3      11.5      11.5      10.4       7.4       7.4
 6 CATFISH           29.2      60.6      90.1     166.4     218.7     189.3
 7 N. PIKE            7.7       7.1       6.6       6.3       5.2       4.4
 8 RAINBOW TRT        5.2      20.7      26.1      35.2      24.4      24.1
 9 BROWN TROUT
10 KOKANEE SAL
11 LAKE TROUT
12 SMALLM BASS        4.5       3.9       6.4       4.7       2.7       2.8
13 STRIPE BASS
14 LNGNOSE GAR
15 BULLHEAD
16 YELLW PERCH
17 CARP,SUCKER      545.3     575.2     601.1     661.5     640.5     657.2
18 WHITE SUCKR       94.2      65.8      75.1      55.5      39.7      34.3
19 GIZZARD SHD
20 THREADFN SH
21 GOLDEN SHIN
22 CYPRINIDS          1.4       3.7       2.8       1.9       2.9       2.5
23 SMELT
24 CRAYFISH           7.4       7.1       4.4       1.9       0.5       0.1

     AREA IN HA       441       435       435       413       436       453

TOTAL WEIGHT IN KG FOR ENTIRE LAKE
                    1979      1980      1981      1982      1983      1984
 1 LARGEM BASS      4575      3272      3725      2428      1503      1481
 2 WHITE BASS       7066      8079     10404     13559     15273     15475
 3 WALLEYE          7763     10012     12275     17091     18227     20835
 4 SUNFISH          1977      1118       941       525       315       326
 5 CRAPPIE          5414      5005      5003      4296      3217      3364
 6 CATFISH         12871     26368     39226     68722     95258     85825
 7 N. PIKE          3415      3090      2871      2588      2252      2006
 8 RAINBOW TRT      2281      9019     11372     14520     10620     10937
 9 BROWN TROUT
10 KOKANEE SAL
11 LAKE TROUT
12 SMALLM BASS      2000      1687      2785      1946      1183      1263
13 STRIPE BASS
14 LNGNOSE GAR
15 BULLHEAD
16 YELLW PERCH
17 CARP,SUCKER    240500    250358    261610    273160    279035    297982
18 WHITE SUCKR     41529     28622     32686     22902     17316     15564
19 GIZZARD SHD
20 THREADFN SH
21 GOLDEN SHIN
22 CYPRINIDS         603      1630      1228       764      1282      1139
23 SMELT
24 CRAYFISH         3282      3077      1920       766       207        67

ALL SPORT FISH     32904     53448     72255    107296    129044    122347
  ALL PAN FISH     14456     14202     16348     18379     18805     19165
 CARP, SUCKERS    282029    278980    294296    296062    296351    313546
ALL OTHER FISH      3885      4706      3148      1530      1489      1206
ALL FISH TOTAL    333274    351336    386047    423267    445689    456264
```

Table 28. Detailed output for Cochiti Lake crappie (an example species) summarizing the population growth (production/ha and in the entire lake) by age class (Printed as seen on the screen).

```
COCHITI        5 CRAPPIE

GROWTH IN KG/HA/YEAR
AGE CLASS       1980      1981      1982      1983      1984
    0           0.68      1.26      0.19      0.01      0.13
    1           1.02      1.19      1.54      0.40      0.19
    2           1.81      1.20      1.21      1.10      0.71
    3           1.25      1.27      0.83      0.80      1.85
    4           0.63      0.65      0.54      0.36      1.15
    5           0.28      0.28      0.24      0.18      0.30
    6           0.13      0.12      0.10      0.07      0.12
    7           0.07      0.06      0.04      0.03      0.05
    8           0.03      0.03      0.02      0.01      0.02
    9           0.02      0.01      0.01      0.01      0.01
   10           0.01      0.01
   11
   12
   13
   14

AREA IN HA      441       435       435      413       436     453

TOTAL GROWTH FOR ENTIRE LAKE, KG/YEAR
AGE CLASS       1980      1981      1982      1983      1984
    0            301       548        84         2        56
    1            461       523       671       174        77
    2            789       544       533       478       310
    3            517       554       378       352       805
    4            275       267       234       163       509
    5            124       124        97        77       137
    6             59        54        43        31        54
    7             30        25        19        13        21
    8             14        13         9         6         9
    9              7         6         4         3         4
   10              4         3         2         1         2
   11              2         2         1         1         1
   12              1         1         1                   1
   13
   14
```

Table 29. The final estimated density of fish (age 0 and up in late summer) and final Cochiti Lake volume. The result can be entered into a subsequent run to continue the simulation.

```
THE CURRENT SIMULATION ENDED IN 1984.  TO CONTINUE
INTO FUTURE YEARS, START A NEW SIMULATION IN 1985
AND USE THE SCENARIO MENU TO SET THE INITIAL
VOLUME IN THE HYDROLOGICAL SUBMODEL AND THE INITIAL FISH
POPULATIONS IN THE BIOLOGICAL SUBMODEL, TO THE FINAL VALUES
FROM THIS RUN INDICATED BELOW:

FOR COCHITI :

FINAL LAKE VOLUME WAS 47593 ACRE-FT

FINAL FISH NUMBERS/HA, BASED ON THE FINAL AREA OF 450 HA, WERE
 1 LARGEM BASS      42.023
 2 WHITE BASS      217.187
 3 WALLEYE          85.376
 4 SUNFISH          60.027
 5 CRAPPIE         377.052
 6 CATFISH         448.628
 7 N. PIKE           3.261
 8 RAINBOW TRT      52.112
 9 BROWN TROUT       0.000
10 KOKANEE SAL       0.000
11 LAKE TROUT        0.000
12 SMALLM BASS      58.789
13 STRIPE BASS       0.000
14 LNGNOSE GAR       0.000
15 BULLHEAD          0.000
16 YELLW PERCH       0.000
17 CARP,SUCKER     531.235
18 WHITE SUCKR     616.428
19 GIZZARD SHD       0.000
20 THREADFN SH       0.000
21 GOLDEN SHIN       0.000
22 CYPRINIDS        80.690
23 SMELT             0.000
24 CRAYFISH          3.124
```

Table 30. Harvest rate per angler day for all species at Cochiti Lake are provided with the detailed output.

```
COCHITI

HARVEST PER ANGLER DAY
                        1980      1981      1982      1983      1984

  1 LARGEM BASS        0.004     0.003     0.001
  2 WHITE BASS         0.570     0.637     0.883     1.219     1.092
  3 WALLEYE            0.068     0.113     0.327     0.462     0.474
  4 SUNFISH            0.001     0.001
  5 CRAPPIE            0.070     0.015     0.014     0.003     0.018
  6 CATFISH            0.039     1.504     0.767     0.346     1.675
  7 N. PIKE            0.003     0.003     0.002     0.001     0.001
  8 RAINBOW TRT        0.216     0.120     0.276     0.196     0.182
  9 BROWN TROUT
 10 KOKANEE SAL
 11 LAKE TROUT
 12 SMALLM BASS        0.005     0.004     0.001     0.001     0.001
 13 STRIPE BASS
 14 LNGNOSE GAR
 15 BULLHEAD
 16 YELLW PERCH
 17 CARP,SUCKER        0.470     0.731     0.432     0.512     0.407
 18 WHITE SUCKR        0.021     0.018     0.006     0.002     0.001
 19 GIZZARD SHD
 20 THREADFN SH
 21 GOLDEN SHIN
 22 CYPRINIDS
 23 SMELT
 24 CRAYFISH
```

such detail. The best practical estimates are for catchable size and production, usually of functional groups of species (feeding groups or game, panfish, carp and sucker, etc.). Therefore, the detailed outputs should be used to analyze "assumption and if what" propositions to improve understanding of how fish populations are likely to interact with their habitat and anglers. An example scenario is: "Assuming that the initial population size structures provided in the historic scenario actually existed and modeled parameters are reasonable, what would happen to fish density, fish biomass, fish growth and fish mortality in each species group if water levels were dramatically shifted downward by more rapid release downstream?"

Of course, the modeled population reactions depend on the accuracy of the parameters that define the fish population interactions with habitat and other species. There are definite shortcomings in the availability of precise knowledge for many of the interactions. Therefore, the user has the opportunity to alter parameters as he or she sees fit, either to make them more realistic based on research, or to analyze the effect of parametric alterations on direction and degree of change in population performance. The model user cannot, however, modify the underlying mathematical structure.

Table 31 illustrates the access options for such changes and Table 32 shows a parametric display example. All parameters have user accessible displays. The user can modify the parameters and record the modification in the displays. This access to population parameters is useful for a form of model-output sensitivity analysis that helps fishery managers understand general community-population-habitat-angler interactions. It also directs research attention to uncertain parameters having large impacts on model output values. The user can create new species by altering all population parameters appropriately.

A consequence of sensitivity analysis is that precise identification of many population parameters for each species affects the dimension of change in general outputs (total production,

Table 31. Display of options for changing population parameters (Printed as seen on the screen).

```
CHOOSE ONE OF THE FOLLOWING TO CHECK, RESET, OR CHANGE FISH
PARAMETERS:

   1   MORTALITY RATE, FISH KILL REFUGE
   2   P/B FOR LARVAE, JUVENILES, AND ADULTS
   3   SEX RATIO AND SEXUAL MATURITY WEIGHT
   4   WATER LEVEL FLUCTUATION
   5   LARVAL GROWTH RATE
   6   MINIMUM JUVENILE SURVIVAL WEIGHT
   7   CATCHABILITY AND MINIMUM CATCHABLE SIZE, COMPENSATORY
       MORTALITY
   8   SPAWNING SEASON, FECUNDITY, LARVAL WEIGHT
   9   INITIAL FISH POPULATION LENGTHS BY AGE CLASS
  10   FISH LENGTH WEIGHT RELATIONSHIP


  11   COMPETITION COEFFICIENTS
  12   BIOMASS FRACTION

   Q   RETURN TO BIOLOGICAL INPUTS MENU

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, OR Q:
```

Table 32. An example display of the natural mortality rates used as defaults and changeable by the user (Printed as seen on the screen).

```
[0]    MORTALITY RATE
[1]     -0.54    LARGEM BASS                  -0.4     STRIPE BASS
[2]     -0.68    WHITE BASS                   -0.45    LNGNOSE GAR
[3]     -0.47    WALLEYE                      -0.91    BULLHEAD
[4]     -0.74    SUNFISH                      -0.7     YELLW PERCH
[5]     -0.7     CRAPPIE                      -0.2     CARP,SUCKER
[6]     -0.22    CATFISH                      -0.51    WHITE SUCKR
[7]     -0.42    N. PIKE                      -1       GIZZARD SHD
[8]     -0.75    RAINBOW TRT                  -1.35    THREADFN SH
[9]     -0.75    BROWN TROUT                  -1.1     GOLDEN SHIN
[10]    -1       KOKANEE SAL                  -1.2     CYPRINIDS
[11]    -0.4     LAKE TROUT                   -0.91    SMELT
[12]    -0.6     SMALLM BASS                  -1.6     CRAYFISH
[                      1                      3                      ]
*****************************************************************

[14]   USE F9 TO ENTER DATA AND CONTINUE
```

catchable biomass, angler days, economic benefit) relatively little compared to other factors like organic loading and presence or absence of herbivorous fish. In other words, some applied management strategy, such as water-level change, will tend to change outputs proportionally about the same regardless of the fish population parameters used. This occurs as long as parameters are reasonable and estimation is not all biased in one direction or the other. If application of a management strategy indicates that catch rate will increase 100 percent, the error associated with estimating the initial catchability in the model is not as important as the error associated with estimating the response in catch rate to the management change. Consistent errors in estimation of catch rate, however, are among those most likely to influence estimated angler days and benefits.

The natural mortality estimate is one of the more critical values in the population model. Table 33 shows that when the natural mortality of crappie is dramatically reduced, it has small impacts on outputs but they progressively increase with time and instable situations would eventually show a small net effect.

Detailed mean daily production information is provided for estimating production by habitat type and season for food groups of fish and trophic groups in different feeding categories. This output provides information about the relative impacts of water management on the proportions of estimated habitat production. It also provides information on the areas of different lake habitats based on light transmission depth and interception with the bottom. Once again, this detail is most useful for heuristic purposes.

Detailed Reports - Economics

Option 6 provides detailed economic output. The user is given the opportunity to review and change several variables. The user can reset all values to the historic default value if changes have been made before running the model. The user can also review (Table 34) user

Table 33. A scenario illustrating the role of natural estimation[1] on general and more specific outputs for crappie in Cochiti Lake.

Parameter	1984	1985	1986	1987
Catchable sportfish (kg/ha)	+ 3.8[2]	+ 2.6	+ 2.2	+ 3.8
Pan fish production	+ 1.7	+ 1.2	+ 1.7	+ 2.9
Game fish production	- 0.30	- 0.1	- 0.4	- 0.3
Crappie no/ha	+286.4	+75.3	+87.4	+39.6
Total catch rate/ha	+ 0.02	+ 0.02	+ 0.01	+ 0.13

[1]/The model-estimated mortality of 0.70 was reduced to -0.45, an extreme variant mortality, thereby increasing crappie survivorship to the extreme.

[2]/For example in 1984, the model estimated total weight of catchable sportfish was increased by 3.8 kg/ha.

Table 34. Output choices available from the economics submodel (Printed as seen on the screen).

```
CHOOSE AN OPTION FOR MORE DETAILED ECONOMIC MODEL INFORMATION:

 1    DETAILED INFORMATION ON FISHING TRIPS
 2    COST INPUTS TO THE ECON MODEL
 3    LAKE QUALITY INPUTS TO THE ECON MODEL
 4    ANGLER POPULATION INPUTS TO THE ECON MODEL
 5    ALL INPUTS (OPTIONS 2,3, AND 4 COMBINED)

 Q    RETURN TO MAIN RESULTS DISPLAY MENU

1, 2, 3, 4, OR 5, (OR Q):
```

fees and site closures, fish catchable mass and area, accessible reservoir shoreline and number of concrete boat ramps, elevation of the site, travel costs, and population by zone.

Detailed economic output includes angler days of use at all counties, the angler days in each county originating from the resident and non-resident angler, any fees collected, the instate benefits to anglers (net economic value) derived in each zone of angler origin (Table 35), the angler visits listed by county of origin, and the change in per capita income for each county in question (Table 36).

Creating a Management Strategy Scenario

The creation of management strategies or examination of anticipated unmanageable changes (like drought) are created at Menu Level 2 (Beginning Menu) with Option levels 5-7. The model user can make multiple or single changes in one to all three option categories. It is important to remember to keep all reservoir years and linkages the same as the reference run, which is the benchmark for comparison.

The changeable hydrologic variables include input-output flows and reservoir volume constraints. For example, a drought could be created to assess its effects by changing monthly flow rates by either using a multiplier, in this case less than 10 for most months, or by introducing actual values. Constant values for all months can be changed quickly otherwise, each month has to be reviewed and changed to the desired values.

Maximum or minimum volumetric constraints can be introduced, for example, to simulate a proposed water storage policy change (e.g., minimum reservoir storage pool), or the effect of storage construction or repair. The user must always remember and recognize that what is physically possible in the reservoir in question may not be legally tolerable or physically possible in downstream reaches or reservoirs. The new values are introduced directly for each month. If the effect of water-level stabilization on fish reproduction is of concern, constraints

Table 35. Detailed output of the estimated per capita and total benefits in zones of origin for Cochiti Lake (Printed as seen on the screen).

```
        PER CAPITA BENEFITS TO ANGLERS IN $ (COMPARED TO 1981 STANDARD)

     ZONES               1980        1981        1982        1983        1984

 1  BERNALILLO        -391.27      -16.20       -7.69      393.69     1043.13
 2  CHAVES            -133.43       -3.65       -2.66       92.03      389.15
 3  CIBOLA            -144.05      109.89      117.28      420.83      963.49
 4  COLFAX            -132.76       -0.47        4.10      107.28      209.35
 5  CURRY             -647.44      -24.05       24.29      532.58     1517.19
 6  DE BACA            -34.74      -56.33      -48.94      153.32      367.52
 7  DONA ANA          -235.94      -18.90      -24.69      267.84      763.61
 8  EDDY              -128.70       -2.44        0.78      359.02      476.81
 9  GUADALUPE           34.13       -2.86        3.33      163.29      271.28
10  LEA               -180.96       -5.70        0.79      172.76      517.60
11  LOS ALAMOS        -234.25       43.90       49.46      505.11     1355.92
12  MCKINLEY           -35.77       49.78       49.92      186.51      355.40
13  OTERO             -125.29       -5.94       -9.35      262.18      656.01
14  QUAY              -352.19       -4.74       27.16      232.94      690.54
15  RIO ARRIBA        -437.66       11.06       23.87      766.87     1787.95
16  ROOSEVELT         -336.55       -8.89       12.28      191.59      592.89
17  SANDOVAL          -309.29       40.88       46.22      431.50     1199.70
18  SANTA FE          -137.33        4.75       15.72      209.62      446.57
19  SIERRA              65.70        1.17       -0.09      424.65      883.79
20  SAN JUAN          -333.07      -13.07       -4.25      189.70      526.52
21  TAOS              -211.03        0.12        5.65      236.82      555.96
22  VALENCIA          -341.03       54.46       96.09      717.95     1570.16

        TOTAL BENEFITS TO ANGLERS IN $ (COMPARED TO 1981 STANDARD)

     ZONES               1980        1981        1982        1983        1984

 1  BERNALILLO    -13,977,972    -587,927    -283,789  14,868,368  40,466,674
 2  CHAVES           -306,846      -8,405      -6,417     231,914     987,680
 3  CIBOLA           -699,478     536,244     557,306   1,844,924   3,807,708
 4  COLFAX           -381,993      -1,332      11,695     304,147     624,243
 5  CURRY          -1,821,901     -68,844      69,745   1,570,063   4,390,787
 6  DE BACA           -31,722     -47,317     -42,859     134,287     321,959
 7  DONA ANA       -1,635,984    -134,780    -183,622   2,076,909   6,289,905
 8  EDDY             -715,024     -14,046       4,645   2,190,720   2,898,023
 9  GUADALUPE          15,057      -1,259       1,434      72,010     119,634
10  LEA              -770,189     -25,702       3,723     846,823   2,556,849
11  LOS ALAMOS       -449,291      85,645      95,436   1,023,845   2,660,283
12  MCKINLEY          -92,140     133,517     137,534     519,981   1,003,643
13  OTERO            -448,056     -21,502     -34,734   1,015,102   2,555,876
14  QUAY             -675,868      -8,909      52,097     451,242   1,450,151
15  RIO ARRIBA       -653,863      17,296      37,655   1,232,345   2,926,900
16  ROOSEVELT        -258,815      -6,801       9,759     155,749     479,659
17  SANDOVAL         -638,329      86,618     100,658     921,692   2,864,893
18  SANTA FE         -662,739      23,022      78,456   1,077,253   2,366,252
19  SIERRA             48,033         884         -68     324,853     707,013
20  SAN JUAN       -2,413,045    -101,370     -33,954   1,564,963   4,296,836
21  TAOS             -395,035         209      11,019     470,541   1,158,067
22  VALENCIA         -777,185     128,552     236,067   1,811,334   3,997,608

            TOTAL -27,742,385     -16,207     821,786  34,709,065  88,930,643
```

Table 36. Detailed output of the estimated per capita trips to Cochiti Lake and to all substitute sites for Cochiti from the zones of origin in New Mexico (Printed as seen on the screen).

```
                          PER CAPITA TRIPS TO  5  COCHITI

        ZONES              1980        1981        1982        1983        1984

  1  BERNALILLO          0.1011      0.1496      0.1707      0.2287      0.3286
  2  CHAVES             -0.9297     -0.9140     -0.9047     -0.8798     -0.8242
  3  CIBOLA             -0.1459     -0.0871     -0.0722      0.0060      0.1755
  4  COLFAX             -0.2054     -0.2002     -0.1878     -0.1760     -0.1326
  5  CURRY               0.4008      0.4814      0.4916      0.5852      0.7668
  6  DE BACA             0.0283      0.0543      0.0592      0.1360      0.2614
  7  DONA ANA           -0.1087     -0.0529     -0.0389     -0.0224      0.0473
  8  EDDY               -0.4029     -0.3730     -0.3699     -0.2858     -0.2441
  9  GUADALUPE          -0.2811     -0.2717     -0.2775     -0.2160     -0.1090
 10  LEA                -0.3942     -0.3725     -0.3636     -0.3381     -0.2905
 11  LOS ALAMOS          7.0543      7.0989      7.1207      7.2516      7.5183
 12  MCKINLEY           -0.6956     -0.6764     -0.6614     -0.6388     -0.5975
 13  OTERO              -0.1245     -0.0760     -0.0579     -0.0550     -0.0188
 14  QUAY               -0.1845     -0.1023     -0.1008     -0.0326      0.1519
 15  RIO ARRIBA          1.6254      1.6928      1.7149      1.7863      1.9321
 16  ROOSEVELT          -0.0257     -0.0023      0.0073      0.0548      0.1195
 17  SANDOVAL            1.6962      1.7318      1.7539      1.8037      1.9138
 18  SANTA FE            5.6107      5.6136      5.6360      5.6778      5.7288
 19  SIERRA             -0.2787     -0.2101     -0.2055     -0.1188      0.0833
 20  SAN JUAN           -0.3486     -0.2502     -0.2478     -0.1928     -0.0504
 21  TAOS               -0.0504     -0.0026      0.0112      0.0772      0.2039
 22  VALENCIA            1.8136      1.8547      1.8757      1.9254      2.0182

         COMBINED PER CAPITA TRIPS TO ALL SUBSTITUTE SITES FOR  5  COCHITI

        ZONES              1980        1981        1982        1983        1984

  1  BERNALILLO          4.6317      5.0428      5.0328      5.3082      6.1200
  2  CHAVES              5.4465      5.5443      5.5150      5.5502      5.9634
  3  CIBOLA              7.9225      8.3176      8.2900      8.7263      9.8672
  4  COLFAX              2.0206      2.1879      2.1556      2.2928      2.4249
  5  CURRY               8.0789      8.5367      8.5069      8.9788     10.0660
  6  DE BACA            11.6706     11.4699     11.4283     11.9261     12.4065
  7  DONA ANA            4.2847      4.4957      4.4563      4.6209      5.2098
  8  EDDY               12.3704     12.4410     12.4039     13.0782     13.1805
  9  GUADALUPE           9.8015      9.4895      9.5377     10.1992     10.6078
 10  LEA                 4.0334      4.1386      4.1043      4.1885      4.5486
 11  LOS ALAMOS          7.9079      8.5510      8.5432      9.1656     11.3644
 12  MCKINLEY            3.1785      3.2784      3.2501      3.4067      3.7184
 13  OTERO               2.6368      2.7135      2.6831      2.8662      3.2770
 14  QUAY               10.0951     10.6331     10.6274     10.8501     11.9464
 15  RIO ARRIBA          5.5194      6.0919      6.0850      6.5180      7.6409
 16  ROOSEVELT           3.0307      3.3061      3.2832      3.3661      3.7719
 17  SANDOVAL            3.4462      3.8075      3.8000      4.0637      4.8783
 18  SANTA FE            0.5531      0.6970      0.6921      0.8391      1.1986
 19  SIERRA             26.1184     24.6501     24.5808     26.9931     28.5753
 20  SAN JUAN           10.4050     10.9815     10.9684     11.3059     12.1024
 21  TAOS                5.7861      6.1676      6.1407      6.5693      7.3866
 22  VALENCIA            3.1802      3.5223      3.5132      3.7695      4.5074
```

can be placed on water values during spawning months to reduce water-level change to tolerable amounts. In this scenario, we intend to increase the release rates during the period March-July to simulate a downstream diversion of spring storage. For inflows and outflows, each of the flow values can be changed by changing the multiplier or actual value. In this instance, we left inflows from all three sources as they were but increased outflows from March to July (Table 37).

Biological Modification

In the biological model, numerous choices exist to reset the biologic condition. Using choice 1 on the menu the user can change the concentrations of organic matter (carbon), phosphorus, nitrogen, or suspended solids in tributary inflows to simulate, for example, the anticipated impacts of altered watershed management, the construction of a sewage treatment plant, fertilization of a reservoir via one of its tributaries or the anticipated consequences of bank stabilization through riparian protection. Other possibilities may exist depending on need and user creativity. We can change these variables on a seasonal basis now but already have identified another issue, the spring release rates of water, and therefore will bypass the opportunity to make changes.

The second choice is to reset all values. However, that would change the reference run conditions we have already created, including stocking and regulations; therefore, the reset choice is bypassed. The reset choice could be selected if the effectiveness of any regulation or stocking was to be examined. If that were desired, the historic practice we established in the benchmark run is easily eliminated with use of the reset choice.

Choice 3 allows the user to introduce historic stocking if it had not already been done. Because we already set up historic stocking in the benchmark run, it is not necessary to repeat it.

Table 37. An example of a management scenario illustrates the effects of altered water management at Cochiti Lake releasing more water downstream (Printed as seen on the screen).

```
*****************************************************************************
HIGH SPRING RELEASE RATE
*****************************************************************************
1/15/1990    15:25

***************   COCHITI         1980      1981      1982      1983      1984

 LAKE ELEVATION - MAXIMUM        5329.4    5324.2    5326.1    5326.3    5325.4
        (feet)  - AVERAGE        5325.2    5323.1    5323.4    5323.8    5323.7
        (feet)  - MINIMUM        5322.8    5322.8    5322.8    5322.8    5322.8

    LAKE VOLUME - MAXIMUM        46891     41478     43388     43606     42696
     (acre-ft)  - AVERAGE        42508     40345     40642     41057     40987
     (acre-ft)  - MINIMUM        40000     40000     40000     40000     40000

      LAKE AREA - MAXIMUM         1090      1013      1036      1039      1026
       (acres)  - AVERAGE         1030      1003      1006      1010      1009
       (acres)  - MINIMUM         1000      1000      1000      1000      1000

    AVERAGE EXCHANGE RATE          154.5      47.9     116.2     149.8     169.3


CATCHABLE PAN,GAME FISH(kg/ha)     88.0      88.0     132.0     140.0     154.0
   CATCHABLE o/o OF TOTAL FISH      8.1       8.1      11.7      12.8      13.1
            TOTAL ANGLER DAYS  36620     41369     35067     33790     33037
              FISH CATCH/HOUR      0.33      0.33      0.61      0.35      0.64

  PRIM PROD + ALLOC (gC/m2/yr)   1717.5    1300.4    1349.8    1983.5    1874.4
      BENTHOS PRODN (kg/ha/yr)    699.3     178.5     548.5     755.4     817.4
  ZOOPLANKTON PRODN (kg/ha/yr)  16298.4    6299.2   13178.2   16884.4   18607.5

MAXIMUM POTENTIAL FISH PRODUCTION:
     CARP,CRAY PRODN (kg/ha/yr)   160.3     153.8     146.4     135.0     163.7
          SHAD PRODN (kg/ha/yr)     0.0       0.0       0.0       0.0       0.0
   BENTH.CONS. PRODN (kg/ha/yr)   111.7      21.7      93.7     114.7     125.3
   ZOOPL.CONS. PRODN (kg/ha/yr)  2453.6     635.5    2095.3    2454.4    2672.9
    FISH CONS. PRODN (kg/ha/yr)   447.2      88.6     408.9     445.5     436.6

ACTUAL OR REALIZED FISH PRODUCTION OF CATCHABLE SIZE FISH:
      PAN FISH PRODN (kg/ha/yr)    11.4      12.1       6.6       7.0       7.5
     GAME FISH PRODN (kg/ha/yr)    50.4      57.7      95.9      98.8      88.8
 CARP, SUCKER PRODN (kg/ha/yr)    154.6     153.9     147.0     131.5     182.3

HERE IS A BRIEF DESCRIPTION OF THE SCENARIO FOR THIS RUN.
MORE DETAILED INFORMATION IS AVAILABLE THROUGH FURTHER EXAMINATION
OF THE RESULTS OF THIS RUN.
```

Table 37 (Cont'd)

```
* * * * * * * * * * * * * * * COCHITI  * * * * * * * * * * * * * * *

INITIAL VOLUME (acre-ft)     46880
MINIMUM VOLUME (acre-ft), January to December,
40000 40000 40000 40000 40000 40000 40000 40000 40000 40000 40000 40000
MAXIMUM VOLUME (acre-ft), January to December,
505700 505700 505700 505700 505700 505700 505700 505700 505700 505700 505700 505700
MAIN INFLOW
                                      MULTIPLIER
         J      F      M      A      M      J      J      A      S      O      N      D
1979                                                                  1.00   1.00   1.00
1980  1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1981  1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1982  1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1983  1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1984  1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
                                       CONSTANT
         J      F      M      A      M      J      J      A      S      O      N      D
1979                                                                     0      0      0
1980     0      0      0      0      0      0      0      0      0      0      0      0
1981     0      0      0      0      0      0      0      0      0      0      0      0
1982     0      0      0      0      0      0      0      0      0      0      0      0
1983     0      0      0      0      0      0      0      0      0      0      0      0
1984     0      0      0      0      0      0      0      0      0      0      0      0


MAIN OUTFLOW
                                      MULTIPLIER
         J      F      M      A      M      J      J      A      S      O      N      D
1979                                                                  1.00   1.00   1.00
1980  1.00  10.00  10.00  10.00  10.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1981  1.00  10.00  10.00  10.00  10.00  10.00  10.00   1.00   1.00   1.00   1.00   1.00
1982  1.00  10.00  10.00  10.00  10.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1983  1.00  10.00  10.00  10.00  10.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
1984  1.00  10.00  10.00  10.00  10.00   1.00   1.00   1.00   1.00   1.00   1.00   1.00
                                       CONSTANT
         J      F      M      A      M      J      J      A      S      O      N      D
1979                                                                     0      0      0
1980     0      0      0      0      0      0      0      0      0      0      0      0
1981     0      0      0      0      0      0      0      0      0      0      0      0
1982     0      0      0      0      0      0      0      0      0      0      0      0
1983     0      0      0      0      0      0      0      0      0      0      0      0
1984     0      0      0      0      0      0      0      0      0      0      0      0
```

Choice 4 allows the user to modify initial fish populations. If, for example, the user had better information on initial populations, he or she could substitute new values for the default values. Eventually it may be best for the modelers to replace permanently the default values, if the new data prove to be better. Other strategies that are important here include testing the effect of partial or total removals of fish or the effect of introducing a fish, which can be done by stocking as well. Stocking may be the best approach when the problem is to examine how long a transplant will take to become established. If the need is to assess the role of an introduced species at some ultimate expected density, the entire population may be introduced more directly at this point. A lake can be totally recovered by eliminating, or nearly eliminating for expected escapement, all fish and "bioengineering" a new community. Leaving small remnants of the overall population can be done to examine time required to regain the original community structure (if ever), given the existing population parameters.

Choice 5 allows the user to change historic regulations or to introduce regulations if none existed. The minimum size, maximum size, slot minimum, slot maximum can all be simulated (Table 20). The historic regulations are sustained in this scenario. Choice 6 allows the user to change historic stocking rates, or to start stocking. The historic stocking is displayed (Table 19) and will be retained in this scenario. Other species could be stocked, or different rates of the same species could be stocked. Fish are stocked as small fry, one-inch fry or fingerlings, and catchable sizes for different semi-seasons. The fish are assumed to be stocked at the beginning of the semi-season.

Choice 7 allows the model user to alter lake limnology, including the temperature, phosporus concentration, nitrogen concentration, suspended solids, ambient light, and allochthonous loads from watershed and tributaries. Generally, there are few realistic strategies that can be designed to alter the limnological properties because they are mostly determined by climatic or watershed conditions. However, if some watershed treatment or river tributary riparian treatment, for example, were expected to change nutrient, suspended solid or allochthonous organic input concentrations, those strategies could be examined for their impact on the lake system by changing the inputs appropriately. Of course, better estimates of the default values could be introduced once they become available.

Another use of these changeable inputs is for sensitivity analysis. How do expected variations, based on observed ranges of variations, influence model outputs of most concern to model users? The greater the impact of uncertainty, the more research attention may be required to gain greater accuracy in estimation of inputs. When the model outputs reveal little sensitivity to a variable, the uncertainty of the measure is of little relevance to model performance and there is little need for research pertaining to the model.

Choice 8 allows the user to reset any previously altered fish population parameters. If fish parameters had been altered for the reference run, they should be preserved for any subsequent comparative run unless changes in the parameters are being specifically examined for their impact.

The model user can change a large number of the parameters that determine a species place in the aquatic community. The natural mortality rate of the species, once it reaches age 1 (after the first winter as a juvenile fish), is assumed to be constant in the model unless some intolerable extremes in temperature and or oxygen concentration are encountered. The model user can alter the natural mortality slope to any appropriate slope. Threadfin shad will winter kill in the model if semi-seasonal temperatures read below 7°C. Trout, salmon and smelt in the model will summer kill if no temperatures exist below 25°C where oxygen is at least 4 mg/liter. However, refuges to protect species from total kill are also provided in the model. The user has the option of assuming that such a refuge exists (e.g., spring tributaries) and protects a part of the population. Once the refuge is designated to exist, the user also is asked to identify the percentage of the population that is protected. It is assumed that the protected population exhibits the parametric characteristics of the original population.

The P/B parameter represents the maximum expected production for the existing biomass present for each life stage of each species. For most species, the maximum P/B for larvae is near 10, between 10 and 5 for juveniles and less than 5 for older fish, falling to low fractions in the oldest fish. If food is not limiting growth, the species will grow at the maximum P/B rate. In other words, the larvae will grow (both survivors and those that die) over each semi-season at 10 times the mean biomass, juveniles at 5 times the mean biomass, and so on for adults at the prescribed parametric rates for the older age classes. Of course, there is much information available about maximum growth rate for fish older than young-of-year and less information available for larvae and small juveniles. Therefore, the levels of certainty included in the model vary and suggest the need for sensitivity analysis to determine the importance of this information for simulating fish population dynamics.

The default sex ratio is assumed to be 0.5 unless otherwise known, and the default age of sexual maturity was identified from the literature (Choice 3). Both can be altered to appropriate values by the user.

The water-level fluctuation effect on egg and larval survival is changeable in Choice 4; either slope or the intercept can be changed. Hatching success is rarely 100 percent, thus the intercept at 0 water fluctuation is usually less than 100 percent for most species. This parameter is among the most difficult to fit; better data can be used for improved fits as the data become available because the user has access to the parameters. One scenario of interest to many fishery managers is the degree of water level fluctuation required to influence the survivorship and recruitment of young fish. In many instances, food availability may limit recruitment more than water-level fluctuations within the normal ranges, sometimes even when the relationship between water-level change and spawning success is intensely negative. Presence or absence of species like gizzard shad may also be at least as impactive as water-level fluctuation.

Larval growth rate, Choice 5, is the rate larvae grow to reach juvenile size. If juvenile size (about 2 cm) is not reached within a semi-season (about 6 weeks), the larvae are assumed to die from starvation or increased exposure to predation. The user may vary this parameter, which tends to be lower for big-egged fish with relatively low productive potential, to examine the impact of initial larval size on the recruitment of young-of-year fish and the length of young-of-year fish and year-old stocks.

In Choice 5, the user can change the minimum size that a juvenile fish needs to attain to survive through the winter period, based on the smallest size yearlings collected in various locations.

Both the harvestability and the minimum catchable size can be modified by the user, thereby increasing or decreasing the catch rate for any particular density of the fish present. For fish basically not catchable, like gizzard shad, the minimum size is set to be impossibly large. Also, the default fish mortality model, which assumes a compensatory interaction between natural mortality and fishing mortality, may be changed to an additive model or any combination of mixed effects, if the information available for a fishery suggests that an alternative is in fact the case, or to test the differences in mortality rates that would exist with any model. The choice of model is determined by selection of a number between 0 and 1.0.

One scenario, for example, for a lake with an expected increase in angler activity, may be to increase the human population in the nearest angler-of-origin zone to drive up the angler population, then run the model with both estimators of the mortality parameter to examine a range of possible impacts. When no data otherwise exist, the most conservative model estimator of impact is the usual assumption. Appropriate protective regulations may be applied to see how they mitigate the fishing mortality. It should be remembered that in this version of the model, hooking mortality is ignored. In intensively fished lakes, hooking mortality will have an impact that can be approximated by increasing the natural mortality estimate to the amount expected by the addition of hooking mortality.

The user can also modify the fecundity, initial size of larvae and the length-weight relationship of the fish. The fecundity influences the birth rate and ultimately, the number and size of young-of-year fish recruited. The initial size of the fish is interactive with the larval-growth parameter. Larger initial sizes have a smaller growth requirement to enter the juvenile size category, thus having a growth advantage over smaller larvae in other species. The length-weight relationship determines the length distribution once weights are calculated.

The initial size of the fish population can be modified whenever data are available or for sensitivity analysis. Initial sizes are interactive with initial densities, and will contribute to determination of relative distribution of growth among different sizes of fish.

Food partitioning coefficients are also modifiable for each species in each age class (larval, juvenile, adult) in each lake habitat. The partitioning coefficient is based on a ranking of the expected advantage of one species or size over another. Factors such as temperature, responsiveness of fish to light, substrate type and size of food items in relation to size of fish all are considered when estimating the relative partitioning rate. Once again, the user can examine the role of resource partitioning from the standpoint of improved understanding of interactions as well as the impacts it may have on the catchable fish.

The distribution of species and life stages in habitats also can be altered by the user. The simplest assumption is that species and life stage are evenly distributed among all habitats. Under that circumstance, the highest potential fish production will be realized. To the extent that habitats are not well occupied, however, the potential for fish production will be diminished. The best example of this is a steep-sided, deep lake with a small littoral zone initially stocked only with sunfish and largemouth bass. The food energy in much of the lake will not be efficiently consumed by fish in such a modeled lake. The fish production will be diminished. Stocking off-shore species like white bass and walleye, in this case, should substantially increase the production, whereas stocking another predominately littoral species, like black bullhead, will not so substantially increase production. The bullhead will mostly compete for resources with the established species. This population parameter can have a marked impact on sportfish population production estimates in low density communities. Thus, it is one of the more critical parameters to estimate accurately.

Economic Detailed Output

The economic model detailed output includes tables of information about angler days of activity by county from both instate and out-of-state anglers. From this information, net income to the state and net income from out-of-state anglers is also identified. Of course, the impacts of various management strategies and anticipated natural events (e.g., drought) can influence local economies and is important to fishery managers from the political standpoint, rather than from the standpoint of angler benefits. Economic benefits (net economic value, consumer surplus) to instate anglers are provided by zone of origin (county complexes). Benefits not only estimate the satisfaction expressed by anglers in a way that can be compared directly to management cost, benefits also are an index to how much more likely anglers will stay inside the state to distribute their wealth rather than leave the state to fish. If a high state exodus of anglers occurs because of poorer fishing in New Mexico, any net state income derived from out-of-state residents will be more than counterbalanced by movement of New Mexico residents out-of-state.

DETAILED DESCRIPTION OF RIOFISH

Hydrologic Submodel Description

General Overview

Unit 1 and 2, (Figure 7). The primary variable in the hydrology component of the Rio Grande Basin model is the quantity of water entering or leaving reservoirs or tailwater reaches as monitored by the USGS and other agencies. The water is modified by precipitation, evaporation, irrigation withdrawals, channel geometry, and other physiographic and hydrologic processes. The hydrology component basically is comprised of two submodels: one for reservoirs and the other for tailwaters. Both models operate on a two-week (semimonthly) time period for measured flows.

Unit 3 and 4. The reservoir submodel is based upon conservation of mass. Therefore, inflows and precipitation entering a reservoir in a semimonthly period causes reservoir contents to increase. Reservoir releases through outflows and evaporation cause contents to decrease. Ungauged inflows and reservoir leakages can create mass balancing difficulties so that the predicted contents do not match measured contents. These difficulties are particularly evident at Cochiti, Abiquiu, and McMillan reservoirs.

Unit 5 and 6. Loadings of total phosphorus, total nitrogen, and total suspended solids are included in the reservoir submodel. These loadings are estimated from USGS data. Reservoir concentrations are computed as described by Bolin (1985) with some specific modifications.

Units 7 and 8. For the connecting water submodel, it is assumed that steady, uniform flows occur in the typical flow reach because two-week flow periods are used. The 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

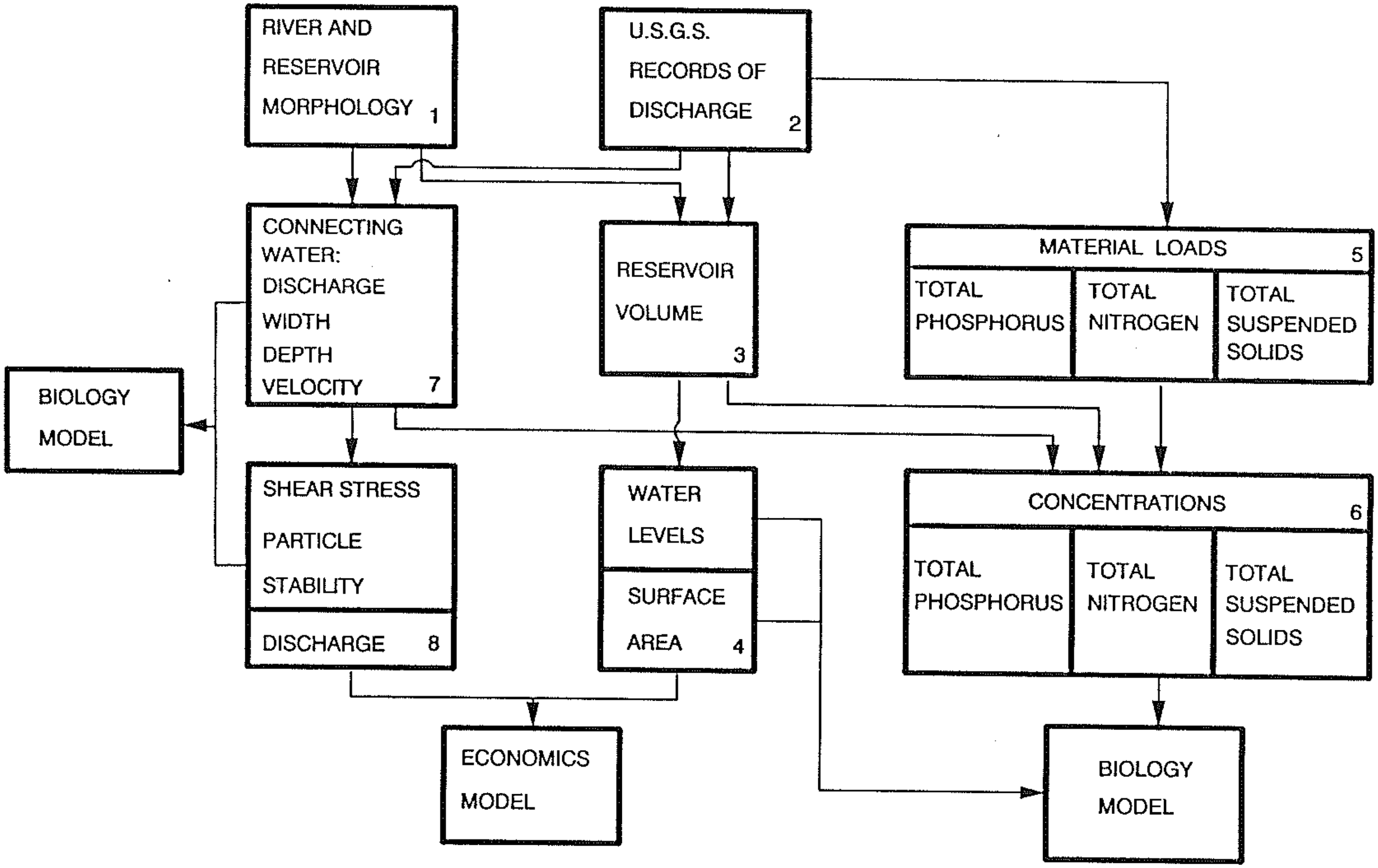


Figure 7. Overview flowchart of the hydrologic component.

(based on average conditions). Mean channel widths and depths of each connecting water are required inputs for calculating channel conditions. The concentrations of total phosphorus, total nitrogen, and total suspended sediment are either computed from empirical discharge-load relationships, or, when appropriate, are assumed to be equal to the immediate upstream reservoir outflow concentration.

Computational aspects of the hydrology submodels are largely devoted to converting external data files (flows and concentrations) to generate the correct sequence of flows. Cochiti Reservoir, for example, has a primary inflow measured at the Otowi Bridge gauging station. Flows at the Otowi Bridge gauging station are determined by the sum of Rio Grande and Rio Chama flows as corrected by an empirically determined constant. The modeled Rio Chama, in turn, is influenced by reservoir operations in its subbasin. Therefore, the modeled flows at the Otowi Bridge gauging station should reflect any changes imposed by the model user on reservoir operation in the Rio Chama. The model user is provided entry to the model for this purpose.

The hydrology submodels provide means for the model user to change water allocation and water transfer conditions 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 submodels in Figures 7 (reservoirs) and 8 (tailwaters). The detailed model description that follows is organized to match with the flowchart units.

Reservoir Submodel

Units 9 to 11 (Figure 8). A number of variables (Table 38) are read into the program, some of which can be adjusted by the model user to analyze how changes in the reservoir system affect RIOFISH outputs. Upon starting the model, the user is prompted for the names of files needed to define inflows, reservoir parameters (i.e., reservoir maximum contents, minimum

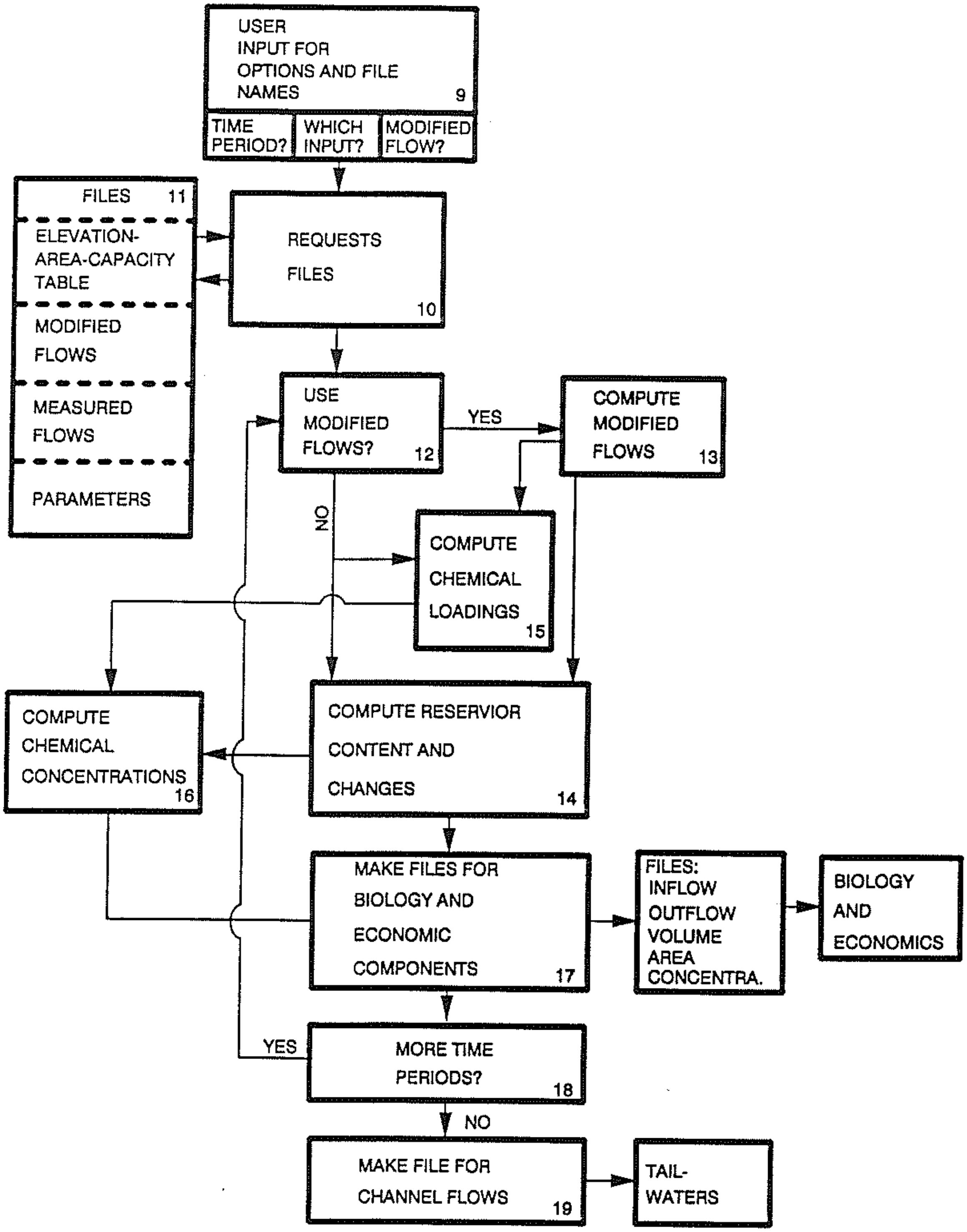


Figure 8. Flowchart of the submodel that simulates reservoir hydology.

Table 38. List of all hydrologic model parameter inputs.

Elevation-area-capacity table

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 measure flow by some number

*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

Measured volumes for the period selected

*An initial reservoir volume, one time step before the selected period

Pan evaporation

Precipitation

*Maximum allowable reservoir contents for each month

*Maximum allowable reservoir contents for each month

*Maximum allowable reservoir outflow for each month

*Minimum allowable reservoir outflow for each month

*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

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

contents, maximum outflow rates, and evaporation pan coefficients) for relating pan and lake evaporation, elevation-area-capacity relationships for each reservoir, and coefficients for calculating stream loadings of nutrients and suspended solids. 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.

Units 12 and 13. The user, at this point, can select either the historical 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 the reservoir inflows being modified by the user. For example, the May flow at the Otowi Bridge gauging station was determined from nine years of flow records to be 1.199 times the combined outflow from Abiquiu Reservoir and the Rio Grande at San Juan Pueblo. Similar relationships were developed for each month at each reservoir inflow gauging station. These relationships can be updated as more data are collected at the gauging stations. With these relationships, it is possible to account for changes in inflow at the downstream reservoirs when outflow from an upstream reservoir is modified.

Unit 14. 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 area-capacity (volume) table previously read into the model. The initial reservoir surface area is multiplied by the net evaporation coefficient (determined from the pan evaporation, pan coefficient and the precipitation) to determine reservoir volumetric changes caused by local weather. The initial volume is then modified to reflect weather effects and a new surface area is then calculated using the area-capacity tables. A second volume estimate is made from the new surface area estimate, then the first and second estimates are averaged to predict volume at the end of the two-week time period. The two estimates of volume are usually close because evaporation is usually small compared to the inflow and outflows.

The volume estimate is also modified by constraints on the 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. The outflow constraints, however, are not used to rebalance volume and flow. After this check on constraints, the volume is used to compute area and elevation for other uses.

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 ungauged 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 and measured inflows and outflows. The watershed inflows were estimated using a fixed evaporation pan coefficient of 0.7. The difference between measured and predicted volumes in the reservoir was attributed to the third inflow to the reservoir. This technique creates negative as well as positive (preferable) values. The positive values are interpreted as unmeasured inflows whereas the negative values are interpreted as unmeasured outflows or losses. Reservoir leakage is an unmeasured loss. This third, "synthetic" inflow is now part of the measured flow file in Unit 11 (Figure 8). When these flows are used, the computed reservoir volumes almost perfectly match the measured volumes. The slight differences are caused by the interactive technique used to find evaporation in the model.

Although rather crude, the balanced volume technique for finding inflow or outflow was determined to be the best approach with current time constraints. Research during this last phase of the modeling study indicated a relationship between missing inflow to Caballo Reservoir and rainfall measured at various sites in the Black Range. Long-term simulation scenarios for planning and management would be best served from such an approach: however, for this phase of the project, we decided to use the balanced volume technique to provide "what if" scenarios using previous conditions. Improved approaches will occur during the next modeling phase.

Units 15 and 16. Reservoir inflows contain phosphorus, nitrogen, and suspended solids. USGS data were analyzed from monitored sites to determine relationships between total loads (tons/day) and stream discharges (ft^3/sec). The relationships took the form of power functions, linear functions or simple constants (no variation with flow), but only power and linear functions were used in the model, depending on the site. These relationships could not be developed for all reservoir inflow locations because only a few locations are monitored by the USGS. 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 semimonthly reservoir concentrations of total suspended solids, total phosphorus, and total nitrogen by equations developed by Bolin (1985) and 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 (Unit 14). Actual 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. The relationships used were calibrated with data from some reservoirs, 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).

One reason a third inflow (or negative inflow, i.e., outflow) was computed using a balanced volume as described above, was to help better define nutrient and sediment loadings from ungauged sources. Such ungauged sources can help explain the observation of high productivity habitat in a reservoir which would not seem that way if only measured inputs were considered. This is particularly true with low elevation reservoirs, such as Caballo, which can receive larger bursts of water, suspended solids, and nutrients from runoff caused by summer rains. When the model was run with the third inflow, computed reservoir concentrations of nutrients and sediments increased to levels that better matched observed values than those computed without the inflows, that is, by volumes determined from balancing with evaporation and correction factors. In the model, positive inflows add materials to the reservoirs whereas negative inflows subtract material.

Unit 17. At this point, hydrologic files are prepared for passage to the biological and economics components of the model. These include the date, number of days in the period (13 through 16 days), computed volume, total inflow, total outflow, evaporation, retention rate and concentrations of total phosphorus, total nitrogen and total suspended solids.

Unit 18. The model either proceeds to the next time-step calculations by reiterating the process already described, or it proceeds to unit 19 when all of the time steps have been completed.

Unit 19. The final action of the reservoir submodel is to create a file with information needed at the next downstream reservoir, if the user decides to follow through to the next reservoir. The created file contains the date, measured primary outflows, computed primary outflow, and computed concentrations of total nitrogen, total phosphorus and total suspended solids. This file, as indicated in Figure 7, can also be accessed by the user of the connecting water submodel.

Tailwater Submodel

The tailwater submodel is detached from the reservoir submodel to allow reservoirs to be modeled by themselves without added storage and time requirements. Conceptually, both submodels function similarly as indicated in the flow-chart shown in Figure 9, except as noted below. The tailwater submodel is temporarily excluded from the APL user-friendly model version, but will soon be reincorporated in an updated version.

Units 20 to 22. As in the reservoir submodel, the model user is prompted for file names and options. The submodel can accept file information on measured flows, modified flows from upstream reservoirs, and concentration of total suspended solids, total phosphorus and total nitrogen.

Units 23 and 24. At this point, the model user chooses either measured or computed inflows. If computed flows are chosen, the model modifies the flows as described for the reservoir submodel. For several different reaches of connecting waters, there will be no modification because the reach is immediately downstream from the reservoir. For reaches

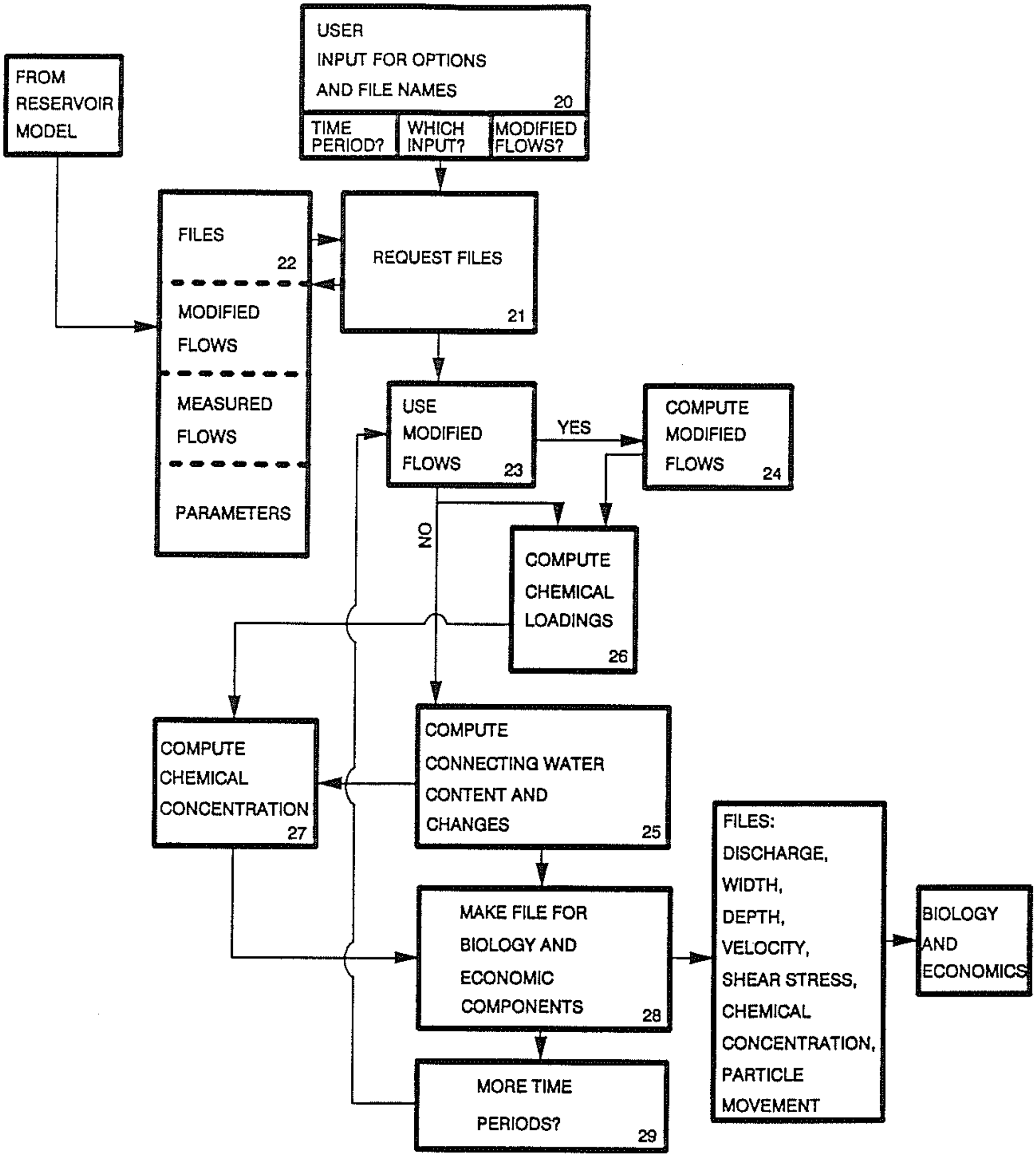

Figure 9. Flowchart of the submodel that simulates reservoir tailwater hydrology.

farther downstream from a reservoir, the flows are modified to develop an estimated flow at that site.

Units 25 and 26. 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 a representative relationship between cross-sectional flow area and channel-wetted perimeter. This relationship is also representative of the interactions between flow and surface width. In addition, representative channel slope and roughness, obtained from channel cross-section data, are used in the computations. The flow rate is used to compute the area for average velocity and surface width, and the width and area for average depth. If applicable, the water quality constituent is computed from stream flow as described in the reservoir submodel (Unit 15). Reservoir concentrations are used for computations when the reach is immediately downstream from the reservoir in the tailwater area.

Unit 28. At this point, the model creates a file for the biologic and economic components. This file contains the date, number of days in the period (13 through 16), flow in the reach, cross-sectional flow area, average depth, average velocity, surface width, average shear stress (computed from velocity), maximum sediment size that can be transported, and concentrations of total phosphorus, total nitrogen and total suspended solids.

The hydrologic submodel is applied to the four main river basins with reservoirs and tailwaters in New Mexico. The location of reservoirs in the basins are shown in Figures 10 through 13.

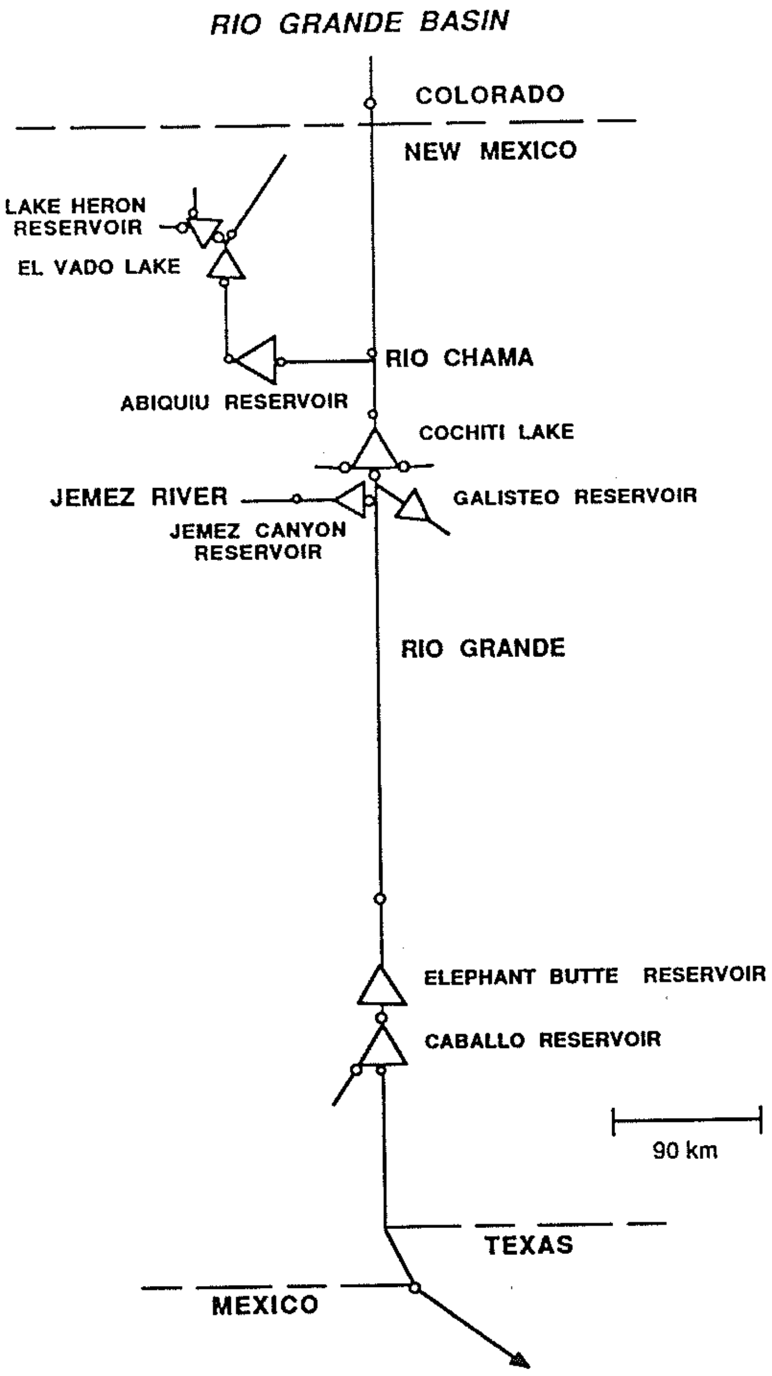

Figure 10. Hydrologic segments included in the Rio Grande Basin. Gauging stations are represented by open circles.

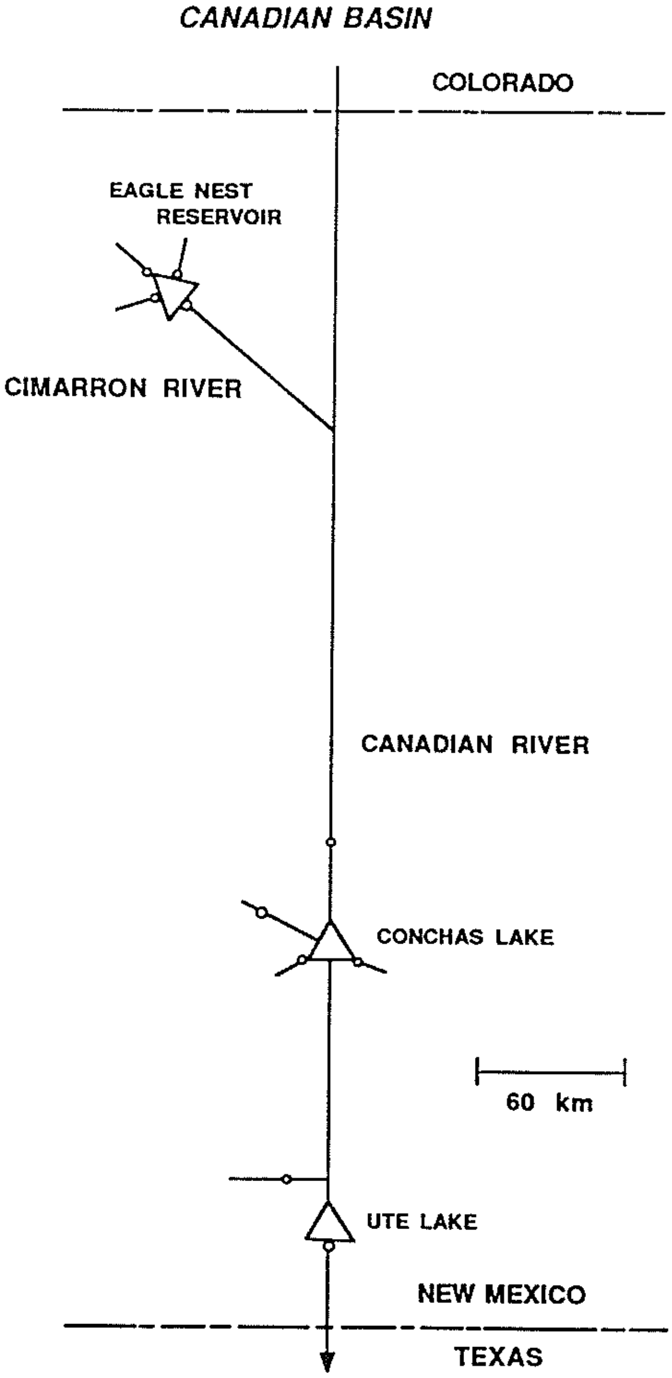

Figure 11. Hydrologic segments included in the Canadian River Basin. Gauging stations are represented by open circles.

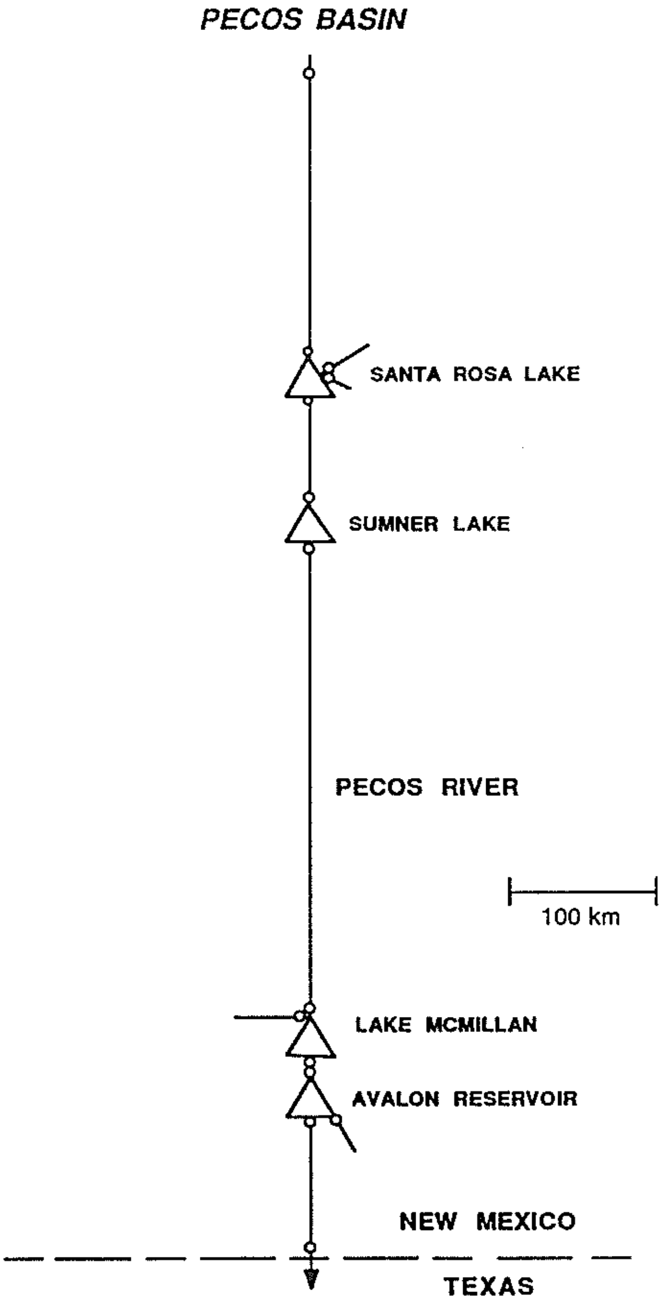

Figure 12. Hydrologic segments included in the Pecos River Basin. Gauging stations are represented by open circles.

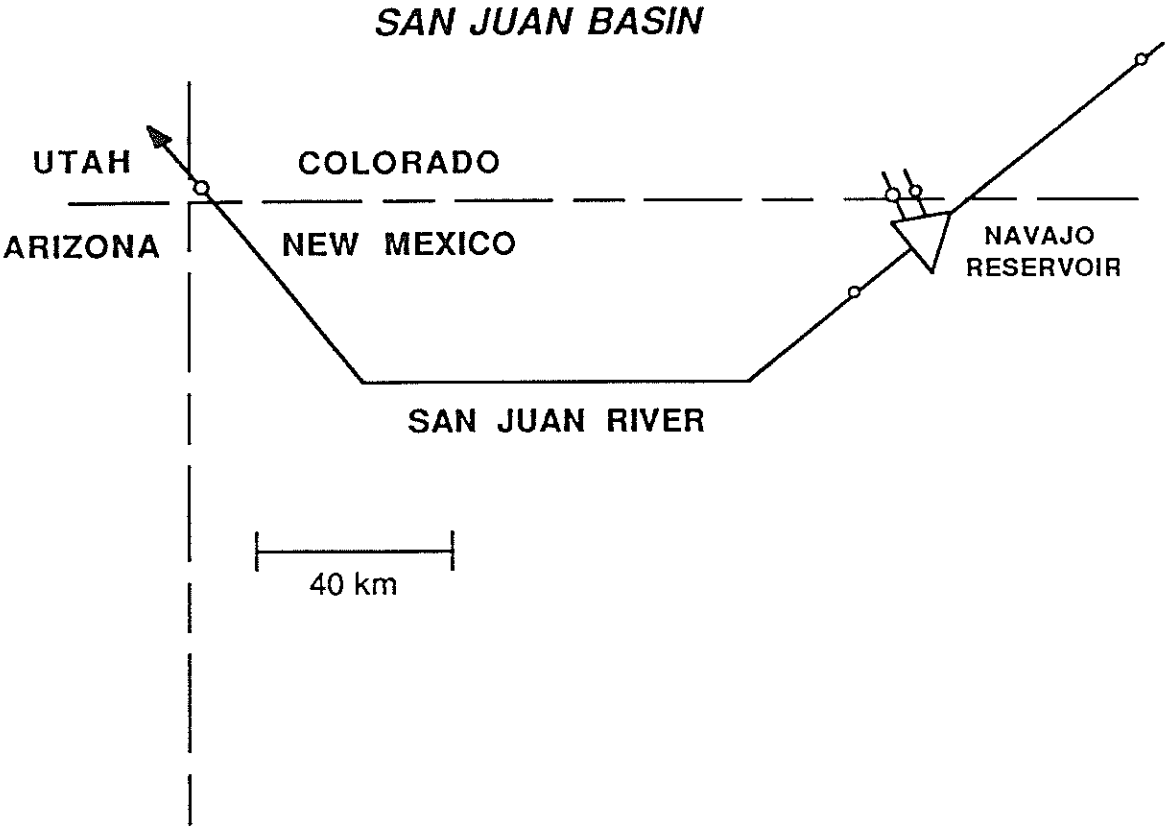

Figure 13. Hydrologic segments included in the San Juan River Basin. Gauging stations are represented by open circles.

Biologic Submodel Description

General Overview

The controlling forces of the biological model are inputs of mean semiseasonal solar radiation, nutrient (total phosphorus and total nitrogen), light transmission through the water (as determined by the concentration of suspended solids imported into the segment), water temperature, and the rate water moves through the reservoirs. Flow rates and basin morphology interact to determine water-level fluctuation, surface area, and water exchange rates. Figures 14, 15 and 16 show flowcharts of model contents that can be used as visual aids for the following descriptions of biological processes. The first part of the biology submodel, depicted in Figure 14, applies with some exceptions to both reservoirs and connecting waters. Figure 15 describes the submodel used to partition energy among fish populations. Figure 16 represents additional components used in the submodel of reservoir tailwaters. All mathematical relationships for RIOFISH are documented in the mathematics appendix.

The Reservoir Production Model

Units 1 and 2 (Figure 14). Phosphorus concentrations are calculated semimonthly as described in the hydrology section. Mean semimonthly euphotic zone (where algae have enough light to use nutrient) concentrations of phosphorus in each reservoir are calculated seasonally from loading-concentration submodels. The euphotic zone depth is defined to equal 1 percent of the mean surface illumination, the approximate compensation point for photosynthesis. Modifications of submodels 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 submodels use measures of hydraulic retention or exchange rate in days and empirically

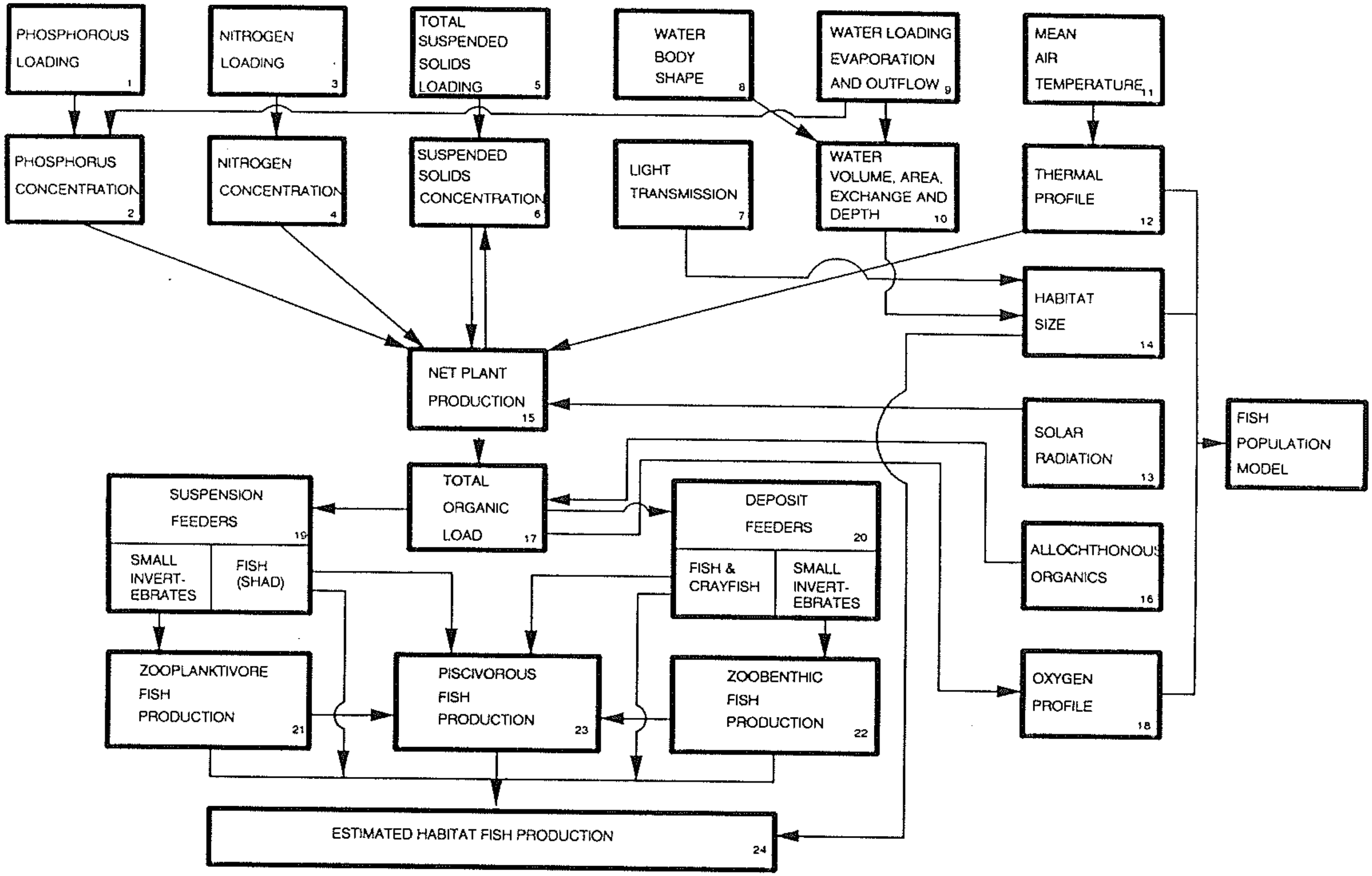

Figure 14. Flowchart of the submodel that simulates production of fish in each habitat by feeding habit.

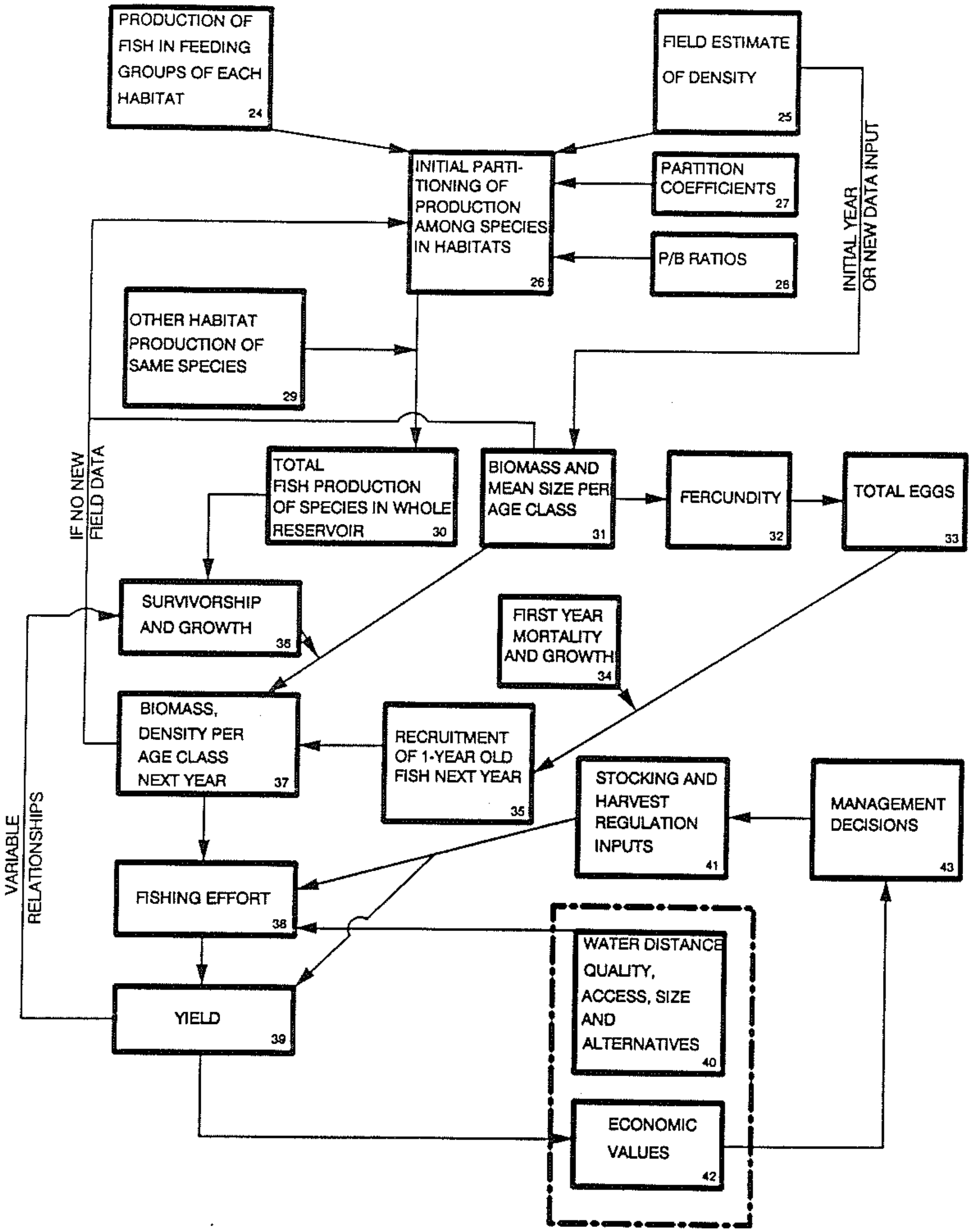

Figure 15. Flowchart of the submodel that simulates partitioning of production among fish populations in reservoirs.

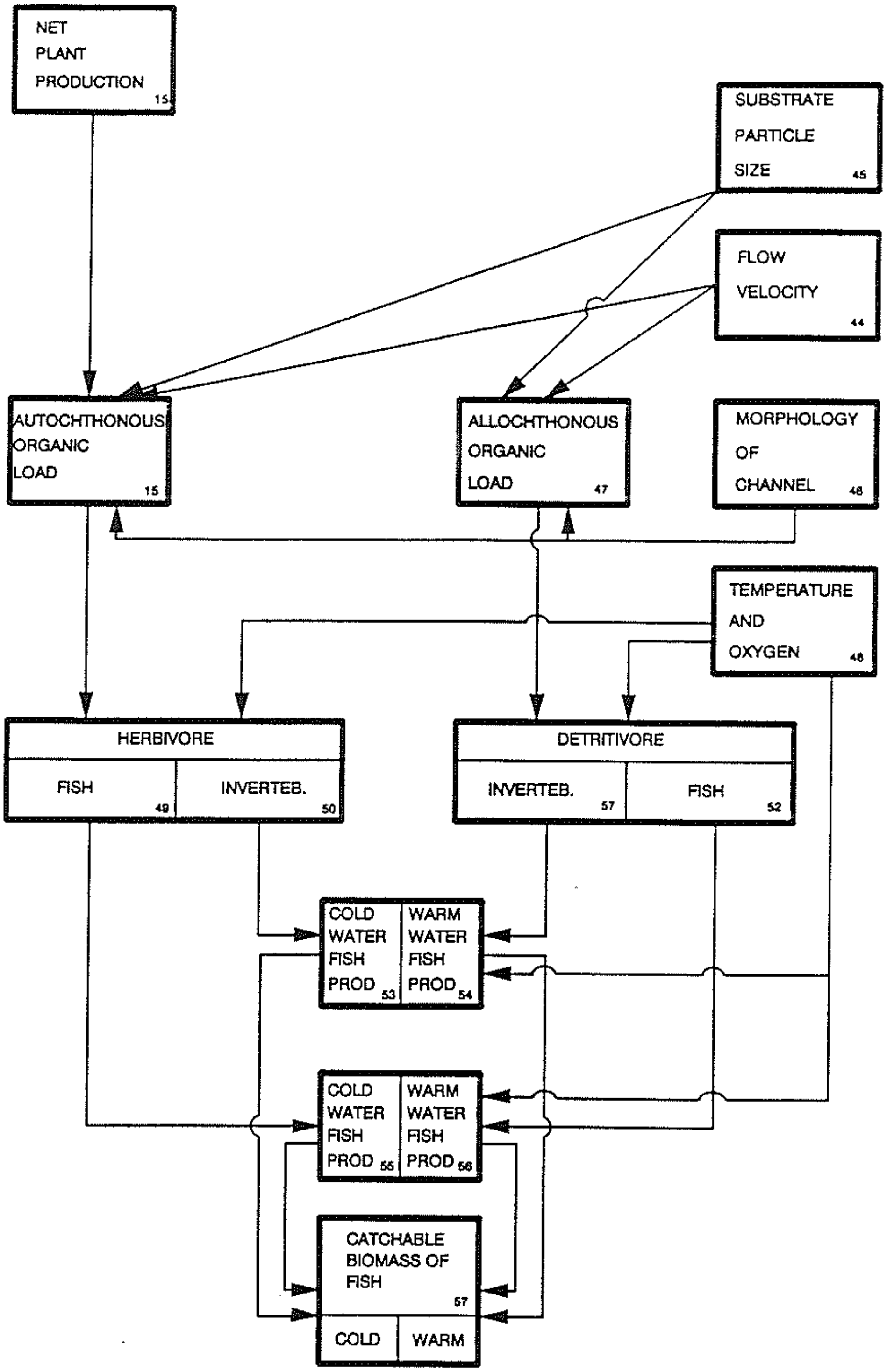

Figure 16. Flowchart of the submodel that simulates tailwater fish production and biomass in warm and cold-water categories.

determined net sedimentation rates (Bolin 1985, Ward and Bolin 1989) and reservoir depth to simulate the reservoir concentration of phosphorus from the measured loadings. The model user can change semiseasonal concentrations of phosphorus to simulate fertilization or nutrient removal.

Uncertain estimation of phosphorus concentrations has little effect on primary model outputs (fish production, fish yield, angler days) under most circumstances. The impacts of uncertainty are greatest when allochthonous organic carbon and nutrient concentrations are low. Large lakes with complex basins tend to be the least certainly simulated with regard to nutrient dynamics. Development of multibasin loading-concentration submodels may be the best strategy to reduce this simulation uncertainty.

Units 3 and 4. Nitrogen loadings are calculated in the hydrology submodel as described in the hydrology section. Mean concentrations of nitrogen in the trophogenic zone were estimated for each reservoir using submodels similar to the phosphorus loading-concentration submodels. The model user can change semiseasonal concentrations of phosphorus to simulate fertilization or nutrient removal.

Concentration of total nitrogen is less reliably simulated than phosphorus, probably because biological process effects the physical process represented in the loading-concentrations submodels. Sensitivity analysis indicates that uncertainty in the simulation has little effect on model output under most circumstances, however. As with simulation of phosphorus concentrations, the greatest sensitivity to uncertain nitrogen concentration occurs in large reservoirs with complex basins. In these reservoirs, loadings of nutrients and organic carbon tend to be lower than average in the main pool.

Units 5 and 6. Allochthonous loadings of total suspended solids (nonliving algal solids) are calculated in the hydrology submodel, which is described in the hydrology segment. Mean concentrations of total suspended solids in the trophogenic zone are estimated for each reservoir using submodels similar to the phosphorus loading-concentration submodels. The model user can change estimated effects of erosion rates or of wind resuspension of sediments by changing the concentration of suspended solids.

With regard to factors that regulate primary production, the modeled fish production and yield are most sensitive to uncertainty in simulation of suspended solids at low concentrations of suspended solids.

Unit 7. Light transmission is determined by variation in the suspended solids generated by allochthonous (from outside the ecosystem) loading and autochthonous (from within the ecosystem) generation of phytoplankton (a small fraction in these reservoirs). Autochthonous plant biomass was incorporated in the estimate of suspended solids as a consequence of its inclusion in the empirical determination of the suspended solids concentration from field observations (Bolin 1985). An empirical relationship (Figure 17) between suspended matter and light transmission was developed from spatially variant data gathered from three Rio Grande reservoirs (Caballo, Cochiti, and Abiquiu). Dissolved organic matter (water color) was assumed not to be an important variable controlling differences in light transmission. Analysis of organic concentration at USGS stations in various parts of the river basins indicate relatively little variation in concentration of dissolved organic carbon. Dissolved organic matter, therefore, is assumed to be constant in the model. At low loading rates of suspended solids, variation of water color may sometimes contribute importantly to the regulation of light transmission and the model simulation of sportfish production and yield. For most fisheries, however, model outputs are more sensitive to other simulation uncertainties.

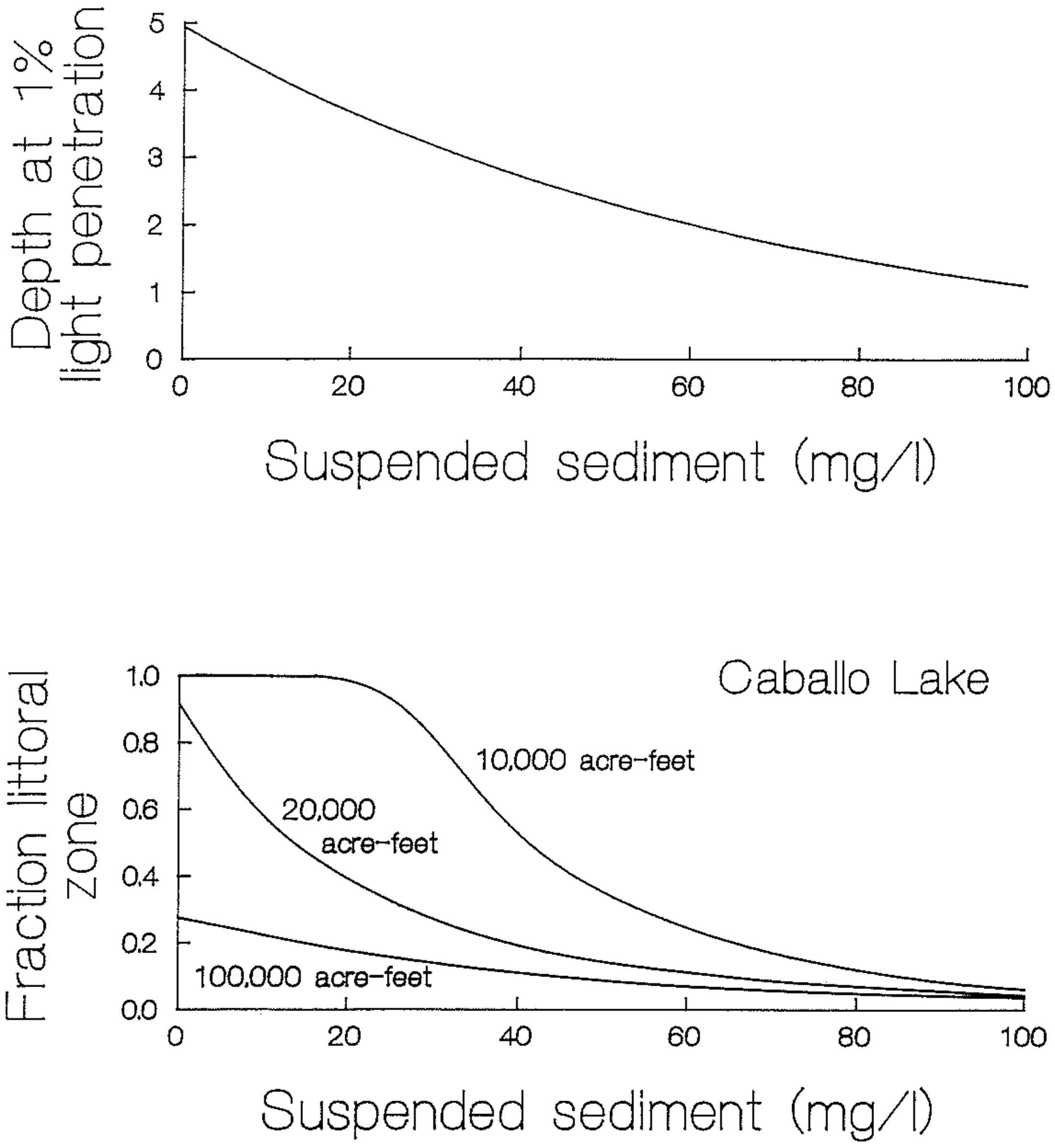

Figure 17. RIOFISH relationships between light transmission and littoral habitat size and the concentration of suspended solids.

Units 8 to 10. The shape of the water-body is developed from USGS or other agency records, as described in the hydrology section. Water loading, evaporation, and outflow from each water segment are estimated in the hydrology model and described in the hydrology segment. 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 defined in the hydrologic section.

Basin morphology has changed to some extent in all basins since depth-volume-area relationships were defined. 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 estimation of loading concentration submodels and fish density.

Unit 11. Mean semimonthly water temperature is determined from empirically determined relationships between air temperature, elevation and time of year. Except during spring, when snowmelt reduces mean semiseasonal water temperature slightly in some reservoirs, the mean seasonal water temperature is nearly identical to mean seasonal air temperature. Unlike mean daily water temperature, mean semimonthly water temperature is not greatly influenced by flow temperatures because the large time interval in the semimonthly period mitigates the effects. Mean semimonthly water temperature is held constant from year to year in this version of the model.

Water temperature variations of ± 2°C affects simulated fish production and yield slightly, and uncertainty in its estimation is not critical. These results also suggest that long-term warming trends would have gradual and small impacts. Therefore, simulations of fish production and yield would not be substantially affected by the inclusion of actual mean air temperatures over the reference period from 1975-1987.

Unit 12. The thermal profile is estimated on a semimonthly basis in each reservoir. We assumed that water equilibrated with air temperature in a mixed epilimnion (the surface layer of a thermally stratified reservoir). Water volume removed at the bottom draws the water downward, and sustains the same temperature as the water mass is drawn below the mixing depth. Every half month, water is drawn further downward toward discharge depth to the extent water volume is discharged downstream. Water entering the reservoir enters whichever thermal layer has the closest temperature to the temperature of the entering water. When the entering water is colder than the lake water, the cold entering water sinks until it reaches a level with its temperature, where it then remains and adds to the volume of that layer. Water discharged from reservoirs is the temperature of the zone from which it is discharged. When more than one temperature zone is discharged, a weighted (by volume) mean temperature is estimated for the semimonthly outflow.

The thermal profile determines survivorship of fish species that are intolerant of warm or cold temperatures. The existence of any tolerable zone will provide refuge to the species. When no refuge remains, the intolerant species are eliminated. The thermal profile also determines the tailwater temperatures.

A graphic output of Elephant Butte model thermal profile in 1980 is shown in Figure 18. This output is not available to the user.

Unit 13. Solar radiation is a required input for generating the energy base for primary (plant) production. Mean seasonal solar-energy inputs (gram-cal/cm^2/day) are based on long-term monitoring at El Paso, Albuquerque and other regional stations extrapolated to other locations in the state (Tuan et al. 1983). 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, etc.). A long-term average solar input is presently used for

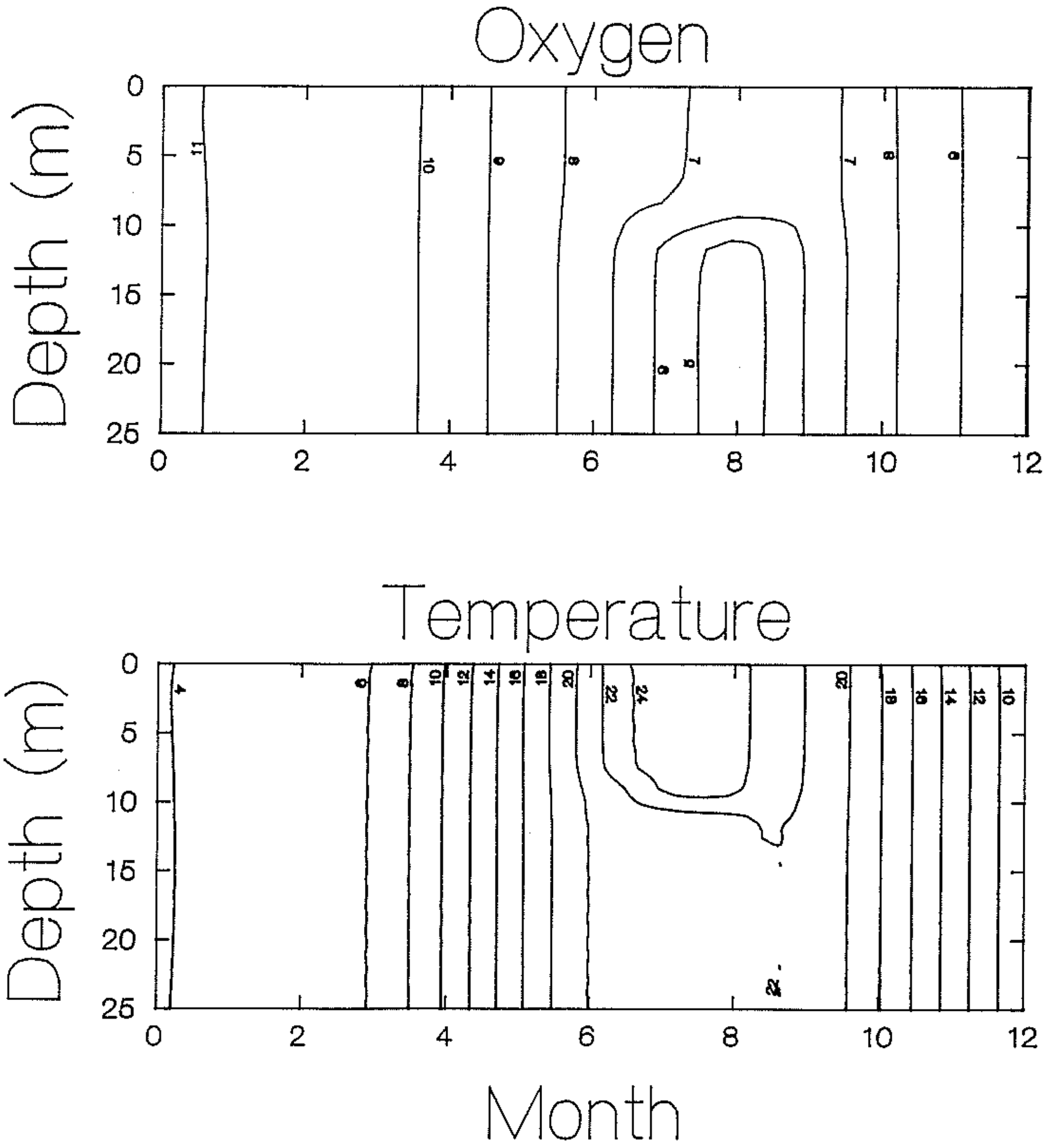

Figure 18. Graphic examples of oxygen and temperature profiles simulated by RIOFISH. Examples are for Elephant Butte Reservoir in 1980.

input. We assume that light reflectance from the water surface varies from 12 percent in winter to 6 percent in summer (Cole 1983). The estimated light is decreased in proportion to the expected effect from the change in angle of incidence.

Uncertainty in solar radiation simulation has small direct effects on simulations of fish production and yield. The constant semiseasonal radiation included in the model reduces variation from year to year. However, real annual variation is relatively small (usually less than ± 15 percent) and sometimes accompanied by counteractive geoclimatic processes. For example, cloudy years have lower solar radiation but higher rainfall and greater erosion of nutrients into the lakes. Eutrophic lakes are more likely to respond to uncertainty in solar radiation than nutrient limited lakes. Although small benefits may be derived from more precise representation of solar radiation, other factors have greater impacts on model output.

Unit 14. Mean seasonal depth of light penetration, depth of the water body, and water surface area collectively determine the numbers and sizes of habitats seasonally occupied by different fish species. The model allows up to five reservoir habitats (Figure 19) to occur in a single reservoir: (1) the littoral zone where light penetrates enough to the bottom to enable benthic primary productivity and clear vision by consumers (see Figure 17 for relation with suspended solids), even to some extent at night (defined as the habitat area in which bottom is illuminated to 1 percent of the surface light after reflectance); (2) the sublittoral zone where light reaching the bottom is insufficient for benthic primary productivity but enough to allow consumer vision during daylight (defined as the habitat area in which bottom is illuminated from 1 percent to 0.01 percent of surface light after reflectance); (3) the deep profundal zone where it remains too dark on bottom for sight-feeding consumers to see clearly at any time (less than 0.01 percent of surface illumination); Figure 19 (4) the limnetic zone offshore where highly illuminated surface waters occur above bottom but light does not reach bottom (defined as

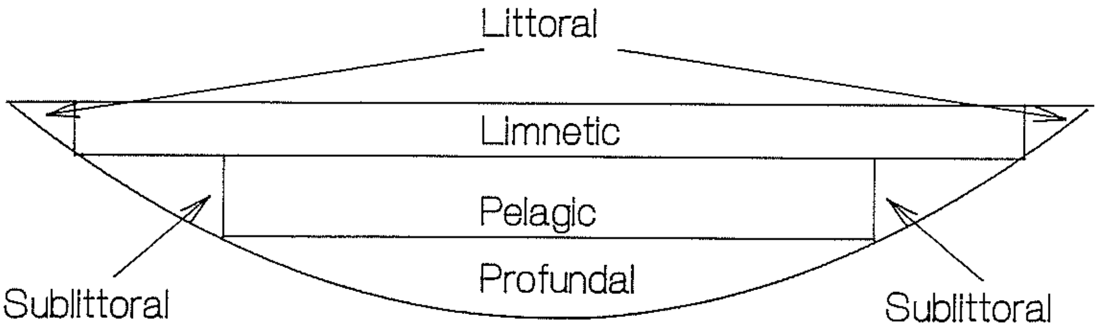

Figure 19. The habitat structure of a reservoir. Habitat depths are determined by light transmission (1.0 percent of the surface light for littoral and limnetic zones and 0.01 percent of the surface light for sublittoral and pelagic zones).

habitat illuminated to 1 percent of surface light and not in contact with bottom); and (5) the pelagic zone, an offshore twilight zone illuminated well enough during daylight for many vision-reliant consumers but unsuitable for plant productivity (defined by illumination between 1.0 percent and 0.01 percent in waters not in contact with bottom). As depth of reservoirs and concentrations of suspended solids vary, the relative areas and volumes of the habitats vary and the relative suitability of the reservoir for various species changes.

The organic product of net plant production and the allochthonous organic load is assumed to be equally distributed among all reservoir habitats by mixing and sedimentation. Therefore, the relative volume of each habitat is the important determinant of the relative contribution of organic loading to total reservoir fish production. This assumption may slightly overestimate phytoplankton in the littoral area and underestimate benthic primary production. Therefore, it may slightly overestimate planktonic energy transfers and slightly underestimate benthic energy transfers.

Relative productions of fish populations are assigned to habitats according to empirical observations of the species in New Mexico waters. Some life stages of species are uniformly distributed in the model while others are concentrated in certain habitats. Food production may go unused by fish in a particular habitat, if that habitat is not occupied by fish. When such "unfilled niches" occur, the trophic efficiency of the consumers declines.

Unit 15. The general form of the submodel used to estimate primary production is $TL_1 = CR (E_{max})(N)(S)(X)(T)$ where TL_1 = net primary production in gCm^{-2}/days for a half-month period, R = daily total solar radiation for the season, 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 exchange (flushing rate), and T is the deviation from optimum caused by temperature, and C is a constant for converting KCal to grams of carbon. The functions used to estimate the net plant production are based on empirical evidence from a variety of sources. 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 percent of the aerial total solar energy (10 calories = 1 gC) based on well mixed, nutrient-rich lakes in tropical Africa (Westlake et al., 1980) and marine field studies (Rhyther 1959). The maximum daily value appears to approach 4 percent based on the annual estimates in rich tropical lakes and maximum daily values found in several of the worlds hypereutrophic lakes (5,000 to 6,000 mg c/m^2/day) according to Wetzel (1983). The high, daily 4 percent value, was not used because ecological limitations, primarily due to inadequate mixing, are likely to make maximum mean semiseasonal percentages less than maximum daily percentages. Several tropical lakes attain close to 2 percent photosynthetic efficiency on an annual basis (Westlake et al., 1980). We assumed that the maximum of 2 percent 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 30^0C, and the exchange rate is more than the 50 days. These conditions are generally met by the tropical lakes with about 2 percent photosynthetic efficiency, and in certain eutrophic temperate lakes during warm summers (e.g., Lach Leven in Scotland and Lake Holloman in New Mexico).

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 based on the lower limit of the Redfield number. 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), semiseasonal mean total phosphorus and total nitrogen (Kjeldahl N + nitrate nitrite) concentrations were used as suggested by Westlake et al. (1980). The relationship for nutrient photosynthesis in Figure 20 is based on Vollenweider, (1979) but corrected for temperature and concentration of allochthonous suspended solids, which reduce light transmission and the size of the euphotic zone. We assumed that the temperate zone lakes used in Vollenweider's (1979) relationship averaged 15^{0}C (4^0 in winter to 26^0 in summer) and adjusted his relationship upward to a 30^{0}C optimum. We also assumed that the maximum nutrient concentration would be, at 30^{0}C, equivalent to that necessary to sustain a 2-percent 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 was 0.

Figure 20 indicates that the maximum production at 30^{0}C (twice as high as the average 15^{0}C) should be 1.9 times higher than at 15^{0}C if there were no allochthonous suspended solids or no limiting exchange rates in Vollenweider's (1979) lakes. In fact, maximum production at 30^{0}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 exchange rates to reduce production. Most of Vollenweider's (1979) sampled lakes are large and have low exchange rates; therefore, that factor was dismissed. Although allochthonous concentrations of suspended solids are likely to be low in large lakes with low exchange 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 (see Figure 17 and 20). A small discrepancy in calculated temperature could also contribute slightly to the difference (Figure 20).

The effect of temperature was estimated as indicated in Figure 20. The relationship is based on laboratory data, presented by Aruga (1964), which showed that the plant productivity

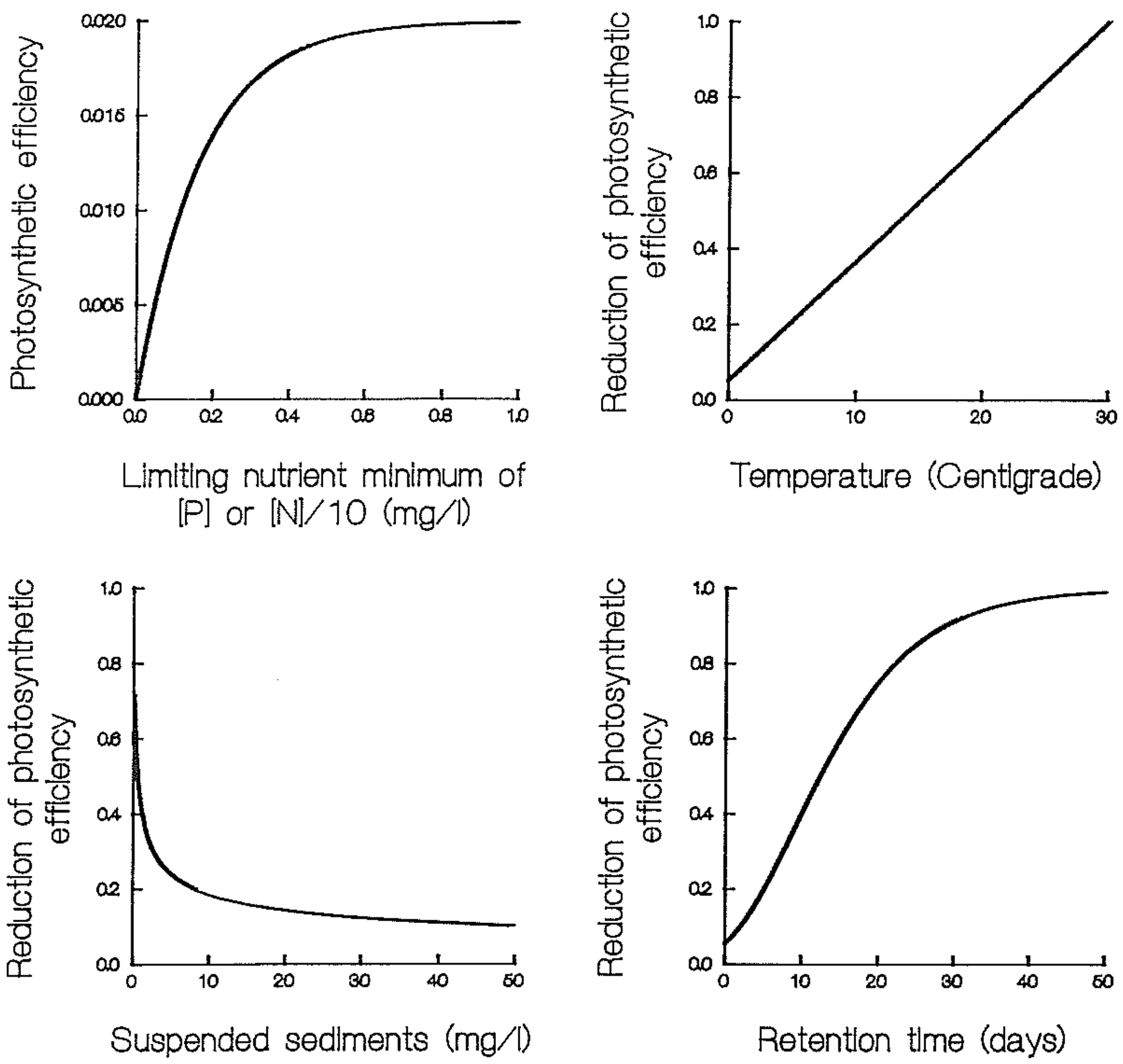

Figure 20. RIOFISH relationships between photosynthetic efficiency and amounts of nutrient, suspended solids, temperature and reservoir exchange rate. A maximum efficiency of 0.02 is assumed (see phosphorus relationship) when all regulatory factors are at optimum amounts.

(growth of laboratory culture) increased an average of about 1.9 x for each doubling of temperature (C⁰). 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). 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°C to 26°C). 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.

Figure 20 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 20, 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 hydraulic retention (opposite of exchange rate and equivalent to the storage ratio). In some half-months, certain reservoirs have relatively low retention of water. Water in those reservoirs may be completely replaced in as little as six days. Little empirical information exists to develop this submodel. Figure 20 shows the relationship we deduced for exchange rate from the following assumptions. First, in otherwise unlimited circumstances and with an initial phytoplanktonic productive mass entering the reservoir that is equal to about the lowest measured anywhere (e.g., Char Lake by Hobbie 1964), we calculated with a maximum observed P/B ratio of 350

(Brylinski 1980) and a maximum equilibrium biomass of 4.5 gC/m^2, that the algae would double daily in a logistic growth form until reaching the equilibrium determined by the nutrient, suspended solids and temperature. We also assumed, regardless of the equilibrium condition, a logistic rate of biomass accumulation to the equilibrium biomass. This assumption implies that the P/B ratio of the phytoplankton is the only important variable, and that it declines as the fertility of the reservoir declines.

In a 10-day period, an average productivity of about 0.5 times the equilibrium level of productivity would be attained, and the photosynthetic efficiency would be reduced 50 percent over the area of the lake involved, if the retention were exactly 10 days. If the entire lake retention were 20 days, the efficiency of conversion would be reduced for the entire time period only about 25 percent. As the exchange rate decreases, the effect of equilibration period at the upper end of the reservoir diminishes. At a 50-day retention, the effect in the model becomes negligible. For retention shorter than 10 days, the reduction is proportional to exchange rate. At a very rapid exchange rate, a reservoir resembles a river with no true phytoplanktonic productivity and too deep for periphytic production.

Whenever a reservoir occurs upstream, phytoplankton can enter the reservoir and the initial mass must be considered. We assumed in this version of the model that no significant biomass survived transport through connecting waters to high exchange lakes. We also assumed that periphytic production was negligible. Both of these assumptions are likely to cause the model to underestimate productivity in rapid exchange circumstances. However, such conditions occur only in certain months of certain large reservoirs, and error in estimation of this parameter has little effect on comprehensive model output.

Model sensitivity to uncertainty in simulations of abiotic factors that regulate primary production has been discussed in Units 1 through 15. The abiotic determinants of primary productivity sometimes counteract one another. High exchange rates usually accompany high loadings of nutrient and suspended solids and lower than average solar radiation. Generally, the uncertainty of the simulation of primary productivity 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. Therefore, research improvements are most desirable for drought conditions.

Unit 16. Mean half-monthly loadings of allochthonous organics are estimated from USGS records at several locations in the river basins and data collected by us. Little spatial variation occurs in mean organic concentrations reported throughout the basins, but loadings tend to be higher in the lower elevations of the basins. For a particular season, loadings vary only with discharge because concentration is constant. In the model, 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. Unmonitored watersheds usually contribute less than 3-4 percent of the annual water volume, but estimated nutrient and organic contributions may exceed half of the total load. This part of the model remains among the most influential and least certain in RIOFISH. Because fish production and yield are so sensitive to the uncertainty attached to simulations of organic load, this aspect of model development is particularly critical.

Unit 17. The total organic load is the sum of the net primary production and the allochthonous organic load.

Unit 18. Oxygen is depleted in the non-mixed zone of the lake below the epilimnion. It is assumed that this zone is deeper than the euphotic zone (it is virtually always) and no significant oxygen is generated by photosynthesis. Oxygen depletion is a function of temperature and the combined calculated load of organic matter and time. 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. An example of oxygen depth variation over time is shown in Figure 18.

The oxygen profile determines survivorship of fish species intolerant of lowered oxygen concentrations and restricted by temperature to zones where oxygen concentrations can fall. Where temperature is adequate for survival but oxygen is not, the fish are eliminated. If tolerable temperatures with tolerable oxygen concentrations exist anywhere in the lake, fish will survive. Particularly sensitive species include the cold-water species, such as trout and salmon, and the warm-water species, threadfin shad, which does not tolerate low winter temperature.

As described in more detail later (Units 18 and 19), fish simulations of fish production and yield are sensitive to the areal extent of oxygen depletion. Thus, the simulated size of the oxygen depleted hypolimnion will influence simulation when in fact no stratification should have occurred. The greatest error will occur when stratification is inappropriately established by the simulation. Uncertainty in the exact size and duration of a hypolimnion, or the oxygen depletion, has small effects on simulation of sportfish production and yield.

Units 19 and 20. Primary consumers are first assumed to be in two categories: suspension feeders and deposit feeders. In some reservoirs, suspension feeders are all invertebrate zooplankton, but in other reservoirs a fraction of the suspension feeders are planktivorous shad (threadfin and gizzard shad are present in some lakes). The fraction of organic matter diverted into suspension feeders depends on depth (Figure 21). At depths over

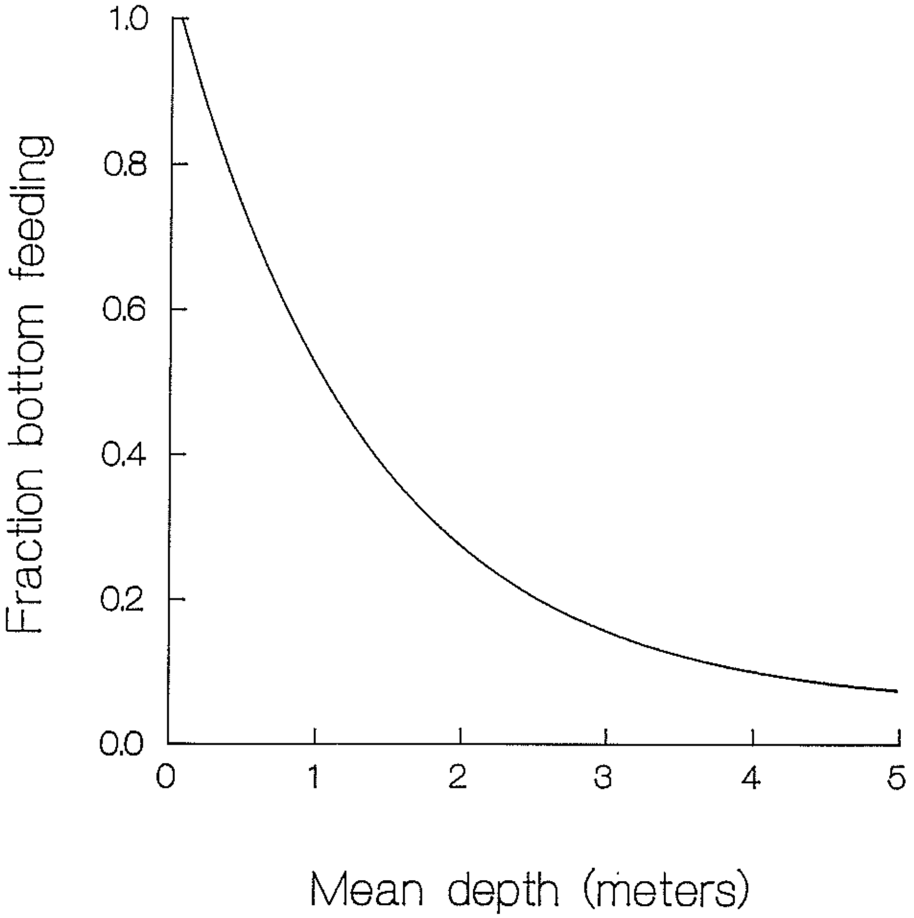

Figure 21. The partitioning of secondary production (second trophic level) comprised of suspension feeders and benthic feeders as reservoir depth varies in RIOFISH.

about 5 m, a nearly constant 90 percent of the organic matter enters the suspension-feeder group and nearly 10 percent is partitioned into the deposit feeders. In waters with less than 5 m depth, the fraction partitioned into suspension feeders decreases as shown in Figure 21. The allochthonous organic load associated with local runoff is estimated as described for the hydrology submodel as a fraction of the total suspended load based on field studies reported in Cole et al. (1987a).

The suspended allochthonous organic matter alone is assumed to enter trophic processes. Dissolved organic matter is considered refractory (since it changes little in passage through water segments). The allochthonous organic matter is not immediately useful to consumers. It requires time to become conditioned by fungi and bacteria and made palatable and more nutritious. Studies by Cole et al. (1987a) show that watershed litter had little biological oxygen demand and developed oxygen demand slowly at room temperatures. We assumed none of the allochthonous organic matter that entered a reservoir in a particular semiseason was consumed. Only after 850 degree days conditioning is material consumable. Thus, the material is stored until the next semiseason.

Consumption and decomposition efficiency of material is temperature dependant (equally so in the model), based on Q_{10} estimates of 1.9. Thus, materials entering in late summer to early fall, for the most part, are stored throughout the colder months, then enter the trophic process during the following spring.

Planktivorous fish take proportions of the calculated organic productions as shown in Figure 22. The function represented in Figure 22 is based on the Figure 21 relative production that shad comprise in lakes of different trophic status in New Mexico (Cole et al. 1985) up to over 1000 g C/m^2/yr. Beyond that point, the model is intuitive based on the assumption that super enriched lakes will support fish just as efficiently as lakes of intermediate trophic status.

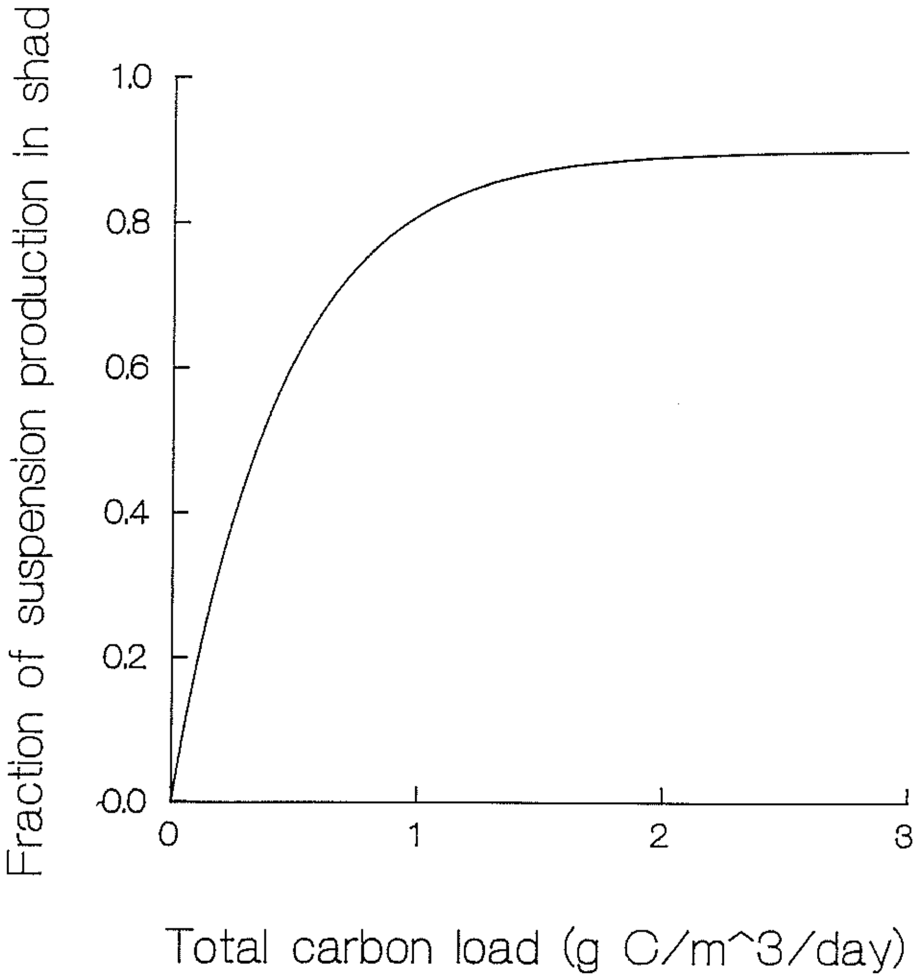

Figure 22. The partitioning of herbivorous suspension feeding fish production and invertebrate zooplankton suspension feeders in RIOFISH.

This approximation indicates that shad feeding effectiveness reaches maximum at high organic loads when particle size and abundance are most appropriate for herbivorous filter feeding. The shad biomass already present also is important. Large shad biomass determines a larger fraction of shad utility of the organic load. No data were available for shad dynamics in extreme high organic loads. The model needs to be empirically calibrated to extremes before it can be applied to such circumstances with any confidence.

The organic matter partitioned into deposit feeding fish and crayfish is 90 percent of the total where they are present. These partition fractions are approximations based on estimated relative production in New Mexico waters (Cole et al. 1985).

The energy transfer coefficient (trophic-level efficiency) used between the organic load and the first consumer level is a function of organic load, temperature, and oxygen concentrations in the hypolimnion ranging from 25 percent at low loadings and optimum temperature and oxygen to less than 1 percent at very high loadings, low temperature, and low oxygen. The function has been changed from that originally used in the prototype of RIOFISH to reflect separate effects of oxygen, temperature and organic loading. A seasonal efficiency is estimated. Maximum efficiency of 25 percent occurs at low organic loadings in warm summer seasons and declines with decreasing temperature according to the relationship indicated in Figure 23. The efficiency also declines with increasing organic load at any particular temperature where mixing is complete (no severe oxygen depletion below 1.5 mg l^{-1}) as indicated in Figure 23.

The amount of oxygen depleted water (below 1.5 mg l^{-1}) also contributes to efficiency depression. The depressive effect is a linear function of the fractional volume depleted of oxygen to 1.5 mg/liter or below over the year. For example, when 25 percent of the volume is depleted below 1.5 mg l^{-1} over 98 percent of the year, the relationship in Figure 19 is depressed

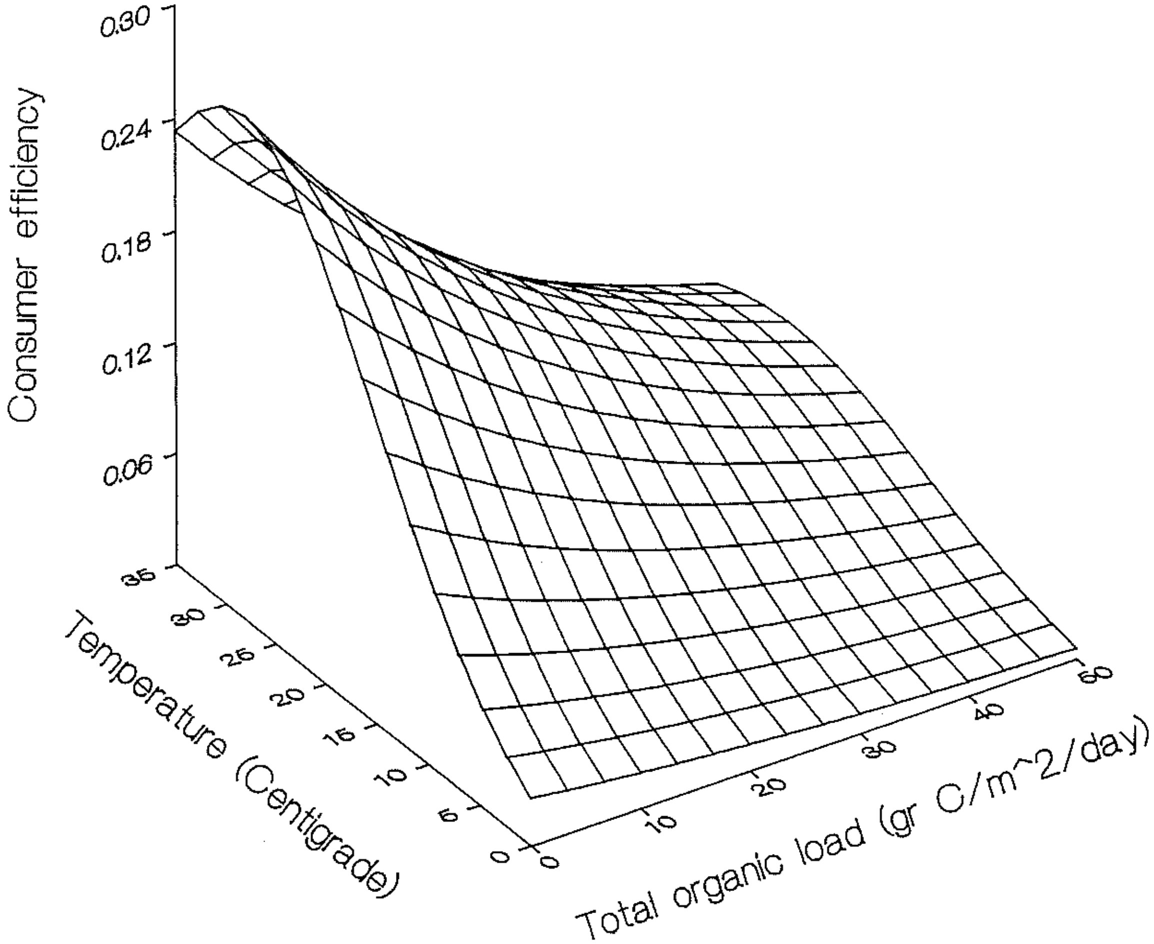

Figure 23. The relationship between organic loading, temperature and trophic efficiency used to estimate transfer of carbon to sportfish production in the simulated reservoir communities.

by 12.0 percent (0.25 x 0.48 = 0.12). The evidence for oxygen impact suggests that all consumption rates cease as oxygen levels approach 1.5 mg l^{-1}; thus, the fraction of water volume depleted below 1.5 mg liter is used as a proportional index of the fraction of the aquatic consumer community that is excluded from consumption. Decomposers are assumed to get the product under these conditions. Organic loading impacts, otherwise, are based on lag effects in instable environments -- the inability of consumers to totally catch up with producers because of slower maximum growth and reproductive rates. This function has been estimated by difference between calculations based on temperatures and oxygen and observed efficiencies in New Mexico waters.

Units 21 to 23. We assumed in the model that carnivore efficiency (including piscivores, zooplanktivores and benthivores) also varies from relatively high to low as organic loads vary from low to high, with the same range in conversion efficiency as occurs for secondary consumers. Conversion efficiencies are less well defined in the literature for this trophic level than for the herbivore level, and the submodel structure is based more on process theory than on empirical evidence. Specifically, for New Mexico reservoirs, which average trophic level efficiency generally reported as an average at many sites (Brylinkski 1980) tend to be mesotrophic to eutrophic, the efficiencies fall to somewhat less than the 10 percent.

There is logical explanation for the use of this range of trophic-level transfer efficiencies (e.g., carnivores are more oxygen demanding, thus are more likely to be limited by the oxygen depression associated with organic loading). Studies of hypereutrophic environments point to the relative scarcity of piscivores in such environments. Actual studies of total fish production including herbivorous fish, reviewed by Morgan et al. (1980), indicate that fish trophic transfer efficiency varies around 10 percent in both ogligotrophic and eutrophic lakes. However, data reported in Morgan et al. (1980) reflect a combination of herbivorous and carnivorous fish. If herbivorous fish increase proportionally in eutrophied environments, the efficiency of total fish conversion will increase.

There is one argument against as great a decline in carnivore fish population efficiency as in herbivores, and that relates to their mobility and capacity to survive long periods without much food. If food is concentrated because of low oxygen concentrations, for example in shallow or epilimnetic waters, the consumer efficiency may increase rather than decrease. If food densities decline, however, the lower consumption efficiency and higher respiratory energy needed to obtain food in low densities may decrease net production trophic efficiency.

In addition to the herbivorous fish already discussed, fish production is split into zooplanktivorous fish production, zoobenthivorous fish production, and piscivorous fish production. Zooplanktivorous production and zoobenthivorous production are determined by the relative productivities of their food items and the food conversion efficiencies indicated by the level of organic loading, temperature and reservoir oxygen dynamics. Piscivores appear to be at a disadvantage in high loading environments because their food tends to outgrow their ability to consume it, thus, the efficiency with respect to organic load appears to hold generally.

Fish production and yield outputs are particularly sensitive to uncertainty in estimation of trophic efficiency. For eutrophic lakes ($1000gCm^{-2}yr^{-1}$), a 1 percent error will alter simulations of sportfish production by 35 percent. A 1 percent error for ogliotrophic lakes ($100gCm^{-2}yr^{-4}$) will alter simulation of sportfish production by 10 percent. The accuracy of this parametric estimate, therefore, is most acute at higher organic loads. Continued trophic research particularly in higher-loading environments, is most appropriate.

Unit 24. The final products of this portion of the model are equivalent to a potential fish production when all habitats are filled with feeding groups at high enough densities to avoid biomass limits to production. Before the model is linked to fish population submodels, this part of the model estimates potential productions of herbivorous, zooplanktivorous, zoobenthivorous, and piscivorous fishes in each habitat. Different species and life stages are unidentifiably mixed; only a fraction of a particular life stage may be classified in one of the feeding categories. In most waters, preliminary potential production is greater than the final estimates of fish production because some habitats are not occupied by fish and forage goes unused by fish. For example, in a large reservoir with all habitats present, but with only largemouth bass and bluegills, only the littoral zone would have substantial fish production, because largemouth bass and bluegill feed mostly in the littoral habitat. In such a lake, much of the potential fish production would not be developed and the offshore waters would be unproductive because no fish use them. RIOFISH, therefore, predicts the maximum potential habitat production once the appropriate species are introduced. Increased diversification results in greater net efficiency in utility of available forage.

Fish Population Submodels

Unit 24 (Figure 15). This is the production of fish in each feeding group from the "production" model (Figure 14).

Unit 25. Minimally, RIOFISH requires identification of the fish populations present in a water body so initial density can be entered for each species. It is not necessary for the density to be very precisely known because the modeled population will come into equilibrium with the modeled environment. However, inaccurate estimates may take longer to equilibrate. Severe underestimates of density can result in biomass limiting productivity. There are currently 23 species in the model, including largemouth bass, smallmouth bass, white bass, striped bass, crappie, sunfish, channel catfish, bullheads, walleye, yellow perch, northern pike, salmon, rainbow trout, brown trout, lake trout, carp-warm water sucker, white sucker, gizzard threadfin shad, shad, cyprinids, golden shiner, smelt, gar, and crayfish. Some taxonomic real species are lumped into a single modeled species. For example, the same population dynamics are used for aggregates of black crappie and white crappie, smallmouth bass and spotted bass, Lepomis sunfish, and all bullhead species.

From the total densities provided either by the model user or the default value, population age distribution and mean weight are estimated from constant length-weight relationships and the total mortality rates used in the model. The length-weight relationships were obtained from a combination of sources in New Mexico and surrounding states (e.g., Carlander 1975; Cole et al. 1985), but a "typical" length-weight relationship was identified. Each species has a total mortality rate, which in an unfished population remains constant except for extreme, intolerable conditions (low oxygen or high temperature, for example). For the initial population of each species, the total density is distributed into each age class, including the 0 age class, at the end of summer (6th semiseason), assuming that the population is stationary.

The population dynamics of each population are defined by a series of parameters (Table 39) that simulate the partitioning of growth among size groups within species (P/B function) and between species (partitioning coefficients), the recruitment of each species, the natural mortality of each species at different ages, and the fishing mortality. For population parameters, the model user can alter coefficients for analysis of impacts or to include a more realistic value.

The fish population models were developed initially to allow the model user to regulate lengths and numbers of fish taken by anglers and to stock fish. They were much simpler than the present version. However, it became evident that a side benefit of the population models is heuristic; analyzing the effects of fish population parameters on fish population dynamics. Therefore, greater population model complexity was developed for heuristic purposes, and not for the primary comprehensive planning purpose. Development of the population model has also enabled more to be done by the model user with fish introductions and controls.

Table 39. List of biological parameter inputs.

	Inputs	User Accessible
1.	Air temperature, Julian date and elevation	
2.	Oxygen saturation at temperature and elevation	
3.	Maximum photosynthesis efficiency	
4.	Kcal conversion to grams of carbon	
5.	Nitrogen: phosphorus limitations	
6.	Water temperature reduction of photosynthesis efficiency	
7.	Suspended solids reduction of photosynthesis efficiency	
8.	Limiting nutrient reduction of photosynthesis efficiency	
9.	Exchange rate reduction of photosynthesis efficiency	
10.	Degree days required to condition allochthonous carbon	
11.	Fraction of allocthonous carbon used as function of temperature	
12.	Table of epilimnetic/hypolimnetic temperature	
13.	Oxygen depletion in the hypolimnion in relation to temperature carbon loading and oxygen concentration	
14.	Carbon export function of carbon production	
15.	Trophic efficiency as a function of temperature, organic carbon loading, and fraction of reservoir with depleted oxygen	
16.	Fraction bottom feeding organisms as a function of mean depth	
17.	Fraction of bottom feeding organisms that are carp and shad	
18.	Fraction of suspension feeders that are shad	
19.	Reduction of piscivore efficiency due to carp/cray fish/shad production	
20.	Depth of 1.0% and 0.01% light penetration	
21.	Maximum temperature for each species	X
22.	Minimum temperature	X
23.	Minimum oxygen concentration	X
24.	Biomass fraction in each habitat, lifestage, and species	X
25.	Partition coefficients for each feeding guild, habitat, lifestage, and species	X
26.	Species maximum production-biomass (P/B) ratio for adults as a function of mean weight	X

Table 39. (Cont'd)

	Inputs	User Accessible
27.	Species maximum production-biomass ratio for juveniles	X
28.	Species maximum production-biomass ratio for larval fish	X
29.	Species death rate (instantaneous)	X
30.	Species fraction of population spawning in each season	X
31.	Species sex ratio of population	X
32.	Species weight at maturity	X
33.	Species initial weight of larval fish	X
34.	Species fecundity as a function of mean body weight	X
35.	Species effect of water-level fluctuation	X
36.	Species growth rate of larval fish	X
37.	Species minimum weight of over-wintering juveniles	X
38.	Species length weight relation	X
39.	Species bounds for length/frequency display	X
40.	Species catchability coefficient	X
41.	Species minimum size caught	X
42.	Species compensation between fishing and natural mortality	X

RIOFISH creates a reference fish community that functions in the context of the historic hydrologic conditions and angler activity over the period from 1975-1987 in the large reservoirs. Because there was no data accurate and precise enough to establish exact recreations of the populations living in the lakes, modeled approximations were developed. The first objective of population development was a reasonable simulated response of the modeled populations to modeled stocking and application of modeled regulations. Modeled population recruitment sustained by stocking was recorded as generally observed during the reference period.

Therefore, a hypothetical modeled community has been created in RIOFISH, which mimics the real community as closely as data and understanding allow, but is not an "exact" recreation. It is important for model users to recognize the modeler's intent was to simulate a fish population composition that could have existed rather than a fish population composition that actually existed. We also intended that the management impacts of stocking and regulation be realistically represented in the model so managers, when faced with conditions like those established in the reference model, can use their management scenario to guide them in objective formulation and project selection with appropriate management strategies.

The history developed in RIOFISH is important only to the extent that it provides a reasonable estimate of how management or natural changes might alter future fish populations. For example, if new regulations are applied to several of the reference model populations, and the long-term yields increase compared to the reference model, the regulations would benefit more anglers over time under the reference scenario conditions. When such scenario conditions are likely to occur in the real world, the new regulations would be worth considering. Then once they are applied; the results need to be measured to contrast with model simulations for verification and refinement.

Unit 26. The model simulates the fish production by age group in each species from (1) the production calculated for a feeding group in each habitat (Unit 24), (2) the initial biomass distribution (Unit 25), (3) the coefficients for partitioning food and spatial resources (percentages of population in each habitat) among species, and (4) maximum production-biomass (P/B) ratios used to distribute growth among age groups in each species.

Unit 27. The partitioning coefficients are calculated based on: (1) the relative contribution that each food group (zooplankton, zoobenthos, fish) comprises in stomach contents (Leidy and Jenkins 1977), (2) the relative abundance of each life stage of the species in the habitat zone, and (3) an estimate of food consumption rates of each life stage for each species (larvae, juvenile, older fish) under optimum conditions and variations from optimum. A partitioning coefficient of 1.0 indicates maximum ability to use food in the food category of the habitat in question. If two species occupy the habitat and each has a coefficient of 1.0, they partition the food equally. If one of the two species has a coefficient of 1.0 and the other has a coefficient of 0.5, the first gets twice the food of the second. For the most part, we assumed that species were about equally capable of getting food within feeding categories based on the difficulty of demonstrating competition effects. However, when a difference was identified, it was usually based on different effects of light and temperature on fish consumption rates. For example, cool-water species present in littoral zones would be designated a partitioning coefficient lower than warm-water species if the average annual temperature is closer to the optimum for warm-water species. A species that is a sight feeder in a low-light habitat is designated a coefficient lower than a non-sight feeder in the same habitat. The users may modify these coefficients to be more like their perception or to calibrate model fish population performance according to an observed pattern. Although a default value is provided in the model to represent an average condition, as the model is applied to cold-water and warm-water lakes, the coefficient ought to be changed accordingly. This particular coefficient requires substantial biological expertise from the model user to adjust it appropriately.

Although variation in the partitioning coefficients has large impacts on the contributions of individual populations, the impact on the total sportfish production is much less. In single species communities, it has virtually no impact. Inappropriate coefficients for abundant species in more diverse communities can influence the management responsiveness of total sportfish production substantially with regard to stocking and regulations. The best level of stocking and regulations depends on the ability of the fish population to partition resource production. From a population standpoint, resource partitioning is one of the most uncertain areas and deserves more research attention.

Unit 28. The production potential is distributed to fish according to a maximum production-biomass (P/B) ratio to determine the production per species for each mean individual weight of fish within a guild, including larval and juvenile-fish life stages. The P/B is equivalent to the population instantaneous growth rate. An example of the P/B distribution is provided for large mouth bass in Figure 24. The functions used were derived from observed growth rates presented in Cole et al. (1985) and data summarized in Carlander (1975). The P/B ratio is equal to the population growth coefficient. The model user may modify the intercept and slope of the relationship as data become available.

The maximum P/B is equivalent to the maximum instantaneous growth rate, which in RIOFISH is used to partition the potential production available in underlying trophic levels among the different size classes of fish within feeding categories. A group with a P/B equal to 5.0 has 5 times the production allocated to its mass as a group with a P/B of 1.0. The logic is based on the idea that in populations where growth is maximum and not limited by food or environment, those groups with a higher P/B make greater net use of the food available.

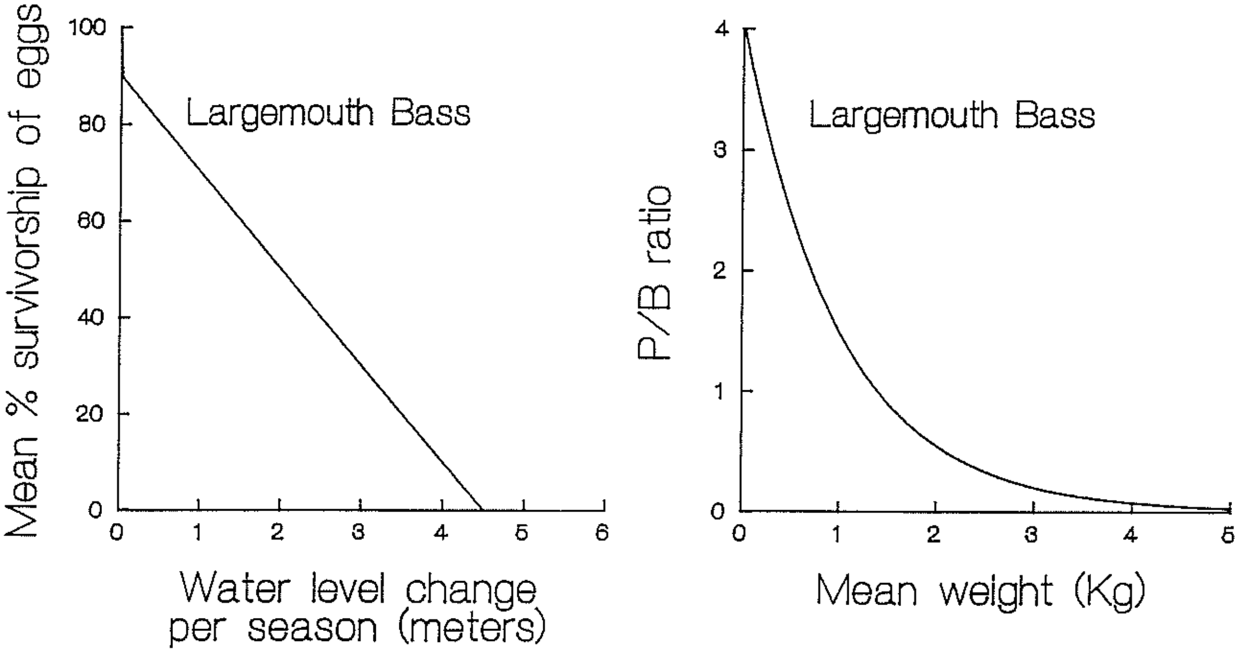

Figure 24. One species example (largemouth bass) illustrating the maximum distribution of production among the biomasses (P/B ratio) of different weight classes of fish in guilds inhabiting reservoirs, and the relationship between water-level, change/season, and mean egg survivorship.

The greater net use of food may derive from higher consumption rates, greater assimilation rates, or lower maintenance costs. Generally, small fish have greater specific consumption rates (food weight/unit body weight) than large fish. To reach their maximum P/B, small fish must have a higher food demand/unit body weight than large fish. But because the biomass of small size classes is often smaller than intermediate size categories, overall demand may not exceed that of larger fish. 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. If that assumption is badly violated, the P/B index will not distribute growth appropriately. Shortages or excesses in appropriate sizes of a particular food group, for example, would in reality reduce or increase the growth of sizes disproportionately from the amount indicated by maximum P/B. When there is less food available than the biomass and maximum P/B will allow to be consumed, fish growth in the food category will be proportionately less than the maximum among all size groups in the feed category.

Fish species, however, can vary in growth rate as the habits change with life stage. Adult fish feeding on other fish may grow at different fractions of the maximum possible growth than younger fish feeding on benthos. Therefore, just as in real world fisheries, dramatic growth spurts or slow downs may occur as RIOFISH fish grow from juvenile into age 1 and older categories.

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 P/B assigned to larval fish and juvenile fish are the least well documented and 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. Variation in the assigned larval and juvenile P/B has little overall impact on sportfish production or yield, however.

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

At this point in the model development, the addition or deletion of predators or anglers does not alter the size composition and the population P/B ratio. Predation, including angling, is assumed to be in equilibrium with the size distribution of prey populations present. When a new predator is introduced on top of an existing predator or angler, there is no net effect on prey structure, mortality rate or production. In other words, predators in RIOFISH are not allowed to accelerate mortality by eating up the biomass capital or prey. Generally, in diverse fisheries this concept holds up fairly well in reality as well as in RIOFISH. But in real fisheries where predators are missing, the addition of a predator would be expected to create some new equilibrium size distribution of prey composed of smaller individuals with more rapid average growth. Production would remain the same but be distributed among smaller fish. This phenomenon is not now 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 catchable biomass present.

Units 29 and 30. The estimates of individual habitat productions for each species are summed to give the total production for each species in the entire reservoir.

Unit 31. The distribution of fish biomass by age class and size (weight/individual) is the basis for estimating fecundity, recruitment, and growth. The fish biomass and size estimates may be derived from the initial field-determined inputs of density, new density data (updating), or model-generated densities. Initial density is distributed among ages according to the total mortality relationship for each species and can only be altered by the user by changing the mortality. The initial distribution of numbers is one that would exist in a stationary population structure. It was chosen as the best compromise distribution from all of the possible distributions that could occur.

The initial density distribution influences the structural production of fish population for several years thereafter. Therefore, when a stationary distribution is installed in the reference period, and in fact some other non-stationary distribution occurred, variations of the model from the observed population structure are inevitable. Because the distribution pattern is fixed and the annual habitat and the events are variable, the structure of the populations in any modeled year will vary as the initial year of the run is varied.

The response of modeled management applied to several runs for a model management scenario will vary depending on the initial year of the run, even though all habitat variables are consistent from one run to the next. For example, if the management strategy is to stock x number of fish fry in 1987, the response of the population to the stocking will vary as the starting year of the initial run is changed from 1983 to 1984, or 1985 or 1986. Because the structure of the initial population is rarely known, several runs using different initial years is advised to assess the variance expected from the application of a specific strategy. The user will determine whether a mean or either extreme response is best to judge the value of the management strategy.

The uncertainty of the population model is associated with any forecasting technique in which data used to imitate the forecasting period is not exactly known. RIOFISH is designed to examine large-scale comprehensive trends and management policies in which large regions over several to many years are simulated. Model development in which very detailed population structure estimates are needed to predict future responses accurately is beyond the feasibility of the field manager to obtain the required data. As use of the model progresses, a need for such specificity of initial density may occur and the model can be refined to include that option.

Unit 32. The calculated biomass in each reproductively capable age group of females and the number of mature eggs per unit biomass is used to calculate the fecundity per age-class. A sex ratio of 0.5 is assumed as a default value in the model for all species, but is changeable by the model user if he or she knows better or wishes to test the sensitivity of that variable's outputs. The minimum size at maturity is also controllable by the model user as is fecundity.

Unit 33. From fecundity information, the total potential egg number for the species is calculated by multiplying weighted mean egg counts per female times total female biomass.

Units 34 and 35. Recruitment into the 1-year-old age class and the size of recruited stock in the next year both depend on the first-year survivorship. The first-year survivorship of each species, with respect to water-level fluctuation, varies uniquely. Figure 22 shows an example of such a relationship. Only spawned eggs and yolk-sac larvae are assumed to be vulnerable to water drawdown. The intercepts are less than 1.0 to account for losses due to inadequate fertilization and tetragenic effects. These intercept values generally are lower for egg broadcasters than for species that build nests.

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 is usually 0.8 to 0.9 in the default values, representing losses due to teratogenic effects and incomplete fertilization. The egg and larval mortality from water-level fluctuation is exacted before other sources of mortality take their toll in the model. The model user can change the water-level parameter. The proportion of the spawning that takes place within each season is incorporated in the model and can be controlled by the model user. Reproduction is assumed to occur at the midpoint of the season.

Post-yolk-sac larvae and juvenile fish are assumed to be vulnerable to starvation as well as to predation. The natural mortality is assumed to be equivalent to the natural mortality rate defined for older fish. A natural mortality of 0.5, for example, would result in a halving of the larval fish population entering a particular semiseason. Once this fraction of the larvae is removed and the food is partitioned, all larval fish not growing more than a minimum rate are eliminated by starvation. All larvae within a feeding group present in the same habitat and semiseason are presumed to be equally capable of converting their zooplanktonic food into biomass regardless of species category (no competitive advantage is assigned). From the distribution of larval fish, based on calculated biomass, P/B ratios and partition coefficients, the growth rates of surviving larvae are estimated, and the biomass and density of the juvenile fish are calculated.

The production of zooplankton food in the semiseasons when larvae are born is the major control of larval fish mortality whenever water levels are reasonably stable. Under stable water level conditions, predation mortality (the total natural mortality excluding fish mortality of older fish) is the only loss when very high zooplankton production occurs for the density of fish larvae present. When very low population fecundity exists because of low numbers of adults in the population, the simulated natural mortality still eliminates a strict percentage of the larvae and probably overestimates mortality under those conditions. All remaining larvae grow rapidly and attain sizes necessary to quality as juvenile fish.

A large starvation mortality occurs when fish population fecundity is high, water levels are stable or increasing, 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 semiseason. 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.

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

Once larvae qualify as juveniles, the mortality rate becomes a constant (the natural mortality rate estimated for the population), unless they do not grow fast enough to survive their first winter. Growth is determined by the P/B for their size and the partitioning coefficients assigned to them, either by the model default values of by the model user.

Juveniles, however, also must grow fast enough to survive a winter successfully and to qualify as age one fish during the next year.

All juveniles do not grow equally, a normally distributed pattern of growth is modeled into the juvenile populations. Only in very exceptional circumstances would the natural mortality function be increased by inadequate growth for carriage through winter. The density and size of fish recruited into age one is thus determined by the total mortality of the fish that were recruited as juveniles. That total is the sum of the natural mortality (due to predation), and whatever part of the population is lost because of too slow growth.

Knowledge of early life history of many species is scant. The major model outputs of sportfish production and yield are not very sensitive to many of the variables under average- to high-water conditions. Size structure, particularly of early life stages is more sensitive to these variables. Under low-water conditions, uncertainty in the early life history parameters have much more critical impacts on estimated sportfish production and yield. Although knowledge of these parameters is increasing, the uncertainty remains high. Research into early life history dynamics under low-water conditions, is particularly of concern as more potential for increased water-level control occurs during critical spawning periods. RIOFISH can be used to direct the research activity most likely to gain the greatest return for the investment required to regulate water levels, and RIOFISH itself may be refined as more information occurs.

Unit 36. Growth of one-year-old and older age classes is calculated by distributing production within the species according to feeding categories, partitioning coefficients, mortality rates and maximum P/B ratios defined in the model for each age class (Figure 24). In unfished habitats with tolerable environments, mortality is a constant estimated from studies in New Mexico and other locations (Leidy and Jenkins 1977 survey, for example) with similar water temperatures and other environmental characteristics. It is assumed that no age or size group has a feeding advantage over any other age or size group. As long as food remains distributed in appropriate size categories reasonably well, this assumption appears to be reasonably valid. The model simulates inappropriately when food sizes are greatly skewed.

Model population mortality can occur through exposure to intolerable temperatures of low oxygen. Cold-water species are killed when no water layer in the reservoir has temperatures below 25°C and oxygen above 4 mg liter. Threadfin shad are all killed when no winter water layer exceeds 7°C. Partial kills can be incorporated in the model. 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.

Unit 37. After all calculations have been mode to simulate growth, mortality, and reproduction, the biomass and density, the output is linked to the economics submodel where angler days are calculated (described later). Then angler days estimated is used to calculate fishing mortality, based on the harvestability and angling effect.

Units 38, 39 and 40. Fishing effort is generated based on several socio-economic parameters, "catchable" fish biomass, and a fish harvestability value assigned to each species. Much of this part of the model is described in the economic version. These empirical relationships have been estimated from angler effort-yield data (collected by researchers at NMGF) and fish biomass data (collected by researchers at NMSU) gathered at New Mexico reservoirs (Cole et al. 1985). The harvestable biomass is defined as all biomass including individuals over a species specific weight per individual. This number can be altered by the model user. The harvestable biomass of the sport species present determines the average per capita yield rate. The harvestability coefficient only accounts for fish lost to harvest, it does not account for increased probability of hooking mortality for returned fish. No hooking mortality is considered. Because hooking mortality occurs, the mortality estimated by the model may be low. The degree this affects the model output depends on the compensation between fishing mortality, natural mortality, and the types of baits and lures actually used by anglers. Parameters associated with mortality may be adjusted to include an approximation of hooking mortality.

Yield to anglers, of course, comprises a source of mortality. In the extreme liberal approach, we assume that natural mortality and fishing mortality are totally compensatory, that is the survivorship is constant as long as the force of fishing mortality does not exceed the estimated force of total mortality in the population (Figure 25; Choice C). When fishing mortality exceeds natural mortality, a new total mortality equals fishing mortality. Only if the harvest rate is calculated to be higher than the natural death rate will it reduce the previously computed survivorship.

The other extreme parameter available for use (Figure 25; Choice A), assumes that the natural mortality and the fishing mortality are partially additive, thus, there is always some impact on the estimated total mortality during the following year at any level of fishing intensity. When this method is applicable, the hooking mortality loss will be underestimated, and is particularly critical in over-fished situations. In average- to high-water conditions, the fisheries in RIOFISH are mostly under-fished, thus the assumption of no hooking mortality may not be critical.

Any compromise value between the two extremes can be chosen, depending on the data available or the heuristic analyses the user wishes to do. Choice B in Figure 25 is the midway compromise between the two extreme models. All intermediate choices between 0 and 1.0 are possible.

To calculate the total fish yielded, the catch rate per visit is multiplied by the total visits. Other factors estimated in the economic model and described in the economic section also

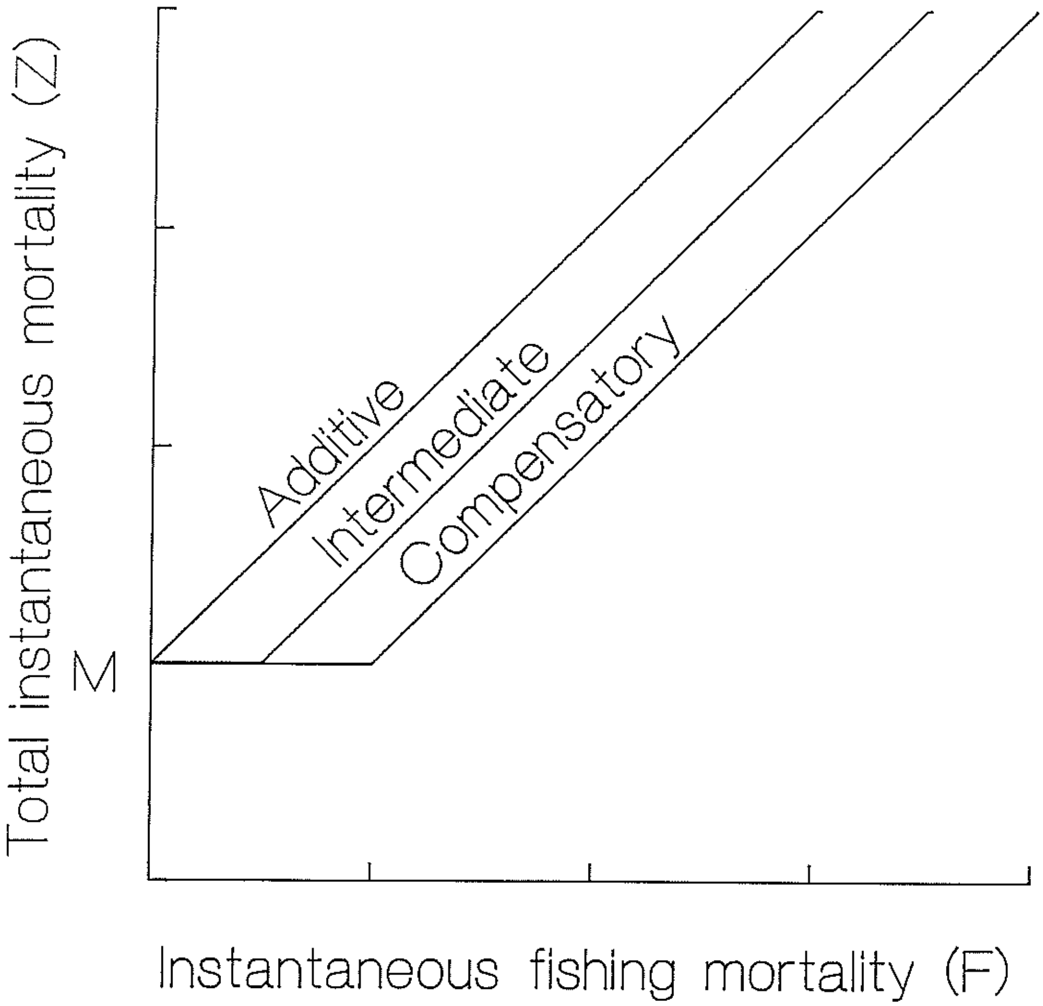

Figure 25. The fishing mortality parameter ranges between two extremes: Compensatory (fishing mortality only adds to natural mortality when it exceeds natural mortality) and additive (fishing mortality adds to natural mortality). The model user can choose the most appropriate mortality parameter for the scenario in question.

influence the fishing effort (hours fished) and determine the yield or harvest (see economic model).

Unit 41. The model operator has the capacity to change stocking and harvest regulations and thereby influence fishing effort, harvest rates, and fish survivorship. The model operator must provide numbers of stocked fish in different size classes (small fry, 1 inch-fry, fingerling, catchable) to estimate the effect of stocking (see Section on outputs/inputs). Fish length limit fully protects (no hooking mortality) from fishing mortality any size category defined by the model operator. The model user can also introduce and remove species. No means are allowed to close "seasons" or to control terminal fishing gear (bait, lures) in this version of RIOFISH. For most of the waters included, these are not favored regulations, but the may be considered in the future.

Units 42 and 43. Economic values are determined as described in the economic section, providing information for management decisions (Unit 43). From management, the biomass of species may also be altered to simulate introduction of new species, partial removal of fish, or total removal of fish. This is done by introducing or reducing the biomass directly in the years proposed. RIOFISH model provides for a reasonable simulation of a total removal and reestablishment of a fishery. For most partial removals of a population, as by commercial fishing, a simple reduction in biomass may be a misrepresentation because it is not size selective, as is commercial fishing. Any of the 23 species in RIOFISH may be introduced into reservoirs. Even a species not specifically identified in the model can be introduced as long as all population parameters are altered to fit the characteristics of the new species.

Reservoir Tailwater Submodel

The reservoir tailwater submodel is simpler than the reservoir model. It is not currently accessible in this user-friendly version of RIOFISH, but will soon be made available in an updated version. The main purpose of the tailwater model is to generate an estimate of the effects of reservoir operation on the potential for developing sportfish biomass in the tailwater. The model user cannot stock, regulate or in any other way manage the tailwater. We assumed that such stocking and regulation continues as it has been done in recent agency history, basically through stocking of catchable or large fingerlings. Tailwaters in New Mexico tend to have more limited versions of the fish composition found in the reservoirs upstream despite management that generally is restricted to stocking of rainbow trout in certain tailwaters.

Unit 15. The tailwater model generates primary production based on mechanisms similar to those generating production in reservoirs. There are, however, certain foundational differences related to flow characteristics through channels. Calculations are made semiseasonally (based on two-week hydrologic simulations in the channels). A maximum 2 percent trophic conversion of solar energy occurs when the semiseasonal conditions are optimum. Optima include temperatures of 30°C, total phosphorus in excess of 0.5 mg liter, total nitrogen in excess of 5 mg liter, 0 allochthonous suspended solids, mean velocity over 15 cm sec^{-1}, particle sizes more than 15 cm in diameter, and generally stable discharges. As regulating factors vary from the optimum, the photosynthesis efficiency declines. The general form of the model is: $TL_p = CR (E_{max}) (N)(T)(V)(S)(B)$ where primary productivity (TL_p) is a function of the total seasonal solar radiation (R), C is a conversion constant from K cal to grams of carbon, E_{max} is the maximum efficiency of solar radiation conversion (2 percent), and nutrient (N), velocity (V), allochthonous suspended solids (S), and bottom substrate size (B) are all limiting states from 0 to 1.0.

The velocity coefficient (V) is developed from work done by Horner et al. (1983) showing that once velocities reach 0.15 cm sec^{-1}, and up to 75 cm sec^{-1}, productivity remains nearly constant (Figure 26). Erosivity of periphytic algae is more influenced by the suspended matter

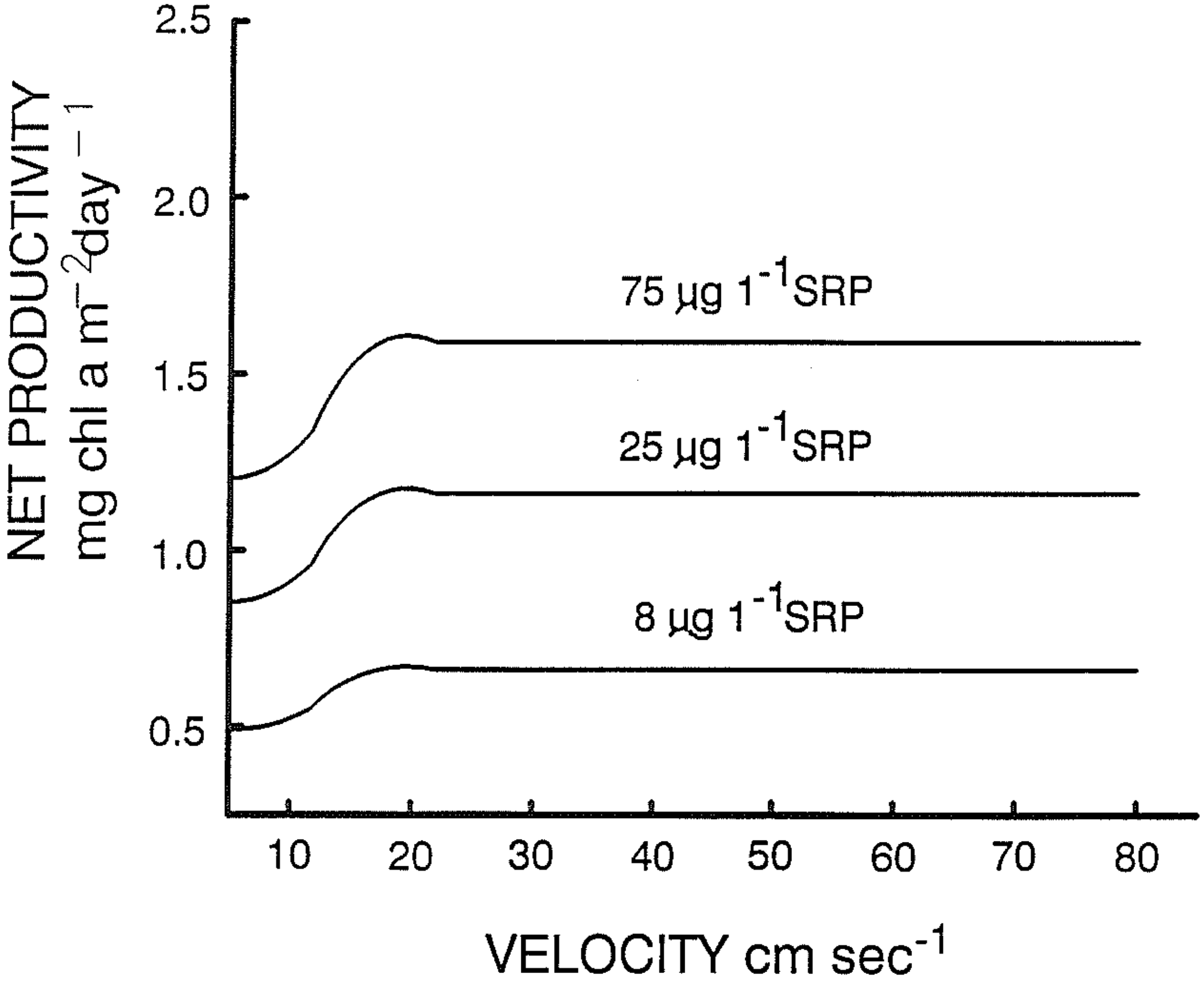

Figure 26. Velocity and primary productivity in tailwaters. Figures were developed from data in Horner et al. (1983).

in the water than by the velocity, but the same suspended solids function is used as in the lake model.

Unit 45. The role of bottom substrate size was estimated by previous work completed by McConnel and Sigler (1959), Duffer and Dorris (1966), and Donaldson (1987). The distribution of impact is shown in Figure 27. Mean substrate size is inserted in the model at 1-km intervals up to 10-km downstream from each dam.

Unit 46. To accommodate variation in flow measured in semimonthly intervals, the average cross-sectional area and depth exposed to semimonthly flow is estimated to be the productive state.

Unit 47. Total organic load in the tailwaters includes the allochthonous organic matter and the autochthonous production. Studies by Donaldson (1987) below Caballo Lake showed that very little of the allochthonous load is derived from riparian canopy in the near vicinity; most came from Caballo Reservoir and virtually all of it passed through the tailwaters. The retention of the allochthonous matter is calculated as a function of depth and substrate particle size. This is based on the concept of boundary flow and sedimentation in the bottom-most centimeter of the water column, where sediment is collected by various detritivores. The entrapment rate is a function of substrate stability, thus increases as particle size increases and remains constant above 50 mm. Periphyton eroded from the bottom contributes to the allochthonous load downstream. The amount eroded is a function of velocity and grazer efficiency.

Unit 48. Temperature is estimated in the reach by air temperature, as in the lake model, and the temperatures of water drawn from the reservoir (See Unit 12). The amount that water temperature equilibrates with air temperature is a function of the discharge and distance. The calculated temperature determines the primary production in each segment.

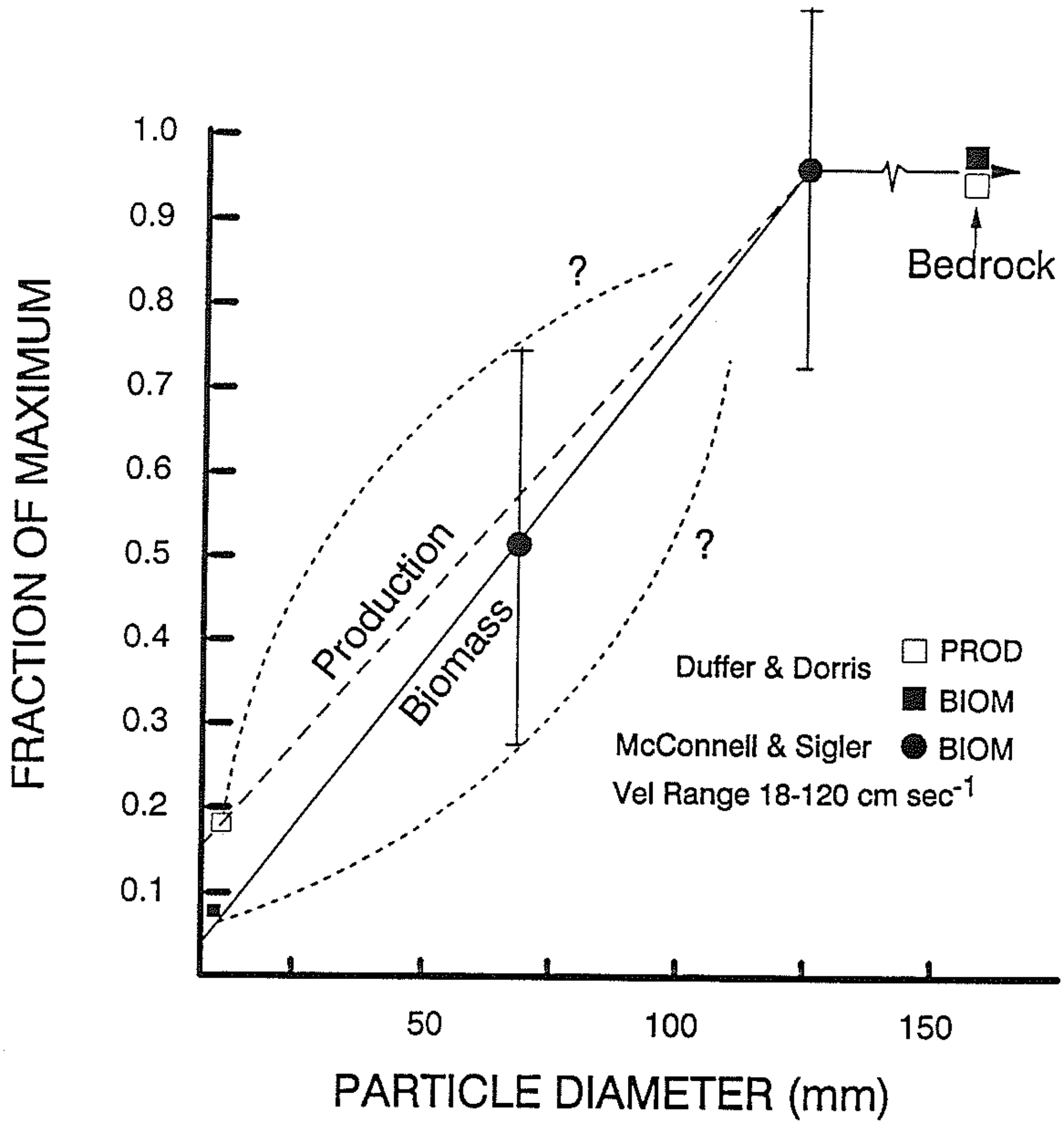

Figure 27. Substrate particle size and production relationships in tailwaters.

Oxygen is assumed to be the saturation temperature or, if depleted in reservoir release waters (See Unit 17), it equilibrates with temperature, discharge and distance. Oxygen concentration does not effect primary productivity in RIOFISH, but does have impacts, with temperatures, on fish production and biomass (described later).

Unit 49 to 52. The primary consumers are either herbivores that graze periphyton, or detritivores that collect allochthonous organic matter form the boundary layer. The trophic efficiency for all secondary production is a function of temperature and oxygen concentration for both herbivore grazers and detritivores. The grazers and detritivores are partitioned into invertebrates and fish production. Fish are favored by small particle size and high pool-riffle ratios (estimated by variation in depth). Therefore, in stream segments where substrates are large and production of periphyton and entrapment of detritus is high, secondary production is high and comprised mostly of benthic invertebrates. When substrates are fine and shifting (velocities over 15 cm sec^{-1}) and there is little variation in depth, periphyton production is low, retention of allochthonous materials is low, secondary production is low, and the production is comprised mostly (fractionally) of herbivorous- detritivorous fishes. Because substrate size is relatively more variable than any other factor in New Mexico tailwaters, it is the single best index to secondary productivity. An estimate of herbivore-detritivore biomass is based on low P/B ratios (instantaneous population growth) determined for their populations as 0.3.

Below reservoirs with severe oxygen depletion, relative trophic efficiency and productivity is reduced.

Units 53 to 56. The secondary consumers (terrestrial producers) are assumed to be all fish (despite the presence of certain invertebrate predators, which are ignored here) in invertebrate feeding and fish feeding categories. Each category includes cold-water and warm-water forms. Temperature and oxygen are the main determinants of their trophic efficiency.

Maximum efficiency varies from optimum as temperature and oxygen tolerances vary from optimum. The small additional production generated by feeding on invertebrate-feeding fish is added to the piscivore category.

Unit 57. All of the third and fourth cold-water levels contribute to an estimate of sportfish biomass. An instantaneous growth rate of 0.5 is used in the conversion. For cool and warm-water fishes, only the piscivorous fraction is used to estimate sportfish biomass. In most habitats, cool- and warm-water suckers and cyprinids dominate the invertebrate feeding categories.

Economic Submodel Description

Overview and Problem

A central goal of public sportfishery management is to maximize the value of fishing to anglers in light of resource limitation as defined by budget, personnel, and competing demands on the environment. One could view the goal of managing a sportfishery as an attempt to identify policies that maximize the value of sportfishing to anglers in light of constraints that preclude providing an ideally satisfying fishing experience to all anglers at zero cost.

Achieving this goal of fishery management is impeded by several kinds of limitations including budget, personnel, hatchery capacity, and habitat production. Fishable habitat is a particularly limiting factor in New Mexico because habitat is scarce and in unpredictable supply. Compounding the habitat limitations that perverse water scarcity leads to high economic values and resultant demands by non-fishing water users. Thus, despite the other resource limitations, the unpredictable nature of fishable waters, more than any other factor, may constrain meeting of fishery management objectives in New Mexico.

Achieving appropriate planning objectives requires identifying management strategies which contribute most to angler benefits, as those strategies are transmitted through the aquatic ecosystem in which the fishery resource and anglers interact. Experimenting on a comupter simulation model to discover strategies that increase angler benefit is a cost-effective method for increasing angler benefit.

Submodel Description

Figure 28 is a flow-chart of the fishery management linkages to statewide angler benefits, as determined by the economics model. Inputs to the economic angler benefits model come from the biology model, hydrology model, direct management control, and outside sources.

Units 1 to 4. By using the model, a water or fishery manager can influence economic angler benefits through several pathways. Fish stocking, harvest, and length limits by size category for 24 species (Unit 2) can be changed by the user to influence economic angler benefits after impacts are processed in the biology model (Unit 3). For large reservoirs in the Rio Grande, Canadian, Pecos, and San Juan basins, the biology model computes sportfish biomass per hectare and distributions of fish size and species (Unit 4) and passes the results to the angler economic benefit model. For each site, mean sportfish biomass in kg/ha over all sizes and species of game fish is calculated from the mean weight multiplied by fish density.

Units 5 to 7. The manager of water or sportfishing can also use the model to affect water distribution and amounts (Unit 5). Such strategies would come about through leases, rental, purchase, or other acquisition of water or water rights. Modified water movements could also occur through changes in operation procedures of dam storage and release patterns made by other water agencies such as the U.S. Army Corps of Engineers or U.S. Bureau of Reclamation (Unit 5). These modifications of water storage and release are processed in the hydrology model (Unit 6), which predicts mean stream discharge and reservoir contents, sediment, and organic loads by semi-monthly intervals. Average summer reservoir volume and

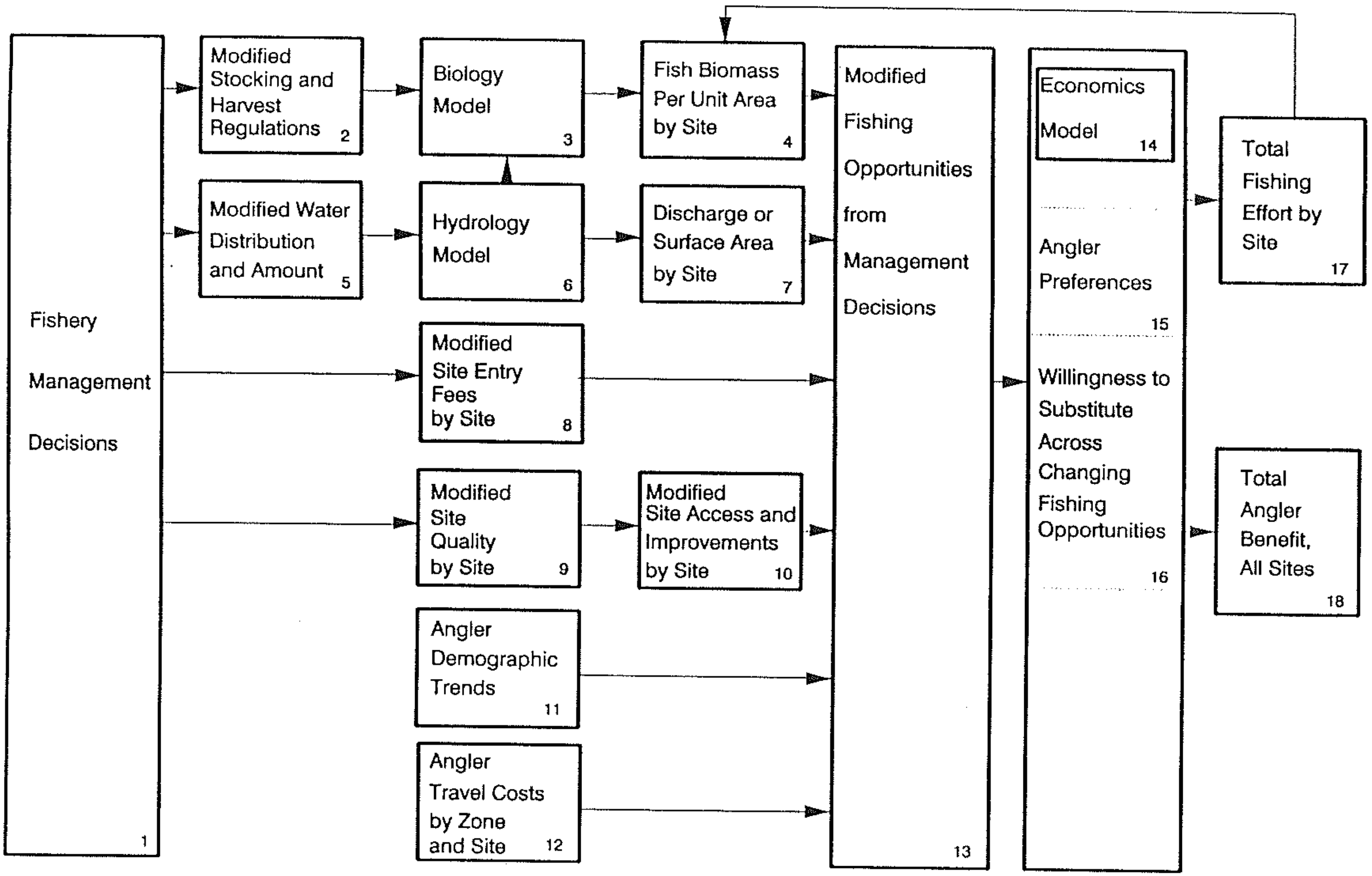

Figure 28. Flowchart illustrating the socio-economic component of RIOFISH.

surface acres, both significant predictors of angler demand and benefit, are then passed to the economics benefits model.

Units 8 to 10. Fisheries management decisions, such as site entry (Unit 8) can be entered by the model user directly into the angler economics benefits model. Site quality changes (Unit 9) significantly effect angler demand and benefits.

Examples of site quality changes that the manager can evaluate include access by way of additional or improved roads and trails (Unit 10). Access to existing fishable waters also may be improved by additional boat ramps (Unit 10). Any improvement in site quality is transmitted to the angler benefits model by way of its effect on attractiveness at all substitute sites. An improvement of fishing quality at a particular site causes additional anglers to use that site and reduces angler demands at substitute sites. All dimensions of site quality at each fishing site act as substitutes for other dimensions as predictors of angler demand and benefits. A significant purpose of the economics angler-benefits submodel is to assist fishery managers in selecting among competing site-quality improvements (management strategies) to increase angler benefits by the greatest amount for a given management cost.

Unit 11. Angler demographic trends are important in planning designed to increase angler benefits. Examples include total angler population by county and the extent of commitment to fishing measured by expenditure on fishing equipment. Managers can use RIOFISH to estimate the effect of future shifts in the structure of angler population or equipment expenditure patterns as these shifts affect the most effective management methods for increased angler benefits. For example, if angler populations are projected to move away from cities to rural areas, more intensive management at rural fishing sites would increase total angler benefits more than improvements made at fisheries near cities.

Unit 12. The cost an angler incurs when travelling to a fishing site has a considerable impact on angler benefits received, and on which management decisions are most effective in generating maximum angler benefits. Angler travel costs are defined by driving distances from each angler zone of origin (New Mexico county or set of contiguous counties) to each major fishing reservoir. The distribution of travel costs depends on average driving speeds, the price of gasoline, other vehicle operation costs, and the value of travel time. Generally speaking, for remote fishing sites where angler travel costs are high, managers' increase in fishing quality will have a smaller impact on total angler benefits than where sites are nearer to population centers and travel costs lower. With 24 county aggregates and 18 sites in New Mexico, there are 432 observations from which to estimate the system of two demand equations.

Unit 13. Fishery management decisions are transmitted through the water by way of the biology model and hydrology model. In addition, decisions can affect angler opportunities independent of the water, such as through improved site access, campgrounds, or other improvements. All fishery management decisions that result in a change in fishing opportunities are summarized in Unit 13, immediately before entering the economic angler benefits model.

Units 14 to 16. The angler economic benefits model is a series of equations constructed with multiple regression methods to estimate instate angler demands and benefits. Equations are constructed using multiple regression methods from data obtained from a year-long telephone survey administered to New Mexico and West Texas anglers in 1988-89. Both angler demand and angler benefits are determined by angler effort, travel costs, and site qualities at each of the 18 reservoirs.

Quality characteristics of all 18 reservoirs including fishing, access, and site improvements are introduced into a flexible form utility function, that approximates the true underlying angler preferences. Mathematical expressions are derived for the anglers' fishing demand equations and benefit function, thus 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 theoretically correct angler benefit from changes in several dimensions of fishing quality, which are induced by management or by outside forces. Such outside forces would include changes in travel costs or angler demographic patterns.

A policy change affecting site i can cause anglers to divert fishing effort to other sites. This is accomplished by embedding the ith site as part of the lumped substitute for the jth site. Thus, since the substitute quality for site j is affected, the demand for a relevant jth site changes in response.

Significant implications exist for fishery management in having an explicit mathematical expression for the angler benefits function. Most important, since the benefits are derived from an underlying angler preference map, and its parameters are estimated from a demand system consistent with that preference map, estimated values of complex strategy changes are consistent with fundamental underlying angler decision processes. By providing exact benefit values, there is no need for complex consumer surplus approximations. As with the ordinary consumer surplus approximations of angler benefit, processing an expression for the exact benefits (expenditure) function still permits one to establish benefit values of single or multiple price changes. But, in addition, it also permits one to perform the much harder task of valuing unpriced quality changes for several related quality dimensions over several substitute fishing sites. The exact benefits function also computes value for complex policies that simultaneously adjust both price and qualities.

The manager can simulate policies that would finance fishing quality improvements through increased user fees. The economic angler-benefits model includes estimated angler preferences for sizes, density, and species composition of sportfishing and preferences for site improvements (Unit 15). Additionally, the economic angler-demand and angler-benefits model estimates anglers' willingness to substitute fishing opportunities (Unit 16).

Unit 17. As a result of fishing opportunities, currently existing or changed as a result of management decisions, the economics model predicts total fishing effort by angler zone of origin at each of the 14 major reservoirs open to public fishing (two reservoirs in the model are not open).

Unit 18. Current or management-induced changes in fishing opportunities also serve to predict total statewide angler benefits for all 16 reservoirs. Total statewide angler benefits only have meaning when defined for a particular fish management policy (e.g., stock additional catchable rainbow trout at Heron Reservoir in summer) relative to a given status quo situation (e.g., actual summer 1981 stocking conditions at Heron Reservoir).

To be correctly applied, benefits should be compared over two successive runs of the economics model, in which the model is configured for an identical set of fishing sites, with the same years for both runs.

Figure 29 is a flow-chart of the major factors that influence angler travel expenditure for the angler benefits model. The configuration of travel expenses from each zone of angler origin to all fishing sites exerts a considerable constraint on angler selection of fishing sites. Generally, sites closer to population centers, and having better fishing and related dimensions of site quality will attract the highest number of anglers. New Mexico sites are quite popular if they have good fishing, cool summer temperatures, reasonably good facilities, and are within a 2-hour drive of Albuquerque. Other things equal, sites that require the highest angler expenditure of time and money to reach will have the lowest benefits, and will generate the smallest increment to angler benefits from management-induced quality improvements.

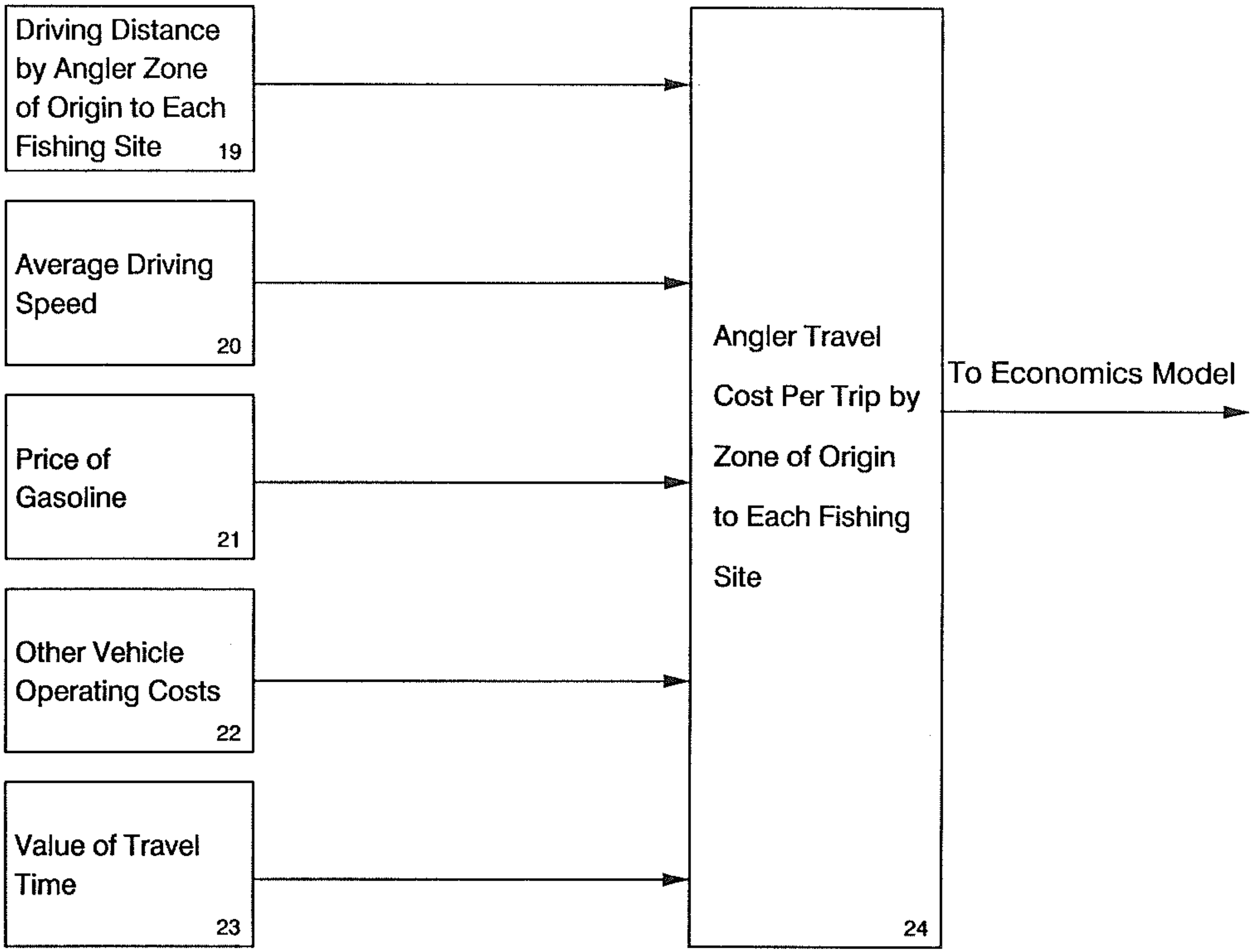

Figure 29. Flowchart of angler travel costs from zones of origin to all major New Mexico fishing sites.

Unit 23. Factors influencing the distribution of travel costs from zones to site include driving distances (Unit 19), average driving speed (Unit 20), the price of gasoline (Unit 21), other costs of operating a vehicle (Unit 22), and the value of opportunities foregone as a result of travel time for fishing (Unit 23).

MODEL SYSTEM BEHAVIOR

If RIOFISH simulates complex planning systems, it should respond to modeled changes as we would expect the real reservoirs to respond if similar real changes occurred. Table 40 summarizes the responses of catchable sportfish biomass and production following some major change in the ecosystem. Catchable fish are over a minimum size estimated to be physically catchable with the fishing gear most often used, usually over 180-200 mm, depending on species. Thus, catchable biomass is a fraction of the total fish biomass, which includes all non-game species and all sizes. The sites chosen for various tests were picked randomly from among the reservoirs in the largest river basin, the Rio Grande.

First a reference run was made. In this reference run, reservoir water-level fluctuation, stocking, regulation, and angler effort were nullified to eliminate their effects on modified fish populations. Fishing was excluded, water levels and exchange rates were held constant, and there otherwise was no management. Initial fish density was estimated from past field surveys conducted by or for NMGF. For each of the reservoirs in the reference run, catchable sportfish biomass was, as expected, stable, under the stable reference conditions, whenever the fish species present had suitable reproductive habitat available. Trends toward slowly increasing (Cochiti, Caballo) or decreasing (Elephant Butte, Abiquiu) fish abundances occur because initial population abundances are not in exact equilibrium with the organic loading created by the reference run. However, they are close enough to equilibrium to demonstrate that the initial estimates were reasonable approximations of modeled system biomass.

Even if an exact representation of the initial population abundances could be recreated, which is unlikely, perfect equilibrium would not occur because of the advantages certain of the populations have following past fluctuations in the real-world environments. It is virtually impossible to create absolutely stable population dynamics using initial biomass estimates from

Table 40. Scenarios for observable behavior of RIOFISH.

	1980	1981	1982	1983	1984
Cochiti Reservoir					
Reference Run					
Catchable biomass	96.3	109.8	114.2	118.9	132.7
Sportfish production	65.0	64.2	63.0	69.3	78.1
No Reproduction					
Catchable biomass	98.9	104.0	97.7	83.2	67.8
Sportfish production	61.5	44.6	28.4	16.9	10.6
Populations Reduced 90%					
Catchable biomass	46.7	61.0	69.4	76.2	87.7
Sportfish production	31.3	32.1	30.5	34.8	43.3
400,000 Angler Days					
Catchable biomass	96.3	79.3	71.2	60.4	62.3
Sportfish production	65.0	54.4	53.6	56.0	59.8
Elephant Butte Reservoir					
Reference					
Catchable biomass	202.8	193.0	185.2	180.1	186.5
Sportfish production	83.3	84.9	81.5	05.8	96.7
No Reproduction					
Catchable biomass	204.6	178.8	158.6	134.5	110.3
Sportfish production	83.3	84.9	80.5	85.8	96.7
Population Increased 10x					
Catchable biomass	1691.2	1165.0	896.2	716.7	605.7
Sportfish production	179.4	175.5	173.9	159.7	146.0
50,000 Angler Days					
Catchable biomass	202.8	193.0	185.2	176.9	177.0
Sportfish production	83.3	84.9	80.5	84.4	92.5
Caballo Reservoir Reference					
Catchable biomass	130.5	146.2	154.0	163.3	171.3
Sportfish production	76.8	71.9	71.2	75.5	81.2
No Reproduction					
Catchable biomass	133.8	153.2	151.1	135.5	112.7
Sportfish production	71.1	62.2	46.4	29.8	17.8

Table 40. Cont'd.

Carp and Shad Removed					
Catchable biomass	148.2	173.8	207.7	231.1	266.3
Sportfish production	105.2	114.0	134.9	153.0	170.0
El Vado Reference (not studied)					
Catchable biomass	33.8	27.7	22.1	17.2	13.7
Sportfish production	19.3	13.8	9.0	5.3	5.9
Stocked					
Catchable biomass	33.8	27.0	27.5	24.8	29.2
Sportfish production	25.2	24.0	24.4	27.3	28.8
Abiquiu Reference					
Catchable biomass	53.8	53.6	50.4	46.0	42.6
Sportfish production	25.3	20.9	15.5	12.6	11.6
Stocked					
Catchable biomass	54.2	53.2	54.2	67.8	71.4
Sportfish production	27.6	32.7	40.8	42.6	43.6
Organic Food Increased					
Catchable biomass	57.9	62.9	59.3	54.5	51.0
Sportfish production	34.3	29.3	22.3	19.8	20.4

the real world. Therefore, we assume that the modeled populations behave enough like real populations to be useful indices for real world changes following management or natural events.

The real-world coldwater lake, El Vado Reservoir, is managed primarily by stocking fingerling salmonids, because natural reproduction is inadequate to sustain the fisheries. This is evident in the modeled El Vado Reservoir; its catchable stock substantially decreases and production decreases even more as older stocks increasingly dominate the fishing over the five-year model run. Because the production-biomass of young fish is higher than for older fish, production falls off more rapidly than biomass as the mean age of the population increases.

Stocking the modeled lakes, as was actually done in the real lakes in 1980-1984, sustains the modeled, catchable stocks and the production as expected. For these stable unfished conditions, historic stocking levels may be greater than necessary for maintenance of modeled fish populations. That was expected because natural water-level fluctuation and angler effort influence stock density.

Among the warm-water sites, failed reproduction (we created a zero fecundity in the modeled population) caused decreased catchable biomass and production similar to the unstocked cold-water sites. In the model, most of the warm-water populations spawn successfully in stable circumstances, thus are able to sustain catchable biomass without stocking (although the relative abundances of different stocks shift as those populations most limited by fluctuating waters gain proportionally greater reproductive advantage). When the initial modeled population density is changed an order of magnitude, the catchable biomass and the production are at first substantially depressed, then return toward equilibrium biomass and production over the following five-year period. The most rapid recovery is in the first year, from 1979 to 1980 in the test run. The model assumes the initial population condition existed in the year immediately before the years for which outputs are reported. Therefore, the catchable biomass in Cochiti Lake, which in 1979 was reduced to about 10 kg/hectare, by 1980 recovered to 46.7kg/hectare.

The equilibration rate was not quite as rapid in Elephant Butte after the initial populations were increased an order of magnitude. Differences in equilibration rates occur among lakes or at different times within lakes because of different compositions of species with different natural mortality rates. Communities composed of species with high mortality rates recover faster than communities composed of species with low mortality rates.

When initial biomass was varied from equilibrium with the modeled ecosystem, the production varied from equilibrium less than biomass. This happens because fish production is a function of both biomass and population growth rate. As biomass increases, growth rate decreases when the organic loading is fixed, as it was in these model runs.

When the fishing intensity is increased substantially to a high effort of 400,000 angler days at Cochiti Lake (about 10 times present real-world effort), the catchable stock falls as expected for an over-fished population. Fish production falls as well, reflecting the lowered reproduction rate as over-harvest removes most of the adult stock. However, when the angler effort is low in relation to the fishing capacity, as created in Elephant Butte (50,000 angler days in the run compared to 200,000 angler day in the real-world lake), the impacts on the fishing are minor. Both population runs in this case assumed that fishing mortality was totally compensatory for natural mortality. That is, natural mortality decreased in exact proportion to fishing mortality. When the fishing mortality is assumed to be other than totally compensatory in the model; the depressive effects of angler effort go up as expected.

Organic loading sustains the fishing forage base. The rates of loading in the stablized reference run were lower than estimated real-world loading rates in Abiquiu Reservoir. When increased by about three times the magnitude in Abiquiu Reservoir, the biomass and production increased but not in proportion to the increased organic load. This relative insensitivity of variations in catchable stocks to variation in organic loading is reflected in New Mexico Game and Fish mail surveys of harvest rates, which increased about 40 percent as estimated organic loading more than doubled in the early 1980s. This natural propensity for aquatic communities to self regulate in fluctuating environments maintains relative stability in both the real-world and in RIOFISH.

The RIOFISH aquatic community creates relatively stable fish production and biomass from less stable habitat fluctuation. Whereas loadings of water and material fluctuate by an order of magnitude in modeled reservoirs, sportfish production and yield potential tend to vary by about 2x. This dampened effect of environmental variation is brought about in the model through several pathways.

Most importantly, the trophic efficiency decreases as organic loading increases, much as Cushing (1971) recognized for estuaries. The reasons for such a decrease of the trophic efficiency are related to the inability of consumers to respond to rapid fluctuations of organic loading as quickly as decomposers can respond, and to the depression of oxygen availability in stratified hypolimnia. Oxygen depletion favors decomposer processing of organic matter. The net effect is a decreasing rate of return in consumer production as organic loading increases. Therefore, dramatic fluctuations in organic load are reduced with each trophic transfer at each trophic level.

Of lesser impact, counteractive changes occur among the abiotic factors that regulate primary productivity as water and material loadings fluctuate. Nutrient and suspended solids concentrations can vary with changes in discharge. Therefore, as nutrient concentration increases or decreases, light occluding suspended sediment also increases and decreases (not exactly proportionally, however). Increases in nutrient concentrations would stimulate primary productivity much more if light diminishment by suspended solids did not simultaneously limit photosynthesis. Also, in extreme loading, water exchange rates become high enough to flush phytoplankton from certain reservoirs.

Fish biomass available for growth is another stabilizing factor. At high levels of organic loading and food production, an existing low biomass of fish limits the potential fish food use and decreases the trophic efficiency from what it would be if biomass were greater. At low levels of loading, fish biomass grows little but sustains the harvestable stocks. Thus, fish biomass tends toward a mean level, which stabilizes fluctuation in food source as it contributes to determination of fish production.

Fish diversity also influences the stability of sportfish production. Under intensively fished situations, low-diversity communities may be either more or less vulnerable than high-diversity communities to factors that limit fish production. Because different species have different harvest coefficients (different overall desirability, catchability and retainability), the production of diverse communities is more resistant to fishing intensity than the production of a low-diversity community comprised of fish with a high harvestability coefficient.

Fluctuations in water level can have more short-term impact than organic loading on fish concentration (density and biomass) and productivity per unit area. Rapid changes in water level will change fish biomass in inverse proportion to the change in surface area. In the long-term, total biomass, productivity and yield tend to increase or decrease with any long-term change in surface area that is positively associated with organic loading. Thus, just as observed in the mail survey reports from 1975 to 1987 (Table 2), the total potential yield increases as surface area and organic loading increase.

There is also a stability in collective angler behavior represented in RIOFISH. Fluctuations in the species of fish available for harvest do not greatly impact collective angler activity as long as the total potential yield of sportfish remains stable, whether or not the sportfish are comprised of a gamefish species, like trout or largemouth bass, or panfish like crappie and whitebass. This model behavior reflects the observed behavior of anglers who reported catch rates in a 1988-1989 telephone survey. It also reflects the long-term trend presented in Table 2, which reveals that anglers in the aggregate shifted effort from trout and salmon fishing to warm-water fishing as the catch rate and yield of panfish increased. The RIOFISH fishing behavior reflects a tendency for satisfied anglers, as a group, to fish for total weight; that is, a 1.0-kg fish is "worth" about five 0.2-kg fish. The major exception to the "all sportfish are equal" rule is the carp and sucker category, which have a much smaller harvest coefficient than other fish of equal size.

The most critical factors determining angler visit rate under prevailing management strategies is the average distance of the site from anglers and the size of the site. Large sites close to a large number of anglers are visited more often than small remote sites. This angler behavior tends to stabilize angler visit rate much more than would be expected based on fish catch rate alone. Therefore, sites close to cities are more likely to be over-fished than more remote sites.

The amount of sportfish production in large lightly fished waters is determined mostly by the physical-chemical environment, particularly factors that determine organic loading rates. In more intensively fished lakes, the production can be determined mostly by angling pressure. Where angling pressure is particularly intense, any year-to-year variation in angler visits may result in fish production fluctuations as large or larger than those caused by fluctuation in organic loading. Fluctuations in travel cost or income could cause such fluctuations in visitation rate.

The presence or absence of herbivorous fish forage and fluctuations in herbivorous forage, also influences the sportfish production (particularly of larger sportfish). An introduction of herbivorous fish forage may increase piscivore production by several times in eutrophic lakes (high organic load), but have little impact in oligotrophic waters. At low food concentrations, shad apparently increase the frequency of selective-feeding on zooplankton and decrease filter feeding.

These general observations of model behavior point to those parts of the model where accuracy of parametric estimation is most likely to influence RIOFISH.

MODEL CALIBRATION AND TESTING

For the biological submodels, parameters of the mathematical simulations were calibrated to fit field estimates of sportfish biomass and production estimates of fish forage in several New Mexico reservoirs. Calibration was done mostly with fish and forage data obtained from 1980-1984 in New Mexico waters and from parametric estimates reported in the literature (for example, summaries of fish parametric information by Leidy and Jenkins (1977). Some subsequent calibration has been done for crayfish populations and certain other model aspects pertaining to cold-water reservoirs. Confidence in various parametric estimations varies, depending on the sampling intensity, inherent parametric variation, and technical limitations.

Production-Model Calibration

Organic Loading

Model simulation of organic loading forms the basis of the simulation of fish production and catchable biomass. The production model parameters include the estimation of material transfer from the primary organic loads (primary production in reservoirs and allochthonous loads to reservoirs) to the secondary levels of production and the partition of materials among the secondary levels. Much of the calibration was based on data gathered from 1980-83 in 12 New Mexico reservoirs (Cole et al. 1985). The organic loads were estimated by measuring the biomass of phytoplankton, P/B ratios and phytoplankton production and the estimated organic loadings from the watershed.

Watershed Loads

First estimates of watershed exports of organic matter, which generate allochthonous imports to reservoirs, were determined from the estimated water yield rate from the watersheds and estimated carbon concentration in the yielded waters. Where water yield rate was monitored by USGS or other services, as in the main-flows to reservoirs, the monitored rate was incorporated directly into estimations of water loading into the lake. There was no clear relationship between discharge and organic concentration, but loading rates were clearly related to discharge. Where there was no direct measures of water loading, we estimated the unmonitored watershed area and a water yield rate (m^3km^{-2}) based on unaccounted changes in lake volume mass balances. These mass balances usually involve less than 2 to 4 percent of total volume change and are prone to large estimation error.

Concentration of organic matter was estimated from USGS records obtained in watershed runoff and in studies conducted with artificial rainfall simulators (Cole et al. 1986, Ward and Bolin 1989) and natural runoff events (Cole et al. 1986). An average percentage of the total suspended matter yielded from watersheds was estimated. Using information on average sediment yield rates/m^3 of water derived from watersheds, we then calculated the organic matter yield rate based on the percentage of total sediment comprised of organic matter in various studies.

Concentrations of organic matter and sediment in runoff from rainfall simulation and natural runoff is much greater than mainstream flows. Average values of 500 to 700 gCm^{-3} are typical of summer runoff events in intermittent runoff channels and infiltrometer studies in relatively steep slopes (Cole et al. 1986). Concentrations in infiltrometer studies conducted in more gentle gradients tend to be much less (100 or 200 gC), thus slope appears to be a critical factor in determining concentrations as well as total yields. The percentage of suspended sediments comprised of organic carbon were similar in the infiltrometer and the watershed studies, averaging nearly 3 to 4 percent. In USGS data summaries, the mean concentrations in mainstream flows was less (10-20 gm^{-3}) than for infiltrometer or intermittent channel runoff, probably for two reasons. First, the major fraction of discharge is from snowmelt with low concentrations of suspended matter and 2) the influence of filtered ground water may be greater in the permanent large river systems than in intermittent runoff systems. The average concentration of organic matter in suspended sediment of USGS data sets averaged less, between 0.5 and 1.0 percent. Winter and spring runoff events usually come from snowmelt. Except for occasional winter rainstorms, these winter events generate little watershed erosion and most suspended material comes from the submerged channels.

We have preliminarily estimated the concentrations of organic matter, phosphorus, nitrogen and suspended solids in runoff for each different plant biome (alpine forest, ponderosa, pinyon juniper, grassland, and desert shrub). Variance is high, particularly for nitrogen. Summer and fall runoff events have highest average concentration estimates whereas winter and spring had lower concentrations. There is much less information available on winter and spring events and less certainty in results. Average seasonal concentration for winter and spring were estimated from USGS measurements of carbon and sediment made in the late 1970s and early 1980s for several locations in New Mexico. Because the concentration of allochthonous organic load is one of the least certain measures, we adjusted the carbon concentration to levels that created the most realistic simulation of fish production and biomass.

The modeled fish production and catchable biomass are sensitive to the range of loadings that may enter lakes directly from adjacent watersheds. This is a potential model refinement research area with high probable dividends for improved model performance.

Primary Production Loads

To estimate mathematical fractions that relate primary production to abiotic factors, solar energy was estimated from data obtained at El Paso and Albuquerque International Airports and other records from the Agricultural Experiment Station facilities distributed around the state. Semiseasonal solar energy varies relatively little from year to year or site to site in New Mexico, thus values used in RIOFISH are kept constant from year to year. In fact, rainy years radiate less radiation than dry years, but the variation is small compared to variation in certain other variables. Sensitivity analysis of variation in solar radiation shows it has little impact on sportfish production, catchable mass, or angler days of activity in the model.

Seasonal mean water temperature was also shown to be, with a small exception during spring snowmelt, closely predicted by mean air temperature and also varied little from year to year (Cole et al. 1985). However, air temperature varies with elevation and each reservoir has a unique temperature file related to elevation. The small variation that occurs in semiseasonal temperatures from year to year generates little impact on production in sensitivity tests, thus semiseasonal temperatures used in the model are the same for every year. No attempt was made to create the actual temperatures that occurred in the past.

Nutrient concentrations and loads were estimated similarly to carbon loading. Data from USGS monitored stations and watershed estimates from nearby monitored sites were used to estimate mean seasonal concentrations. Like carbon, variation in discharge had a much greater impact on semimonthly loading estimates than did variation in concentration. Phosphorus concentrations were consistently some fraction of suspended solids in natural and artificial storm events (Cole et al. 1986; Ward and Bolin 1989), but nitrogen was much less dependably predicted by suspended solids.

The net loading into reservoirs and resulting concentration in the water is simulated by an empirically determined loading concentration function based on studies at Caballo, Cochiti, and Sumner Lakes (Bolin et al. 1987). This sub-model is most accurate for simple basins, like the reservoirs at which it was developed, and is least accurate for reservoirs with more complex basins (e.g., Elephant Butte, Conchas). Basin complexity is often a function of reservoir fullness (e.g., Santa Rosa); thus, the existing sub-model may be most accurate at low water when a simple morphology exists and less accurate at higher water levels, particularly when phosphorus concentrations are less than 0.1 mg liter, and suspended sediment is less than 10. The model simulations of primary production are sensitive to the simulated concentrations. All estimates of nutrient and suspended loads are based on calibrations made before 1985. After 1985, variation in discharge and reservoir exchange rates are the two most critical determinants of the concentration simulated in RIOFISH reservoirs.

The relationship between primary production and the abiotic regulation was tested for an early model (Cushing 1971) and further calibrated with data obtained at 12 reservoirs from 1981-83. Phytoplankton were sampled 7 times annually in each reservoir to estimate their biomass and mean unit volume. From relationships determined by Banse and Mosher (1980) and Nelson (1988), the P/B was estimated from mean unit volume and production was estimated from mean annual (or mean seasonal) biomass and mean algal volume. The estimates of primary production at large reservoirs included Lake Sumner, Caballo Lake, Ute and Elephant Butte. The values agreed generally closely with model predictions and no adjustment was made to calibrate the model. The primary production model was also tested for simulation of seasonal productivity at three reservoir sites in 1987 using data reported by Nelson (1988). One reservoir was large, the other two were small. Production in Elephant Butte Reservoir was closely predicted (Figure 30). In contrast with allochthonous organic loads, primary production tends to contribute less than allochthonous organic load to total organic load, thus the simulation of sportfish production and catchable fish biomass is more sensitive to uncertainty in allochthonous organic load.

Simulation of Forage Production

Sportfish forage production is simulated in the model. The total forage production is most critical in determining total fish production and the partitioning of the forage production has secondary impacts on the relative production and abundance of game fish (black bass, trout,

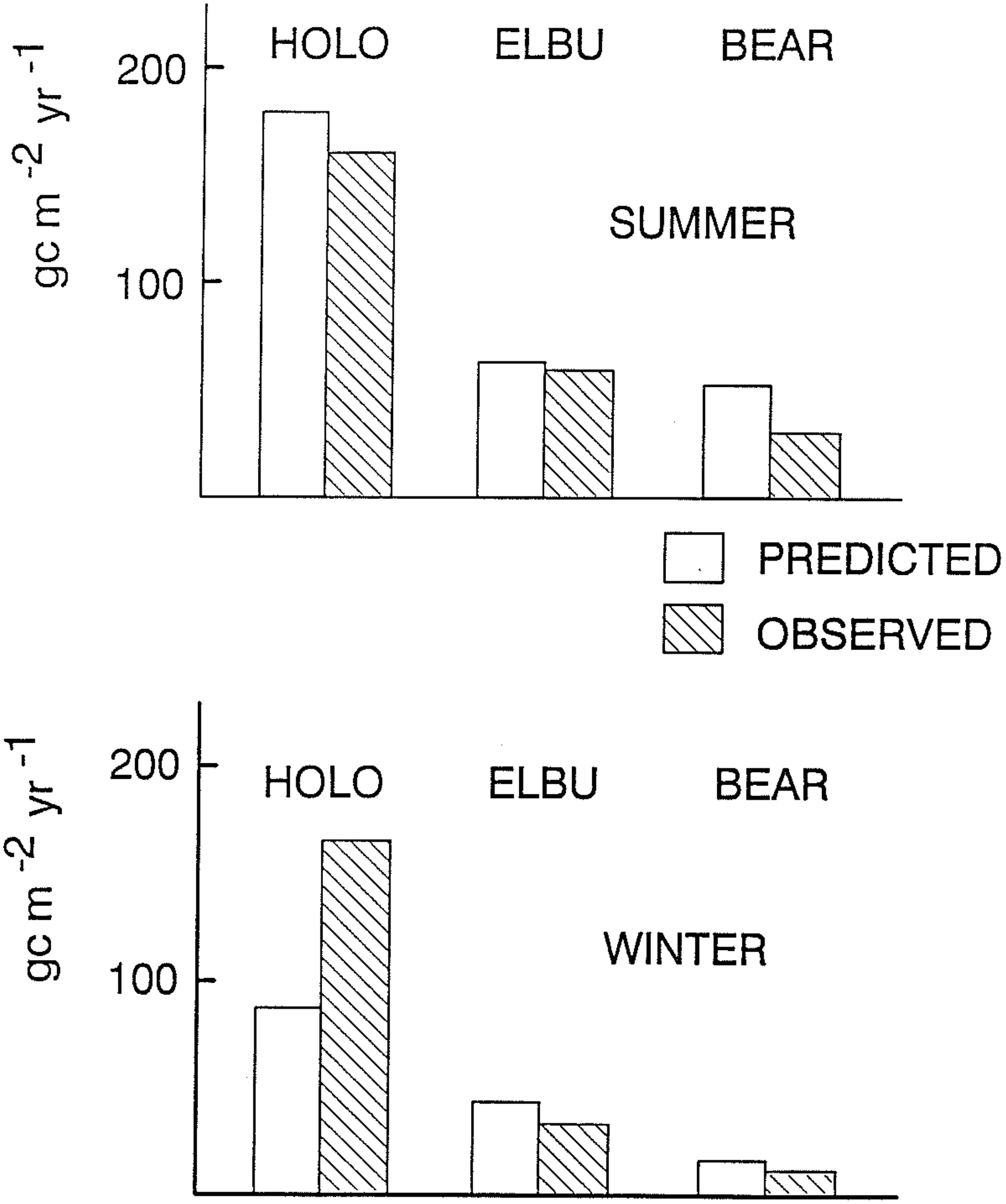

Figure 30. Simulated and measured seasonal primary production at Holloman Lake (HOLO), Elephant Butte Reservoir (ELBU), and Bear Canyon Reservoir (BEAR).

salmon, catfish, walleye, striped bass), panfish (crappie, sunfish, white bass, bullheads), and carp and suckers. At the secondary production level (first consumer level) the organic resource is partitioned into the production of small invertebrate benthos, benthic feeding fish (carp), crayfish, invertebrate plankton and suspension feeding fish. Both trophic-level transfer coefficients and partitioning coefficients were estimated from data collected from 1980-84 except for crayfish, which were estimated in 1986-88.

Production of fish and invertebrates was estimated (Cole et al. 1987a) and contrasted with the total organic load to estimate a relationship between organic load and secondary production (Cole et al. 1987a). The relationship was refined as described in Section 4 using the same data and additional data obtained in Burn Lake (Hoffman de Carvalho 1988), a small lake in Las Cruces, New Mexico. The refined relationships included water temperature, volume of oxygen-depleted water, and organic loading rate to estimate trophic efficiency. This new model was used to predict secondary production estimated in 1980-83 and generally fit well for large lakes included in the study (Elephant Butte, Caballo, Ute).

Partitioning coefficients included 1) partitioning between suspension feeders and bottom feeders, 2) partitioning among invertebrate suspension feeders and fish suspension feeders (shad), 3) partitioning among the small invertebrate benthic feeders and the larger crayfish and fish suspension feeders, and 4) partitioning among the fish and crayfish benthic feeders. The functional relationships existing between all but fish and crayfish were estimated from data collected before 1984 in large reservoirs in New Mexico (Cole et al. 1985). More recent studies of crayfish and fish partitioning have been used for that calibration, based on studies mostly in Burn Lake.

The estimation of carnivorous fish production from 1980-84 assumed a similar trophic-level efficiency. Partitioning of food production among the different groups is done with the fish population model. Population parameters used in the model were based on literature parametric values and volumes estimated before 1984.

Model Testing

The model is best tested by monitoring outputs such as catch rate, catchable biomass or angler days before and after some management strategy is applied. The model would be verified by such tests if the relative change in model output (e.g., increase of 50 percent) were approximated by real-world monitored changes. No such verification by application of a management scenario has been done to date. Several projects are now in progress and are related to specific management techniques (e.g., changing fry stocking, building boat ramps, etc.).

A less satisfactory model test is to calibrate the model with historical information pertaining to the fishing, then follow the simulation into subsequent years and examine trends to see how well they agree with field recorded data. Field data is available for estimates of fish catch rates to evaluate estimation of trends in fishing opportunity.

Several sources of error are associated with comparisons of field data and model simulations. Firstly, the statistical error associated with sampling can be relatively high. For estimating the catch rate, error is associated with the mail survey data, which has not been properly estimated for error amount. Thus, testing or verification of RIOFISH illustrates a need for defining allowable uncertainty, then gaining the appropriate data to meet the allowable uncertainty. Because halving statistical confidence intervals often involves quadrupling sampling costs, the uncertainty allowance also has practical economic meaning.

Model construction also prohibits exact reproduction of events as explained elsewhere. The model performance is affected by the initial biomass introduced into the model. There is a recovery time required for that biomass and the density of catchable sizes to come into equilibrium with modeled conditions. Therefore, to exactly recreate history, we would have to exactly guess the initial biomass and population structure. Thus, the best that can be expected is generally similar trends.

As previously explained, two of the least understood phenomena now limiting model performance include watershed loadings of organic matter and angler site substitution. Considering those limitations, we arranged a test of model performance by comparing card survey estimates of angler catch rates with model simulations that have been calibrated with new estimates of organic loading. Table 41 shows the results for Rio Grande lakes. In this comparison, an initial model run was conducted from 1978-1983 and the equilibrated last three years, 1981-1983, were compared to card survey results collected for those years. A two-year equilibration period was used to allow the initial estimation of fish populations to equilibrate with the modeled habitat conditions.

In most runs for 1981-1983, the model tends to over-estimate catch rates, Cochiti Lake being the only exception in the six lakes tested. One possible explanation is an over estimate of organic loadings. Another explanation is that the minimum size of small fish kept is set too small. For this test, we calibrated the model by estimating the amount of decrease in organic loading needed to reduce the catchable stocks into a catch rate range more like that reported in the card-survey range. These calibrations estimates of organic load were as much as an order-of-magnitude lower for certain warm-water reservoirs (Table 41).

The model was rerun from 1982-1986, allowing for a two-year equilibration period to simulate 1984-1986 and contrasted to the mail survey results. In all reservoirs, the calibration improved the simulated mean annual catch rate for the three-year period. However, apparent trends over the three-year period were not precisely reflected. In some instances, the variance in the card survey data is too great to establish any real catch rate trend. The initial population

Table 41. Mail survey catch rate estimates and model estimates of catch rates in 1981-1983 compared to calibrated model[1] catch rate in 1984-1986.

	Before Calibration				Calibrated Test Run				Organic Load
	1981	1982	1983	Mean	1984	1985	1986	Mean	multiplier[2]
Heron									
Survey	0.58	0.73	1.30	0.64	1.00	1.15	1.02	1.06	
Model	0.79	0.94	1.11	0.94	1.00	0.89	0.87	.92	0.5
El Vado									
Survey	0.43	0.36	0.33	0.37	0.52	0.43	0.51	.49	
Model	0.54	0.57	0.62	0.57	0.44	0.44	0.54	.47	0.5
Abiquiu									
Survey	0.60	0.32	0.47	0.46	1.27	1.48	2.51	1.75	
Model	1.60	1.36	1.93	1.63	1.03	1.21	0.96	1.07	0.1
Cochiti									
Survey	1.22	0.83	0.90	0.98	0.68	0.65	1.31	.88	
Model	1.14	0.96	0.75	0.95	1.09	0.77	0.81	.89	0.0
Elephant Butte									
Survey	1.17	1.25	1.19	1.20	1.35	1.24	0.96	1.18	
Model	2.02	2.43	1.73	2.06	1.51	1.27	0.97	1.25	0.1
Caballo									
Survey	1.09	1.02	0.71	0.94	0.60	0.97	0.58	.71	
Model	1.91	3.15	2.78	2.61	0.74	0.82	0.86	.80	0.1

[1] /The model was rerun for 1978-1983 with a new estimate of the organic loading needed to improve agreement with the NMGF mail survey results. Then the model was run from 1982-1986 to allow a two year equilibration with the new organic loading and to simulate catch rates for 1984-1986.

[2] /The amount that the organic load was altered to calibrate the model.

structure used also affects the observed trends. Because the initial population structure rarely can be estimated exactly for an historic condition, subtle trends cannot be recreated. In one case, for crappie in Abiquiu Reservoir, the observed card survey trend appears to be real and related to the establishment of a new fish population. Considerable model refinement is needed to improve the understanding of such specific processes. In other cases, the yearly differences could be caused by imprecise representation of annual variation in either organic loading or angler substitution effects, especially as lake water-levels changed. All three sources of uncertainty, specific population dynamics, organic loading and angler site substitution, need further investigation to improve model simulations.

With some important exceptions, RIOFISH simulations behave like the fisheries in New Mexico reservoirs. Exceptions will be discussed further in the next chapter. Model performance appears to be representative enough to compare results of management scenario runs with reference runs to obtain reasonable estimates of the effects of management or fishing opportunity and angler benefits over three- to five-year periods. Possible natural changes can be simulated similarly.

LIMITATIONS OF RIOFISH

Review of Intent and Accomplishment

The intent of RIOFISH was to develop a planning model that would help NMGF to:

1) Organize information bases into a meaningful synthesis for fishery management analyses and decision making,
2) Provide a forecasting tool that would facilitate formulation of realistic management objectives,
3) Facilitate selection of appropriate management strategies for objective accomplishment,
4) Help decision makers allocate budgets through cost-benefit analyses,
5) Provide a communication tool that, as a "strawman" for planning system structure, helps to focus management and research efforts.

Organized Information

RIOFISH organizes thousands of discrete observations collected from USGS, U.S. Weather Service, various literature sources and NMGF mail surveys, telephone surveys and field surveys into a user manageable structure that simulates a sportfishery planning system. RIOFISH is not a data storage and retrieval system. The user cannot request a printout of all past USGS discharges or material content at all reservoirs, for example. But, the user can obtain much of the integrated information often sought from such data, such as estimates of surface areas and storage ratios.

One goal of RIOFISH was to stretch the data base into an inventory of resources. Much as field surveys sample certain waters, from which fishery managers extrapolate to the larger statistical population of similar waters, RIOFISH uses available data to extend estimates of resource availability. Just as with statistical methods, there are limits to the accuracy and precision, which can only be improved with more intensive sampling and improved technique. For this reason, the structure of a model like RIOFISH always has room for improvement, just as real fishery planning systems are far from perfectly refined.

One RIOFISH asset is the inventory of uncertainty that it provides, and the potential importance of that uncertainty. RIOFISH does not always provide the simple and expected answers, often because complex antagonistic and synergistic interactions occur. These complications demonstrate real world complications and uncertainties.

Sometimes model uncertainties are associated with misunderstanding of process or with statistical imprecision. The structure of RIOFISH enables, through sensitivity analysis, the identification of the most impactive uncertainties, so that they may be studied most intensively to improve model performance and understanding of planning environment interaction. Two of the most important research areas for RIOFISH, based on sensitivity analysis, are simulations of organic loading from watersheds and angler impact on fishery resources.

Forecasting Tool

RIOFISH encourages acceptance of a fundamental planning truth: The future is unknowable, and a number of possible futures have to be anticipated for effective planning. RIOFISH allows the model user to construct a variety of possible futures for the fishery management planning environment in New Mexico. Most of the critical forecasting variables are included, and some not now included are intended for inclusion as soon as relevant information becomes available. The most important elements are habitat availability and quality and demographic variables including population change, travel costs, and income levels. Strategic planning objectives are often unrealistic because they are based on only one possible future, not many possible futures. With RIOFISH, a family of strategic objectives can be developed, each objective being appropriate for a particular planning environment if it should materialize.

Management Strategy Selection

Part of the RIOFISH inventory includes projections of resource or resource user responses to management strategies (e.g., water-level control, stocking). Once objectives are defined, various combinations of strategies can be tested in RIOFISH to assess the best combinations for maximizing opportunity and benefits. Management strategies are among the most actively evolving areas of human knowledge in fishery management, and sensitivity analysis often highlights areas of important uncertainty. Once again, some of RIOFISH's limitations reflect the general limitations of information available in fishery management. RIOFISH is limited to the uncertainty associated with some management strategy impacts, but RIOFISH has the capacity to point the way toward the most potentially rewarding research activity for improving projections of management strategy impacts.

Budget Allocation

Decision makers who allocate budgets must project allocation effectiveness. Accurate foresight is much more valuable than accurate hind-sight in a dynamic planning environment. Budget allocation is an investment technique. Ideally, management revenues increase resource user opportunities where resource user satisfaction is most likely to be increased. The responses to management of the best single index to resource user satisfaction before management costs are considered, net willingness to pay (angler benefit), is simulated by RIOFISH, as are other less acceptable indices (angler days, total yield). The response of fishery opportunity to management is also simulated (catchable fish; fish production and yield/unit efforts). As long as decision makers can estimate costs reasonably well, they can estimate the net economic value (angler benefit-management cost) to be expected from proposed management strategies and allocate budgets to the most promising strategies.

Communication Tool

Once information becomes available, the usual impediment to effective fishery management is communication. One of the most difficult challenges is the justification of management costs to the revenue paying public. There are many reasons for this, but a basic reason is that agencies often do not know how to spend revenues effectively. In combination with a good internal costing procedure, which tracks individual strategy (project) costs, the use of RIOFISH can help with this problem.

RIOFISH is a communication-problem identification tool. Where different opinions exist about the magnitude of a problem or the source of a problem, RIOFISH can help focus the issue. With RIOFISH, authorities can be brought together to discuss the variables involved in the issue, and semantic difficulties can be reduced.

RIOFISH already has brought model developers and potential model users together to discuss issues addressed by RIOFISH. In a number of instances, management directions have changed or accelerated partly as a consequence of such interactions. There has been, for example, an increased emphasis on managing fisheries closer to where the public resides. Stocked trout are being redistributed after decades of static distribution. Growing questions continue about the effectiveness of certain fry stocking programs when habitat conditions are appropriate for natural spawning. A new strategy, reservoir aeration, has been implemented after past discussions of potential. An effort is being made to control water-level fluctuations at certain reservoirs. RIOFISH development did not originate these changes, but results of RIOFISH supported or countered various agency observations and contributed to directional changes in policy. Such synergistic interaction between model developers and model users is one of the most important side products of model development.

RIOFISH is also a heuristic tool. It provides a menu-guided tutorial for the model user. In a few weeks, the model user can examine responses of modeled fish communities to experiments that would take a lifetime to complete in the field. The model user can examine the relationship of modeled community dynamics to many contemporary fishing management indices such as proportional stock density, growing seasons, and morphoedaphic indices. The model user can improve his or her concept of how recruitment, natural mortality and fishing mortality all interact with stable to fluctuating habitats. Many educational uses are available and, when accomplished, more can be developed from the user's inputs. Such heuristic use encourages greater communication between theoreticians who develop models and users of the models. It also encourages greater acceptance of a larger range of management tools and a greater willingness to investigate the literature and other sources to help resolve thorny issues.

General Limits

Many of RIOFISH limitations have been described by the previous summary of RIOFISH accomplishment. The following are some of the most important limits to model utility (specific limits are described in the detailed description of RIOFISH in an earlier section):

1) A model designed to simulate a planning system approach to management cannot do so if a planning system approach is not adopted by the agency.
2) RIOFISH deals with a complex and uncertain world; thus, it has a complex structure. RIOFISH, therefore, encourages more thoughtful management. For those seeking automation in management, RIOFISH will be a disappointment.

3) The user-friendly version of RIOFISH is not generalizable to any area; it is grounded in the habitats for which it was designed and user access to parameter dimensions limits user independence from model developers.

4) RIOFISH is not a perfect simulator of reality; it has many inaccuracies and imprecisions. However, it also has the potential, through sensitivity analyses, to identify the most fruitful research to reduce structural limitations.

Planning in NMGF

New Mexico Game and Fish is evolving toward a planning system approach to management, but it has not quite been reached. Part of the problem rests in a chicken-or-egg dilemma: How can an agency plan, based on benefit-based objectives in fluctuating environments, if benefits cannot be estimated very well under such conditions? RIOFISH now provides "first cut" estimates of economic benefits for benefit-cost analyses for certain planning futures. Thus, RIOFISH has addressed a major planning impediment of NMGF. Now the two, RIOFISH and the agency, can evolve more closely together.

One other practical agency impediment is cost accounting. Because NMGF needs to estimate strategy costs, a cost accounting system based on projects would be much more useful than one based on administrative units (they are not, however, mutually exclusive accounting systems). Although it is possible to estimate costs in advance to select the most probable cost-effective strategies (with or without use of RIOFISH), it is difficult to evaluate whether or not the costs were estimated correctly with the present cost-accounting system.

Modern approaches to planning are just recently being framed in such a way (Crowe 1983) as to be attainable in the context of recreational fishery management. And modern planning tools, like RIOFISH and other models are just now becoming available. Therefore, NMGF should be applauded for its foresight and capacity to change as the appropriate technologies emerge.

Complexity

Some managers hope for automation. The best that a model like RIOFISH can provide is a mathematical sorting tool to help make complex issues a bit less chaotic than they seem without the tool. RIOFISH is complex because the fishery manager's job is complex and multidisciplinary. Real world complexity can be ignored through traditional approaches. RIOFISH will not eliminate real world complexity. If it is to be used, it will force thought and confrontation with complexity. To some managers, that is a disadvantage; to others, an advantage.

Generalizability

Although RIOFISH has been made very generalizable at the biological submodel level, it is grounded in certain hydrologic and economic data bases unique to New Mexico. The economics submodel may be more generalizable, but is limited by real world interactiveness with hydrologic sites outside the hydrologic model. Thus, substitution impacts of nonmodeled sites can effect simulation of visit rates and benefits. A hydrologically and economically expanded model that includes important substitute sites is needed to overcome this limit.

Also, RIOFISH is not as sensitive to watershed process as it should be, particularly in low-water years. Thus, a watershed-based hydrology model would be a better alternative than the present one and it would not be limited to USGS monitored areas.

The user's ability to change the fish population model parameters allows flexibility. However, there remain many equations that are not user changeable. This limits the utility of the model for conditions both inside and outside New Mexico. As more access is provided to model users for adjusting parameters, user independence from the model developers will grow.

Accuracy and Precision

The accuracy and precision associated with RIOFISH decreases as the model progresses from comprehensive (first priority) to specific. The following discussion of accuracy and precision relates to the model development objectives.

In keeping with the hierarchy of model development objectives, precision and accuracy are of greatest concern for its primary purpose, comprehensive planning analyses, and of least concern for the lower-level purposes. The purposes in hierarchical order were:

Objective Level I. Develop a planning model that simulates net economic value (angler benefits) of mainstream river-basin fisheries to resident anglers for comparison purposes of those total values with other water values determined elsewhere.

Objective Level II. Develop a model to simulate the effects of those variable factors that most impact net economic values of mainstream river-basin fisheries, including distribution of water surface area, distribution of catchable sportfish biomass, the distribution of human population, and important impediments to utility of the fishery resource (e.g., site fees, campsites, ramp access quality, and road access quality). Also develop a user-accessible model so that variable factors that most influence benefits (catch rates, recreational days of activity, and net economic value) can be modified by water quality and quantity management, stocking, regulations, and other commonly used management strategies.

Objective Level III. Develop a model that simulates fish total production and biomass of important catchable size groups of fish such as cold-water sportfish, warm-water sportfish, and warm-water panfish groups, as they are believed to contribute to angler's satisfaction and net economic benefits generated.

Objective Level IV. Develop a model of individual fish species population dynamics that can be used heuristically to analyze the impacts of variations in population parameters and the meanings of commonly used fishery indices and statistics in changing planning environments.

Accuracy at Objective Levels I and II. The initial program narrative emphasized a simulation structure that culminated in an estimate of net economic value so that such values could be compared with other values. The model is designed to be most useful at this level, in order to make management decisions based on the benefits obtained. The benefits model is based on empirical data gathered in telephone and mail surveys from among the most visited sites in New Mexico. The most important variables are included. Among those variables, human population and water relative distribution are most important (over 70 percent of variance in visit rates) because travel distance is such a great factor determining site visitation rate by anglers. At a secondary level of importance in explaining visitation rate, but significant factors because they are manageable, are the size of the water bodies, biomasses of catchable sportfish, and a variety of site quality factors. Species composition per se is not an important variable explaining variation in visitation rate as long as the catchable biomass includes species considered to be high-quality sportfish, such as black basses, salmonids, and channel catfish, walleye and striped bass. This implies that the most cost-effective general management for sportfish groups most suitable for the habitat is generally a suitable management strategy. Spending much effort solving species specific management problems is not useful, unless the solutions will greatly increase total fish yield to anglers. As long as a reasonable diversity of sportfish exists, adding more species will generally add little value to the fishery.

In model simulations, the greatest single determinant of sportfish biomass generated in the mainstream river basin habitats is the watershed erosivity of nutrient, suspended matter and organic matter. This erosivity of nutritional materials determines levels of forage production.

The second most important factor determining sportfish production and biomass is the presence or absence of planktivorous fish (herbivorous-detritivorous). In unproductive waters, herbivorous fish convert to invertebrate diets and compete with sportfish. As organic loading increases, the herbivorous fish convert more to a plant-detritus diet and provide greater forage for piscivores. In fluctuating environments the interactions are complex because larvae of all species are carnivores (feeding on zooplankton mostly) and vie for the same food resources.

The third most critical element in low waters is the impact of anglers on sportfish biomass. Particularly in low-water scenarios, angler pressure increases and drives up sportfish mortality up in the most attractive waters, forcing anglers to seek alternative and otherwise less attractive (farther away) substitute sites.

Under high-water conditions, the conditions under which the model was developed for the most part, the relative errors associated with nutrient loading and organic loading have relatively low impact on estimates of sportfish productivity, biomass, and benefits generated. At this time, people are least impacted by any management because natural subsidies tend to provide good fishing close at hand. However, benefits may be more sensitive to substitution effects during low-water conditions, as indicated by the shift in recreational days from one lake to another and the impacts of fish survival over the long-term. The impact is particularly great when the more conservative fishing mortality model is used.

For the primary objective of model development, the most uncertainty exists when water levels are low, because watershed effects are greater on low waters, and are inadequately understood. Improved watershed-based submodels, improved substitution impacts in economic submodels, and improved forage partitioning submodels will have the most impact on the simulation of the comprehensive fishery. Further research efforts should concentrate in those areas.

Accuracy at Objective Level III. The model provides a great diversity of user modifications applicable for analyses of impacts. Basic modifications are the most useful management activities, such as fertilization, water-level control and stocking catchable size fishes or fry and fingerlings where natural reproduction will not occur. Any activity that most promotes increased biomass of catchable fish (both total and per unit area) will increase benefits, particularly if the impact is close to population centers. Management decisions that impede total harvest rate (e.g., regulations) generally reduce benefits. Management that decreases fishery availability (close a campsite, apply a site fee) also decreases angler recreational days and benefits. The model provides very effectively for user access to simulate management decisions.

As nearly as any records in NMGF can document, the model reasonably simulates the biomass of sportfish, panfish and other categories. The information on hand agrees generally with mail survey information, although it tends to under-predict visits reported at Elephant Butte Lake. The best data available to estimate sport and panfish biomass indicate that it generally fits within the ranges of statistical confidence available (i.e., $\pm$ 40 percent average confidence interval).

Generally, a doubling of effort is needed to reduce uncertainty each additional 10 percent. To attain a 10 percent confidence interval for netted fish biomass would require 85 nights of fishing 6 nets in the average reservoir, a total cost about equal to half of the fish survey budget presently allocated for NMGF ($170,000/year). A contrast of the estimated pooled biomass of sportfish at all lakes studied from 1984-87 with the model version reveals close agreement. Therefore, the model is most accurate for pooled averages over years and groups of waters, and decreases in accuracy as the modeler progresses to specific years and specific sites.

Because major shifts in management decisions are rarely possible on an annual basis, 3- to 5-year average impacts of management strategies are more reasonable to judge. The model is now least adequately verified in its response to an actual management decision. Some of these tests with management activities are now in progress, and are about to be monitored if the present plans of the NMGF are followed. These plans include destratifying certain waters, increasing fish catchability by removing macrophytes, starting new fish populations, evaluating quality trout water performance, and redistributing waters among the storage reservoirs.

Accuracy at Objective Level IV. The lowest-level objectives concerned provision for an analytical, heuristic tool for fishery managers to evaluate various fishery indices and sportfishery statistics. Although this objective is important and conducive to improved fishery management, it has relatively little to do with the accuracy or precision of results pertaining to the model's comprehensive planning objective. Whether or not the simulated populations actually represent real populations is not a necessary assumption to analyze the meaning of fishery statistics and indices with regard to fish population dynamics. Many questions can be asked with the model and contrasted with fish population indices to examine the implications. For example, if angler effort doubles because of human population increase (applied to the model), how does the change in yield from reservoirs in New Mexico compare to other yield indices, such as the morphoedaphic index? If a manager fertilizes lakes, stocks lakes, or otherwise does anything reasonable to lakes, other than change temperature or depth, how will the modeled results compare to simple yield indices?

If a manager alters the relative mortality rate and growth rates of fish populations, how does that alteration impact on the proportional stock density (PSD)? What does the PSD do with regard to indication of potential recreational angler days activity? Does the PSD indicate the impact of angler pressure or not? How does habitat fluctuation influence the PSD as an index of fishery condition? What do predator-prey ratios (production, biomass) appear to indicate as far as sportfish biomass and yield rates are concerned in stable and unstable modeled habitat conditions?

Total catch rates are often used to indicate the trends of a fishery and the fishery's ability to sustain anglers. How does total catch rate respond when biomass of various species are changed, and how is the long-term sustainability of the catchable population related? How do benefits respond? How does the stability of habitats influence these relationships? How about stocking rates?

All these heuristic questions are intended to simulate direction of change. Does the population increase or decrease? Does growth increase or decrease? Although simulated data are provided by RIOFISH, they need to be viewed with full realization of the uncertainty associated with them.

RECOMMENDATIONS

1. Concentrate further model development on watershed-based models that stochastically forecast runoff of water and materials from precipitation records and watershed process.
2. Focus refinement on the modeled linkages between fish communities and anglers as improved data about the fishery resource (harvestable resource biomass) and fish catchability become available.
3. Complete development of tailwater and tributary submodels to improve management strategy accessibility for users and to refine simulation of collective angler movements among sites (substitution effects).
4. Improve the submodels that forecast angler recreational days of activity through enlarging and improving survey data gathered to estimate angler activity and success in New Mexico.
5. Refine estimations of parameters that most impact the model's critical outputs, such as total catchable sportfish biomass and angler benefits.
6. Accelerate technical transfer between RIOFISH developers and NMGF model users.
7. Verify RIOFISH simulation of fishing opportunity and benefits response to management strategies through actual application of management strategies by NMGF personnel, including as much as possible, modifications of habitat configuration, stocking, regulations, introductions, boat ramp construction, altered road access and other strategies.

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MATHEMATICAL DOCUMENTATION

Hydrology

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 streamflow 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

Program RIOHMAIN. This is a short program that is used to make the initial call to the functional parts of the model through subroutine HYDRO. In this portion, the user selects the reservoir number which in turn sets up the file and name identifiers.

Subroutine HYDRO. This subroutine is the primary computational part of the model. It calls all other subroutines including DATIN, FLOMOD, DATER, VOLDIS, and NUTR. Each of these is explained below. The first call is to DATIN to read the necessary data. The next call is to FLOMOD (if necessary) to modify inflows as affected by upstream reservoir operation. The call to DATER returns the year, month, and number of days in the simulation period. The inflows and outflows to the given reservoir are then modified based upon at-reservoir conditions by the basic equation

(1.1) $Q_m = A_m * Q_o + B_m$

where:

Q_m = modified discharge, desired by model user

(m = "in" for inflow; "out" for 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)

* = "multiplied by"

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.

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 maximum volume constraint, the primary outflow (#1) is increased as needed. A warning message is displayed if the maximum outflow is exceeded. The redistribution, if necessary, is performed in subroutine VOLDIS. The volume determined at this step is

$$(1.2) \quad V_c = V_{(i-1)} + Q_{in} - Q_{out}$$

where:

V_c = computed volume (acre feet)

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

Q_{in} = total (adjusted as needed) inflow

Q_{out} = total (adjusted as needed) outflow

The surface area for this volume is

(1.3) $A_1 = f(V_c)$

where:

A_1 = initial estimate of surface area (acres)

$f(V_c)$ = an interpolated number from function FCTN which uses a table of elevation, area, and capacity values unique to each reservoir.

A first guess at the volume is

(1.4) $V_1 = V_c - A_1 * (Kp * E - P)$

where:

Kp = pan coefficient for the reservoir (=0.7)

E = pan evaporation (inches), and

P = precipitation (inches).

Equation 1.4 accounts for the net weather effects in the bimonthly period. At this point, V_1 is used in place of V_c in equation 1.3 to calculate A_2. The new area, A_2, is used in equation 1.4 to obtain a new estimate of Volume V_2. The best estimate of volume is the average of V_1 and V_2 or

$$(1.5) \quad V_c = \frac{V_1 + V_2}{2}$$

The new V_c is then checked for minimum volume constraints, and, if necessary, primary outflow is decreased all the way 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 model which is used to predict angler use and benefits at reservoirs.

The next operation is 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

(1.6) $L = (A_i * Q_i ** B_i + C_i * Q_i + D_i)$

where:

L = mass load of the constituent P, N, or SS entering the reservoir (tons per day)

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

** = "raised to the power of"

The results from these computations are written to two files. One for the biological and economic models and one for use, as needed, in downstream reservoir computations.

Subroutine DATIN. This subroutine is used for each reservoir to read:

1) Thirteen years of base data for flows and volumes (can be a synthetic record for years other than observed values)

2) The parameter file containing initial or base volume (such as September 30, 1974); monthly maximum volume, minimum volume, maximum outflow, and minimum outflow; the Am and Bm values chosen by the user for equation 1; the load modifying factors and the pan coefficients of equation 1.4.

3) The appropriate elevation-area-capacity table for the reservoir. The user can also select the appropriate starting and stopping dates for the simulation in this subroutine.

Subroutine FLOMOD. This subroutine performs the complicated task of modifying upstream reservoir outflow and thus upstream capacity, as predicted in an earlier model run, 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 the primary upstream outflow (#1) by

(1.7) $QI1 = At * Qx + Bt$

where:

QI1 = primary inflow 1 to the reservoir under consideration (measured in Cfs)

Qx = index flow, usually the primary upstream outflow

At, Bt = the deduced or regression derived transfer parameters

QI1, the calculated reservoir inflow, is only used if it differs by more three cubic feet per second from the measured flow at that reservoir and time.

Subroutine NUTR. This subroutine uses reservoir volume, area and outflow, and constituent loadings to estimate the in-reservoir concentrations. The general equation is

$$(1.8)\quad C_1 = \frac{nL}{vs + Qs}$$

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/sq. m of reservoir surface/half-month

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

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

Z = hydraulic depth = Vc/A (m)

Vc = computed volume (in millions of cubic meters)

A = surface area corresponding to volume, Vc (sq. km)

T = retention time = Vc/Qout (half-months)

r = exchange rate = 1/T

Qout = outflow rate (volume (cubic meters) in the bimonthly time period)

The settling velocity, vs, is computed for each constituent from equations (Table A1) 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:	vs = 25.1*(1/T)**0.845	= 320.4*(L/Z)
Total Nitrogen:	vs = 1.71 - 0.234*Qs	= Z*0.648*(L/Z)**0.618
Total Suspended Solids:	vs = 7.82*Qs**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 :

(1.9) $R = 0.142 * Y^{(-0.525)}$

where:

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

XL = length of the reservoir in feet

W = average particle size of sediment entering the reservoir in feet

V = a settling velocity in feet per second computed as XL/T

T = water retention time in seconds computed as volume/outflow

D = average reservoir depth in feet computed as volume/area

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

$$(1.10)\quad TSS = \frac{LSS * R * 704.12}{VOL}$$

where:

LSS = suspended sediment entering into the reservoir in tons per half month

R = percent of sediment retained in the reservoir water column

VOL = reservoir volume in acre-feet

Channel Submodel

The channel submodel is structured similarly to the reservoir submodel. However, there are some unique differences.

Program RIOHCHAN. This is the main calling program for subroutine CHANL. This main program offers the user a menu of 16 channel reaches, all of them reservoir tailwaters, from which to choose. The choice is then transferred to CHANL.

Subroutine CHANL. This subroutine reads the flow files created by the reservoir model. When the flow values are set, the model then proceeds to a series of hydraulic computations. The first computations are to determine two parameters for Manning's equation as:

$$(1.11)\quad P_1 = \frac{1.486*S^{1/2}}{n} * a^{-2/3}$$

where:

$$(1.12)\quad P_2 = \frac{3}{(5 -2b)}$$

where:

P_1 and P_2 = parameters needed in further computations

S = channel bed slope for the representative cross section

n = Manning's roughness coefficient for the representative cross section

a and b = best fit parameters from the wetted perimeter flow area relationship of:

(1.13) p = a*A**b

where:

p = cross-sectional wetted perimeter, (feet) and

A = cross-sectional flow area (square feet)

The a and b parameters are determined by channel cross section surveys. The "b" parameter is usually about 0.5 and the "a" parameter usually varies (for wide channels) between 5 and 20. Also for wide channels, the "a" and "b" parameters are approximately the same for the relationship between water surface width and flow area as:

(1.14) T = a*A**b

where:

T = surface top width (feet).

With these parameters, the other relevant computations become

(1.15) $A = (Q/P_1)^{**}P_2$

$$(1.16)\ V = \frac{Q}{A}$$

$$(1.17)\ D = \frac{A}{T}$$

$$(1.18)\ T_s = \frac{p^*f^*V^2}{8}$$

and

$$(1.19)\ Ds = \frac{Ts}{(S_s - 1)^*w^*\delta}$$

where:

Q = channel flow (cfs)

V = average velocity in the cross section (fps)

D = hydraulic depth (feet)

Ts = shear force against the sediment particles (lbs per square foot)

p = density of water

f = Darcy-Weisbach friction factor (0.025 in the model, may be as high as 0.06)

Ds = maximum particle size that can be moved (feet)

w = unit weight of water (= 62.4 pounds per cubic foot), and

δ = Shield's parameter (= 0.047, but may vary between about 0.01 to 0.06)

S_s = specific gravity of sediment (=2.65)

The next step in the model is to estimate the P, N, and SS concentrations in the streamflow. The channel reaches are immediately downstream of reservoirs, therefore the reservoir concentrations are used. Finally, the model writes the hydraulic characteristics and water quality constituent concentrations to a file for use in the biological and economics submodels.

Subroutine DATER. This subroutine performs the same function in the channel submodel as it did in the reservoir submodel. The subroutine takes the date of the time step and returns the year, month, number of days in the month, and number of days in the period.

Submodel Linkage. The reservoir and channel submodels are not physically linked. Instead the reservoir model transfers information to the channel submodel via output data files which are also used in other reservoir submodel operations. This allows a submodel to be run without the extra memory and computations that may be required for the submodel. In addition, the user can pick-and-choose between reservoirs and channel reaches for analyses. The challenge is to sort out what upstream sites to include in Qx and to select appropriate values for At and Bt. Table A2 lists the present configuration chosen, which can be modified in future model updates.

In addition, at Elephant Butte, the total inflow is partitioned between the San Marcial floodway and conveyance channel based upon historical splits and channel capacity.

Table A2. Index Flows and Transfer Function Parameters for Each Reservoir.

Reservoir	Qx Index Flow	At	Bt
Rio Grande System			
Heron	None *	1.0	0.0
El Vado	Heron Outflow + La Puente	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 fit parameters which vary from month to month.

Biology

Biology - Production

Unit 7. Light Transmission.

Transmission of light through the water column depends on the extinction rate which is related to suspended solids. Water depth at any percent transmission is independent of total irradiation at the surface and declines exponentially as suspended solids increase. The equations:

$$(2.1)\quad D_1 = b_{depth,0}e^{b_{depth,1}S} \qquad \text{and}$$

$$(2.2)\quad D_0 = 2D_1$$

represent depth at 1 percent (D_1) and .01 percent (D_0) transmission respectively. S is the concentration of suspended solids. Depth at .01 percent transmission is twice D_1 as a consequence of $.0001 = .01^2$.

Unit 11. Air Temperature.

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

$$(2.3)\quad T_a = b_{airt,0} + b_{airt,1}COS(.0172(D_t - 200)) + b_{airt,2}E_t$$

where D_t is the julienne day representing period t and E_t is elevation. This equation assumes that the hottest mean temperature is always day 200 (19 July or, for leap years 18 July). The number 0.0172 is an approximation of $2*\pi/365$.

Unit 12. Thermal Profile.

The thermal profile consists of a variable number of strata, say N_{strata}. Each strata will have an associated volume and temperature and oxygen content (V_i,T_i,O_i). The first strata is the topmost (or only) layer representing the epilimnion and the last strata is the bottommost layer or hypolimnion. Any strata in between represents the sinking of a previous epilimnion due to reservoir drawdown. The previous strata is modified in four steps.

The modifications begin with the previous period's profile. The initial profile is assume to have one strata with temperature equal to the air temperature and oxygen content at saturation.

First, inflows are added to the strata that is closest in temperature with inflow temperature. The temperature and oxygen content of that strata becomes a weighted mean of the two, i.e.

$$V_i = V_i^* + V_{in}$$

$$(2.4) \quad T_i = \frac{T_i^* V_i^* + T_{in} V_{in}}{V_i}$$

$$O_i = \frac{O_i^* V_i^* + O_{in} V_{in}}{V_i}$$

where i is the index of the strata that is closest in temperature with the inflow; V_i^*, T_i^*, O_i^* are the values associated with the i'th strata before inflows are added; and V_{in}, T_{in}, O_{in} are the volume,temperature, and oxygen content of the inflow.

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

Thirdly, a theoretical epilimnion is formed based on reservoir fetch. Epilimnetic depth is the fourth root of lake fetch in <u>meters</u>. The volume of this epilimnion can be found using the area capacity tables of the reservoir. This volume is compared to the profile and it is adjusted so that the theoretical epilimnetic volume is the first strata and all strata below that are left intact. The temperature of the epilimnion is considered to be the same as air temperature or 4 degrees centigrade, whichever is warmer. Oxygen concentration of this epilimnion is at saturation.

Oxygen saturation is based on surface elevation and water temperature by the equation

$$(2.5) \quad O_{sat} = e^{b_{osat,0}+b_{osat,1}T+b_{osat,2}T^2+b_{osat,3}T^3+b_{osat,4}E}$$

where T is temperature and E is elevation. This regression equation is the line of best fit with standard published tables of oxygen concentrations.

Lastly, the temperature of the epilimnion is compared to the temperature of the strata immediately below that. A table lookup is made to determine if the epilimnion is warm enough to warrant stratification. If it is, the model is finished. If the epilimnion is not warm enough to stratify, the first two strata are combined into one. Temperature and oxygen content of the new first strata is an average of the two old strata weighted by volume. This process is repeated until there is a temperature difference large enough to warrant stratification or there is only one strata in the profile (the entire water column is mixed).

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

Unit 14. Habitats.

The basin is divided into five habitats based on light transmission as described in unit 7. Elevation at each level of light penetration is the subtraction of the respective depth from elevation at the surface. From those elevations the total surface area and volume of the water body at the surface (S_T,V_T), depth at 1% transmission (S_1,V_1), and .01% transmission (S_0,V_0) is found using the area-capacity tables described in the hydrology section.

Surface area of each habitat is easily derived from the above quantities. They are:

$$\begin{aligned} S_{littoral} &= S_T - S_1, \\ S_{limnetic} &= S_1, \\ S_{sublittoral} &= S_1 - S_0, \\ S_{pelagic} &= S_0, \text{ and} \\ S_{profundal} &= S_0. \end{aligned} \tag{2.6}$$

The volume of the offshore habitats are a multiplication of their respective surface area with depth and the onshore volumes are found by subtraction. These equations are:

$$\begin{aligned} V_{littoral} &= V_T - V_1 - D_1S_1 \\ V_{limnetic} &= D_1S_1 \\ V_{sublittoral} &= V_1 - V_0 - (D_0\text{-}D_1)S_0 \\ V_{pelagic} &= (D_1\text{-}D_0)S_0 \\ V_{profundal} &= V_0 \end{aligned} \tag{2.7}$$

where D_1 and D_0 are described above.

Shallow water bodies may not have deeper water habitats. In this case the elevation of a level of light penetration would be below the bottom elevation of the reservoir. The associated surface area and volume is defined to be 0 and the above equations will work.

Unit 15. Primary Productivity.

The rate of plant growth is the product of solar irradiation on the basin and photosynthetic efficiency, relative to maximum possible photosynthetic efficiency (E_m). Actual photosynthetic efficiency (E_1) is affected by temperature (E_t), nutrient availability (E_n), suspended solids (E_s), and exchange rate (E_X). These effects operate jointly, and independently, to reduce the maximum efficiency by a given fraction. The equations are:

$$E_t = b_{t,o} + b_{t,1} T \tag{2.8}$$

where T is temperature of the epilimnion and E_t is restricted to be between 0 and 1.

$$E_s = \begin{cases} b_{s,o} S^{b_{s,1}} & \text{if } S > 0.1 \text{ or} \\ 1.0 & \text{otherwise} \end{cases} \tag{2.9}$$

where S is average suspended solid concentration,

$$E_n = 1.0 - e^{b_{n,1} N} \tag{2.10}$$

where N is the limiting nutrient value -- the minimum of ([P], [N]/10.0), [P] and [N] are average phosphorus and nitrogen concentrations.

$$E_X = e^{b_{X,1} e^{b_{X,2} X}} \tag{2.11}$$

where X is the exchange rate of the basin expressed in days. Photosynthetic efficiency (E_l) is the product of maximum efficiency and equations (2.8)-(2.11) or:

$$(2.12) \qquad E_l = E_m E_t E_s E_n E_X$$

Primary productivity is expressed as:

$$(2.13) \qquad P_l = L_o E_l b_{pconv}$$

where P_l 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. This productivity is immediately available for consumption as opposed to allocthonous carbon loading described next.

Unit 16. Allocthonous Carbon.

The hydrology model calculates a total volume of water that enters the reservoir at a certain time from three sources. 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. In addition, each reservoir has associated with it user supplied seasonal mean carbon concentrations for each source. The total mass of allocthonous carbon 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 allocthonous carbon entering the reservoir is aged 750 degree days before it is available to the food chain. When it has aged this amount it is added to the stored carbon available. Available allocthonous carbon that enters the food chain is a fraction of this stored carbon and is based on temperature. Allocthonous loading for a period (P_a) is computed as:

$$(2.14) \qquad P_a = \frac{C_{avail} b_{clag,0} e^{b_{clag,1} T_1}}{S_T \, \delta t}$$

where C_{avail} is the total weight of carbon available for use, T_l is the temperature of the epilimnion, and δt is the length of the period.

Unit 17. Total organic load.

Total primary production (P_{prim}) is the sum of primary and allocthonous production ($P_{prim}=P_l+P_a$).

Unit 18. Oxygen depletion.

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

$$(2.15)\quad V_{max} = b_{oxy,0}P_{prim}2^{\frac{T_i + 10}{10} - 1}$$

daily oxygen depletion follows a Michaelis-Menton type of equation.

$$(2.16)\quad O_{i,d} = O_{i,d-1} - \frac{V_{max}\, O_{i,d-1}}{O_{i,d-1} + 0.75}.$$

which is repeated for each day in the period. The final value is the oxygen content of the i'th strata for the period in question.

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

Unit 19. and 20. Consumer Production.

Primary consumer efficiency (E.) is a function of total carbon loading, temperature of the epilimnion, and fraction of water column oxygenated. The regression equation is:

$$(2.17)\quad E. = F_{O_2}e^{b_{eff,0}+b_{eff,1}T_1+b_{eff,2}T_1^2+b_{eff,3}P_{prim}}$$

where T_l is the average temperature of the epilimnion, P_{prim} is total organic load and F_{O2} is the fraction (by volume) of the reservoir above 1.5 mg/l oxygen.

Productivity of the primary consumers is divided into four guilds cross classified as suspension feeders vs. deposit feeders and vertebrate vs. invertebrate species. The fraction of productivity that is suspension feeders is

$$(2.18)\quad F_{susp} = .95 - e^{b_{susp.1}D_{bar}}$$

where D_{bar} is the mean depth of the lake. The fraction of vertebrate suspension feeders is

$$(2.19)\quad F_{shad} = .9\ (1 - e\ \frac{b_{shad}P_{prim}}{D_{bar}})$$

In this equation P_{prim}/D_{bar} expresses productivity per volume rather than area. The fraction of deposit feeders that are vertebrate (F_{carp}) is defined as 0.9.

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

$$
(2.20)\quad
\begin{aligned}
P_{shad} &= P_{prim}\ E_{.}\ F_{susp}\ F_{shad}\\
P_{zoopl} &= P_{prim}\ E_{.}\ F_{susp}\ (1-F_{shad})\\
P_{carp} &= P_{prim}\ E_{.}\ (1-F_{susp})0.9\\
P_{ben} &= P_{prim}\ E_{.}\ (1-F_{susp})0.1
\end{aligned}
$$

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

The biomass of vertebrates is known from the population model or initial conditions. Using the function for determining maximum production described later the maximum productivity of vertebrates is known. If the productions above exceed these maximums, the productivities are adjusted so that the vertebrate productivity (P_{shad} and P_{carp}) are at maximum and the respective invertebrates guild receive the excess.

Units 21 and 22. Invertivores.

Zooplanktivore and benthivore productivity (P_{zvore} and P_{bvore}) is a product of the ecological efficiency described above (E.) and the productivity of the respective feeding category.

$$P_{zvore} = P_{zoopl}\, E. \text{ and}$$
$$P_{bvore} = P_{ben}\, E. \tag{2.21}$$

Unit 23 Piscivore productivity.

The source of piscivore productivity is the four other vertebrate guilds. The pathway between primary vertebrate consumers and piscivores is modified based on their productivity. This modification is a fraction reduction in efficiency expressed as:

$$F_{fish} = 1 - b_{fish,0}(P_{shad}+P_{carp}). \tag{2.22}$$

Piscivore productivity is described as

$$P_{pisc} = (P_{zvore}+P_{bvore})E. + (P_{shad}+P_{carp})F_{fish}E. \tag{2.23}$$

Unit 24 Total production by habitat.

Total production is expressed as total carbon per habitat per time period. It is found by multiplying the productivity computed above with the duration of the time period and proper habitat size. The habitat size is surface area for bottom dwelling organisms and volume for suspension feeders. For example; production of benthivores in the littoral zone is expressed as $P_{bvore}\delta t S_{littoral}$ where δt is the length of the period in question and the production of zooplanktivores is $P_{zvore}/D_{bar}\delta t V_{littoral}$. P/D_{bar} expresses productivity per volume rather than areally.

Biology - Population

Overview

The population submodel tracks the numbers and biomass ($N_{s,x,t}$ and $B_{s,x,t}$) of the fish populations occurring in the basin at the end of period t. Each population cell is indexed by species (s) and age class (x). An age x fish is defined as being born during the calendar year y-x+1 if y is the calendar year associated with t. Each population cell is considered to belong to some lifestage of the population indicating the different trophic relationships an individual passes through its lifetime. The larval lifestage represents the first semi-season of an individual's existence and their numbers are represented by $N_{s,yos,t}$. Surviving larval fish are recruited into the juvenile (juv) lifestage which lasts to the beginning of the next calendar year (i.e $x=0$). All of the cells (e.g. $N_{s,x,t}$, $x>0$) represent adult fish.

Unit 27. Production Partitioning.

The result of the production model is total production by feeding guild and habitat without regard to the composition of fish in the reservoir. Let $P^*hi_{,g,t}$ be the total production occurring in the h'th habitat and g'th feeding guild (a production guild) during the t'th time period expressed as total wet weight of fish flesh. Let $G_{s,x,t}$ and $G_{s,yos,t}$ be total production of the population cells. This submodel is responsible for allocating the previously calculated potential production (P^*'s) into a realized production in each population cell. The allocation is proportional to the maximum growth rate of each population cell weighted by an interaction coefficient. The maximum production of a population cell depends on the lifestage, total mass, and (with adults) the mean size of an individual within the cell. The equations

$$
\begin{aligned}
& G_{max,s,yos,t} &&= \delta t\, b_{yospb,s}\, N_{s,eggs,t}\, S_{spawn,s}\, b_{wtyos,s}, \\
(2.24)\quad & G_{max,s,0,t} &&= \delta t\, b_{juvpb,s}\, B_{s,0,t-1}, \text{ and} \\
& G_{max,s,x,t} &&= B_{s,x,t-1}\, \delta t\, b_{ptob,0}\, e^{b_{ptob,1} W_{s,x,t-1}} \\
& && \qquad \text{for all } x > 0
\end{aligned}
$$

define the maximum production for each cell. The value $W_{s,x,t-1}$ is the mean weight of the of the age class in the previous time period ($B_{s,x,t-1}/N_{s,x,t-1}$) and δt is the length of the period. The mean weight of the larval fish at the beginning of the period is a constant $b_{wtyos,s}$ and the term $N_{s,eggs,t}\, S_{spawn,s}\, b_{wtyos,s}$ is the total weight of the larval fish at the beginning of the period (see units 32-34). The number of larval fish alive at the beginning of the period is described below.

The fraction of production in the g,h'th production guild that goes into each population cell is based on the logistic relationship:

$$
\begin{aligned}
& Q_{s,yos,g,h,t} &&= \frac{b_{comp,yos,s,h,g}\; G_{max,s,yos,t}}{Q^{*}_{\cdot,\cdot,g,h,t}}, \\
(2.25)\quad & Q_{s,0,g,h,t} &&= \frac{b_{comp,juv,s,h,g}\; G_{max,s,0,t}}{Q^{*}_{\cdot,\cdot,g,h,t}}, \text{ and} \\
& Q_{s,x,g,h,t} &&= \frac{b_{comp,adult,s,h,g}\; G_{max,s,x,t}}{Q^{*}_{\cdot,\cdot,g,h,t}} \quad \text{for all } x>0
\end{aligned}
$$

The sum of the $Q_{s,l,g,h,t}$ across all populations and age classes and within production categories must sum to 1 hence the denominator for the above equations is the sum

$$Q^{*}_{...,g,h,t} = b_{comp,yos,s,h,g}G_{max,s,yos,t} + b_{comp,juv,s,h,g}G_{max,s,0,t} + \Sigma \sum_{x=1}^{n_{age}} b_{comp,adult,s,h,g}G_{max,s,x,t}$$

Production for each lifestage is then:

(2.26)

$$G_{s,yos,t} = \sum_{h} \sum_{g} Q_{s,yos,h,g,t} P^{*}g_{,h,t}$$

$$G_{s,x,t} = \sum_{h} \sum_{g} Q_{s,x,h,g,t} P^{*}g_{,h,t} \qquad \text{for all } x = 0,1,2,3 \ldots n_{age}$$

where $P^{*}g_{,h,t}$ is the total production of the h'th habitat and g'th guild during the period.

This method does not guarantee that some population cells will not exceed their maximum production rate. The G's are compared to the G_{max}'s. If any population cell exceeds its maximum growth rate, the cell is set to maximum and the excess is distributed to other populations in a manner like above.

Unit 32 Fecundity.

The number of eggs a female will lay is a power function of the mean weight of the age class. The function for total number of eggs for species s at time t is:

$$(2.27)\ N_{eggs,s,t} = \sum_{x:W_{s,x}>b_{mat,s}} b_{seas,s,t} b_{sex,s} N_{s,x,t-1} b_{fec,0} W_{s,x}^{\,b_{fec,1}}$$

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 season associated with t and the parameter $b_{sex,s}$ is the sex ratio of the population.

Unit 33. Egg survivorship.

The survivorship of the spawn is a linear function of water level fluctuation or

$$(2.28) \quad S_{spawn,s,t} = b_{wlfl,s,0} + b_{wlfl,s,1} \delta E_t$$

where δE_t is the absolute value of the net change in water elevation during 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.

Unit 34 Larval growth and survivorship.

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

$$(2.29) \quad b_{rec,s} = 1 + \frac{G_{yos,s}}{z\, B_{yos,s}} (1-e^{-z})$$

with respect to z. This z (say, $Z_{yos,s}$), when put in the survivorship and growth equations will result in an individual growth rate $b_{rec,s}$. The number of larval fish at the end of the period is the product

$$(2.30) \quad N_{s,yos,t} = N_{s,eggs,t}\, S_{spawn,s,t}\, e^{-Z_{s,yos,t}}$$

The biomass of the $N_{s,yos,t}$ is

$$(2.31) \quad B_{s,yos,t} = N_{s,yos,t}\, b_{wtyos,s}\, b_{rec,s}$$

since the growth weight and initial weight are the constants $b_{rec,s}$ and $b_{wtyos,s}$. Growth and survivorship of juveniles operate like adults (see unit 37).

Unit 35. Recruitment to adults.

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

$$(2.32)\quad p_{s,0,t} = 1 - \Phi \left[\frac{b_{wtjuv,s} - W_{s,0,t}}{0.25 W_{s,0,t}} \right]$$

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 $\Phi()$ 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

$$(2.33)\quad B_{s,0,t'} = B_{s,0,t} \left[p_{s,0,t} + \frac{1}{4\sqrt{2\pi}} e^{-\frac{1}{2}\left[\frac{bwtjuv,s - w_{s,o,t}}{0.25 W_{s,o,t}} \right]} \right]$$

In this equation, the subscript t' denotes the instant after truncation takes place and $p_{s,0,t}$ is defined in the above equation.

Unit 37 Survivorship and growth.

The change in numbers and biomass is based on a constant survivorship and the growth calculated earlier (equation 2.26). Larval fish are recruited into the juvenile age class at the end of the period. The equations are:

$$N^{*s}_{,0,t} = N_{s,0,t-1}e^{b_{z,s}\delta t} + N_{YOS,s,t} \tag{2.34}$$

$$B^{*s}_{,0,t} = B_{s,0,t-1}e^{b_{z,s}\delta t} + \frac{G_{s,0,t}}{b_{z,s}\delta t}\,[e^{b_{z,s}\delta t} -1] + B_{YOS,s,t}$$

and

$$N^{*s}_{,x,t} = N_{s,x,t-1}e^{b_{z,s}\delta t} \tag{2.35}$$

$$B^{*s}_{,0,t} = B_{s,x,t-1}e^{b_{z,s}\delta t} + \frac{G_{s,x,t}}{b_{z,s}\delta t}\,[e^{b_{z,s}\delta t} -1]$$

where δt is the length of the time period.

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 function 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 $L_{s,x,t}$ 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 period there does not exist a strata that is within these constraints a (large) fraction ($b_{s,refuge}$) of the population will die. This is done during the middle of each season.

Angling, also, may change the total weight and size of certain population cells. This is described next.

Unit 39a. Unconstrained Angler harvest.

The number of fish caught ($Y_{s,x}$) follows a typical catch-per-unit-effort formulation where the instantaneous catch rate is the product of catchability and effort expended. Catchability of a population ($K_{s,t}$) is inversely proportional to the mean weight of the population or

$$(2.36)\ K_{s,t} = b_{ctblty,s} \frac{\sum\limits_{x:L_{s,x,t}>b_{mnctch,s}} N^{*}si_{,x,t}}{\sum\limits_{x:L_{s,x,t}>b_{mnctch,s}} B^{*}s,_{,x,t}}$$

where $b_{ctblty,s}$ is a species specific coefficient. The sum of the $N^{*}_{s,x,t}$ and $B^{*}_{s,x,t}$ is over all age classes that are above a species specific minimum size catchable ($b_{mnctch,s}$). Fish populations that are not catchable (e.g. shad) have a large value for this coefficient, effectively removing them from the fishable population. The fraction of total effort directed at the population is proportional to the population's contribution to the total weight of the fishable population. The effort expended for a particular population ($A_{s,t}$) is expressed as

$$(2.38)\ A_{s,t} = \frac{\sum\limits_{x:L_{s,x,t}>b_{mnctch,s}} B^{*}_{s,x,t}}{\sum\limits_{s} \sum\limits_{x:L_{s,x,t}>b_{mnctch,s}} B^{*}_{s,x,t}} A_{,t}$$

where $A_{.,t}$ is the total effort for the period expressed as angler days.

Instantaneous catch for each population is the product

$F_{s,t} = K_{s,t}\, A_{s,t}$.

Unit 41.a Harvest regulations.

There are two types of regulations which reduce the unconstrained catch. Length regulations limit the creel to certain length classes. The model compares the mean length of each age class to the length regulations. If the mean length in that class is illegal, the age class is excluded from the catch. The unconstrained catch per age class is represented by the equation

$$(2.37)\quad Y^{*}s_{,x,t} = \begin{cases} N_{s,x,t}\,[1-e^{-F_{s,t}}] & \text{if } L_{s,x} \text{ is legal} \\ 0 & \text{otherwise.} \end{cases}$$

This catch can be further reduced by a number limit. The unconstrained catch per angler day is assumed to have a poison distribution. The maximum harvest for any one angler day is the creel limit (i.e. the number of creels = $A_{s,t}$). Catch per creel for a population is

$$(3.39)\quad C^{*s}_{,t} = \frac{\sum_{x} Y^{*}so_{,x,t}}{A_{s,t}}$$

The actual expected catch per creel is the sum of the unconstrained catch per creel if the creel is not over the limit and the creel limit if the unconstrained creel is over the creel limit times the probability of each catch. Since this is distributed poissonly,

$$(2.40)\quad C_{s,t} = \sum_{i=0}^{R_{limit,s}-1} i \frac{e^{-C^*_{s,t}} \, {C^*_{s,t}}^{i}}{i!} + \sum_{i=R_{limit,s}}^{\infty} R_{limit,s} \frac{e^{-C^*_{s,t}} \, {C^*s_{,t}}^{i}}{i!}$$

where $R_{limit,s}$ is the limit of number of fish per creel.

Actual yield is reduced by the fraction $C_{s,t}/C^*si_{,t}$ i.e.

$$(2.41)\quad Y_{s,x,t} = Y^*xl_{,x,t} \frac{C_{s,t}}{C^*_{s,t}}.$$

Unit 41b. Stocking.

The model user can also manipulate the populations by stocking fish. Stocking for the time period t occurs at the end of the time period. 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 adults. Since the mean weight of this is $b_{wtyos,s}b_{rec,s}$, 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 in unit 38 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).

Unit 38b Fishing mortality.

The catch calculated above represents the catch during the time period in question. The numbers of fish alive at the end of the period may be adjusted due to the fishing pressure. The numbers at time t computed previously($N^*s_{,x,t}$) represent the numbers loss if only natural mortality was operating. Actual instantaneous mortality is of the form

(2.41) $Z_{s,t} = \text{MAXIMUM}(M, F + b_{CTCOMP,s} M)$

where

$$M = -\ln\left[\frac{N^*s1_{,x,t}}{N_{s,x-1,t-1}}\right]$$

and

$$F = -\ln\left[\frac{N_{s,x-1,t-1} - Y_{s,x,t}}{N_{s,x-1,t-1}}\right]$$

M and F are the force of mortality from natural and angling respectively. The parameter $b_{CTCOMP,s}$ changes the degree of compensation between the two sources of mortality and is explained in the text. The numbers and biomass at the end of period t is

$$N_{s,x,t} = N_{s,x-1,t-1}\, e^{-Z_{s,t}} \tag{2.42}$$

and

$$B_{s,x,t} = \frac{B^*s_{,x,t}}{N^*si_{,x,t}} N_{s,x,t}. \tag{2.43}$$

Table A3. Values of coefficients used in reservoir production model.

$b_{depth},0$	4.95
$b_{depth},1$	-0.015
$b_{air}t,0$	24.82
$b_{airt},1$	11.32
$b_{airt,2}$	0.002404
$b_{t,o}$	0.05
$b_{t,1}$	0.03167
$b_{s,0}$	0.43
$b_{s,1}$	-0.3665
$b_{n,1}$	-6.1087
$b_{X,2}$	-2.9185
$b_{X,1}$	-0.11585
bp_{conv}	0.09524
$b_{clag,1}$	0.11
$b_{clag,0}$	0.075
$b_{oxy,0}$	0.2
$b_{eff,0}$	-3.659
$b_{eff},1$	0.168
$b_{eff},2$	-0.003
$b_{eff,3}$	-0.029
$b_{susp,1}$	-0.75
b_{shad}	-2.3
$b_{fish,0}$	-13.6875

Table A4. Definitions of variables in reservoir production model with units used

D_1	Depth at 1% light transmission (meters)
S	Suspended Sediments (g/l)
D_0	Depth of .01% light transmission (meters)
T_a	Ambient air temperature (degrees centigrade)
D_t	Julienne day
E_t	Surface elevation (feet)
V_i	Volume of i'th stratum (acre-feet)
V_{in}	Volume of inflow (acre-feet)
T_{in}	Temperature of inflowing water (degrees C.)
T_i	Temperature of i'th stratum (degrees C.)
O_{in}	Oxygen concentration of incoming water (g/l)
O_i	Oxygen concentration of the i'th stratum (g/l)
V_{out}	Oxygen concentration of inflowing water (g.l)
T_{out}	Temperature of outflow (degrees C.)
O_{out}	Oxygen concentration of outflowing water(mg/l)
S_T	Total surface area (acres)
S_1	Surface area at D_1 (acres)
S_0	Surface area at D_0 (acres)
$S_{littoral}$	Surface area of littoral zone (acres)
$S_{limnetic}$	Surface area of limnetic zone (acres)
$S_{sublittoral}$	Surface area of sublittoral zone (acres)
$S_{pelagic}$	Surface area of pelagic zone (acres)
$S_{profundal}$	Surface area of profundal zone (acres)
V_T	Total Volume (acre-feet)
V_1	Volume at D_1 (acre-feet)
V_0	Volume at D_0 (acre-feet)
$V_{littoral}$	Volume of littoral zone (acre-feet)
$V_{limnetic}$	Volume of limnetic zone (acre-feet)
$V_{sublittoral}$	Volume of sublittoral zone (acre-feet)
$V_{pelagic}$	Volume of pelagic zone (acre-feet)
$V_{profundal}$	Volume of profundal zone (acre-feet)
E_t	Elevation at time t (feet)
T	Temperature (centigrade)
E_s	Reduction in efficiency due to suspended solids
E_n	Reduction in efficiency due to nutrient
N	Limiting nutrient (mg/l)
X	Exchange rate (days)
E_X	Reduction of efficiency due to exchange rate
E_1	Total reduction in efficiency
E_m	Maximum efficiency
C_{avail}	Allocthonous carbon available (mg/l)
P_a	Allocthonous productivity (g/m2/day)
δt	Length of time period
P_{prim}	Primary productivity (g/m2/day)

Table A4. (Cont'd.)

V_{max}	Maximum productivity
E.	Total efficiency
F_{O2}	Fraction water column with O > 1.5 mg/l
F_{susp}	Fraction of primary consumers that are suspension feeders
D_{bar}	Mean depth (meters)
F_{shad}	Fraction of vertebrate suspension primary consumers
P_{shad}	Productivity of vertebrate suspension primary consumers (gr/m2/day)
P_{zoopl}	Productivity of invertebrate suspension feeders (g/m2/day)
P_{carp}	Production of vertebrate bottom feeder (gr/m2/day)
P_{ben}	Productivity of invertebrate bottom feeders (gr C./m2/day)
P_{zvore}	Productivity of suspension feeding secondary consumers (gr/m2/day)
P_{bvore}	Productivity of bottom feeding secondary consumers(gr/m2/day)
F_{fish}	Fraction reduction in piscivore efficiency
P_{pisc}	Productivity of piscivores (g/m2/day)
$N_{s,yos,t}$	Number of larval species s at time t
$N_{s,x,t}$	Number of species s and age class x at time t
$P^{*}he_{,g,t}$	Total production of the h'th habitat and g'th guild during period t (kg wet weight)
$G_{s,x,t}$	Total growth of the $N_{s,x,t}$ during time period t (kg wet weight)
$G_{s,yos,t}$	Total growth of the $N_{s,yos,t}$ during time period t (kg wet weight)
$G_{max,s,yos,t}$	Maximum growth of the $N_{s,yos,t}$ during time period t (kg. wet weight)
$N_{s,eggs,t}$	Number of eggs produced by species s during time t
$S_{spawn,s}$	Survivorship of the Ns,eggs,t
$B_{s,x,t}$	Biomass of the $N_{s,x,t}$ (kg. wet weight)
$W_{s,x,t-1}$	Mean weight of the $N_{s,x,t}$ (kg. wet weight)
$G_{max,s,x,t}$	Maximum growth of the $N_{s,x,t}$ (kg. wet weight)
$S_{eggs,s}$	Survivorship of the eggs (kg. wet weight)
δE_t	Change in elevation in reservoir during time t (feet) $S_{s,x,t}$survivorship of the
$S_{s,x,t}$	Survivorship of the $N_{s,x,t}$
$Y_{s,x,t}$	Number of $N_{s,x,t}$ caught by anglers
$F_{s,t}$	Instaneous angler harvest
A_t	Number of angler days
$Y^{*}so_{,x,t}$	Unconstrained angler harvest
$N_{creel,s,t}$	Number of creel limits directed at species s
$C^{*}sa_{,t}$	Unconstrain catch of the s'th species in period t
$R_{limit,s}$	The daily bag limit for species s
$C_{s,t}$	Actual catch of species s
$Z_{s,t}$	Total mortality of the s'th fish during period t

Table A5. Population model parameters

TEMPERATURE /OXYGEN CONSTRAINTS

SPECIES	MAX. T	MIN. T	MIN O2
Largemouth B	100.00	.00	.00
White Bass	100.00	.00	.00
Walleye	100.00	.00	.00
Sunfish	100.00	.00	.00
Crappie	100.00	.00	.00
Catfish	100.00	.00	.00
Northern Pike	100.00	.00	.00
Rainbow Trout	24.00	.00	4.00
Brown Trout	24.00	.00	4.00
Kokanee Salmon	24.00	.00	4.00
Lake Trout	24.00	.00	4.00
Smallmouth B	100.00	.00	.00
Striped Bass	100.00	.00	.00
Longnose Gar	100.00	.00	.00
Bullhead	100.00	.00	.00
Yellow Perch	100.00	.00	.00
Carp and Sucker	100.00	.00	.00
White Sucker	100.00	.00	.00
Gizzard Shad	100.00	.00	.00
Threadfin Shad	100.00	7.00	.00
Golden Shine	100.00	.00	.00
Cyprinids	100.00	.00	.00
Smelt	100.00	.00	.00
Crayfish	100.00	.00	.00

COMPETITION COEFFICIENTS

GUILD IS : BENTHIC EAT

SPECIES/LST	LITTORAL	LIMNETIC	SUBLITTOR	PELAGIC	PROFUNDAL
Largemouth B					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
White Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Walleye					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Sunfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.900	.000	.000	.000	.000
Crappie					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.200	.000	.800	.000	.000
Catfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.067	.000	.400	.000	.400
ADULT	.067	.000	.400	.000	.400
Northern Pik					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Rainbow trou					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.500	.200	.200	.100	.000
ADULT	.500	.100	.300	.100	.000
Brown Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.500	.200	.200	.100	.000
ADULT	.500	.100	.300	.100	.000
Kokanee Salm					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.125	.000	.125	.000	.000
Lake Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.300	.700	.000	.000
ADULT	.000	.000	.080	.000	.000
Smallmouth B					
LARVAL	.000	.000	.000	.000	.000

JUVENILE	.800	.000	.200	.000	.000
ADULT	.160	.000	.040	.000	.000
Striped Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.125	.000	.025	.000	.000
ADULT	.000	.000	.000	.000	.000
Longnose Gar					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Bullhead					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.800	.000	.200	.000	.000
ADULT	.800	.000	.200	.000	.000
Yellow Perch					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.700	.000	.000	.000	.000
ADULT	.700	.000	.000	.000	.000
Carp and Suc					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.600	.000	.400	.000	.000
White Sucker					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.500	.000	.500	.000	.000
ADULT	.500	.000	.500	.000	.000
Gizzard Shad					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Threadfin Sh					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Golden Shine					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.080	.020	.000	.000	.000
ADULT	.400	.100	.000	.000	.000
Cyprinids					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.050	.000	.050	.000	.000
Smelt					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.050	.000	.050	.000	.000
ADULT	.050	.000	.050	.000	.000
Crayfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.100	.000	.100	.000	.000
ADULT	.100	.000	.100	.000	.000

GUILD IS : ZOOPL EATER

SPECIES/LST	LITTORAL	LIMNETIC	SUBLITTOR	PELAGIC	PROFUNDAL
Largemouth B					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
White Bass					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.025	.008	.008	.008	.000
ADULT	.000	.000	.000	.000	.000
Walleye					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Sunfish					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.100	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Crappie					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.100	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Catfish					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.007	.000	.040	.000	.040
ADULT	.000	.000	.000	.000	.000
Northern Pik					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Rainbow trou					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.250	.100	.100	.050	.000
ADULT	.000	.000	.000	.000	.000
Brown Trout					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.150	.060	.060	.030	.000
ADULT	.000	.000	.000	.000	.000
Kokanee Salm					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.125	.000	.125	.000	.000
ADULT	.250	.250	.250	.250	.000
Lake Trout					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.000	.150	.350	.000	.000
ADULT	.000	.000	.000	.000	.000
Smallmouth B					
LARVAL	.200	.200	.200	.200	.200

JUVENILE	.400	.000	.100	.000	.000
ADULT	.000	.000	.000	.000	.000
Striped Bass					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.250	.250	.250	.250	.000
ADULT	.000	.000	.000	.000	.000
Longnose Gar					
LARVAL	1.000	.000	.000	.000	.000
JUVENILE	.500	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Bullhead					
LARVAL	.800	.000	.200	.000	.000
JUVENILE	.800	.000	.200	.000	.000
ADULT	.160	.000	.040	.000	.000
Yellow Perch					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.280	.000	.000	.000	.000
ADULT	.070	.000	.000	.000	.000
Carp and Suc					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.500	.000	.000	.000	.000
ADULT	.120	.000	.080	.000	.000
White Sucker					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.100	.000	.100	.000	.000
ADULT	.000	.000	.000	.000	.000
Gizzard Shad					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Threadfin Sh					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Golden Shine					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.800	.200	.000	.000	.000
ADULT	.560	.140	.000	.000	.000
Cyprinids					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Smelt					
LARVAL	.200	.200	.200	.200	.200
JUVENILE	.250	.250	.250	.250	.000
ADULT	.125	.125	.125	.125	.000
Crayfish					
LARVAL	1.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000

GUILD IS : PISCIVORES

SPECIES/LST	LITTORAL	LIMNETIC	SUBLITTOR	PELAGIC	PROFUNDAL
Largemouth B					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.900	.000	.100	.000	.000
White Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Walleye					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.200	.100	.500	.200	.000
ADULT	.200	.100	.500	.200	.000
Sunfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Crappie					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Catfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Northern Pik					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.800	.200	.000	.000	.000
Rainbow trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.250	.050	.150	.050	.000
Brown Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.050	.020	.020	.010	.000
ADULT	.500	.100	.300	.100	.000
Kokanee Salm					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.050	.050	.050	.050	.000
Lake Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.060	.140	.000	.000
ADULT	.000	.200	.400	.400	.000
Smallmouth B					
LARVAL	.000	.000	.000	.000	.000

JUVENILE	.400	.000	.100	.000	.000
ADULT	.800	.000	.200	.000	.000
Striped Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.125	.125	.125	.125	.000
ADULT	.250	.250	.250	.250	.000
Longnose Gar					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	1.000	.000	.000	.000	.000
ADULT	.500	.000	.000	.000	.000
Bullhead					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Yellow Perch					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.280	.000	.000	.000	.000
ADULT	.140	.000	.000	.000	.000
Carp and Sucker					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
White Sucker					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Gizzard Shad					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Threadfin Sh					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Golden Shine					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Cyprinids					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Smelt					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.050	.050	.050	.050	.000
ADULT	.100	.100	.100	.100	.000
Crayfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000

GUILD IS : PHYTO EATER

SPECIES/LST	LITTORAL	LIMNETIC	SUBLITTOR	PELAGIC	PROFUNDAL
Largemouth B					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
White Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Walleye					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Sunfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Crappie					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Catfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Northern Pike					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Rainbow trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Brown Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Kokanee Salm					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Lake Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Smallmouth B					
LARVAL	.000	.000	.000	.000	.000

JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Striped Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Longnose Gar					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Bullhead					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.160	.000	.040	.000	.000
Yellow Perch					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Carp and Suc					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.500	.000	.000	.000	.000
ADULT	.600	.000	.400	.000	.000
White Sucker					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Gizzard Shad					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Threadfin Sh					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Golden Shine					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Cyprinids					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Smelt					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Crayfish					
LARVAL	1.000	.000	.000	.000	.000
JUVENILE	.500	.000	.500	.000	.000
ADULT	.500	.000	.500	.000	.000

GUILD IS : DETRITIVORE

SPECIES/LST	LITTORAL	LIMNETIC	SUBLITTOR	PELAGIC	PROFUNDAL
Largemouth B					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
White Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Walleye					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Sunfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Crappie					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Catfish					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Northern Pik					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Rainbow trou					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Brown Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Kokanee Salm					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Lake Trout					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Smallmouth B					
LARVAL	.000	.000	.000	.000	.000

JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Striped Bass					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Longnose Gar					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Bullhead					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.160	.000	.040	.000	.000
Yellow Perch					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Carp and Suc					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.500	.000	.000	.000	.000
ADULT	.600	.000	.400	.000	.000
White Sucker					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Gizzard Shad					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Threadfin Sh					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.250	.250	.250	.250	.000
ADULT	.250	.250	.250	.250	.000
Golden Shine					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Cyprinids					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Smelt					
LARVAL	.000	.000	.000	.000	.000
JUVENILE	.000	.000	.000	.000	.000
ADULT	.000	.000	.000	.000	.000
Crayfish					
LARVAL	1.000	.000	.000	.000	.000
JUVENILE	.500	.000	.500	.000	.000
ADULT	.500	.000	.500	.000	.000

MAXIMUM P/B RATIOS

SPECIES	$b_{ptob,0}$	$b_{ptob,1}$	b_{yospb}	bjuvp	b_z
Largemouth B	4.06	-1.00	10.00	5.00	-.54
White Bass	2.24	-5.00	10.00	5.00	-.68
Walleye	4.06	-1.00	10.00	5.00	-.47
Sunfish	3.82	-2.25	10.00	5.00	-.74
Crappie	2.24	-5.00	10.00	5.00	-.70
Catfish	4.22	- .80	10.00	5.00	-.22
Northern Pike	2.94	- .78	10.00	5.00	-.42
Rainbow Trout	5.21	-1.86	10.00	5.00	-.75
Brown Trout	5.00	-1.86	10.00	5.00	-.75
Kokanee Salmon	5.00	-8.00	10.00	5.00	-1.00
Lake Trout	3.00	-3.00	10.00	5.00	-.40
Smallmouth B	4.00	-2.00	10.00	5.00	-.60
Striped Bass	5.00	-2.00	10.00	5.00	-.91
Longnose Gar	4.00	-1.00	10.00	5.00	-.20
Bullhead	2.00	-5.00	10.00	5.00	-.91
Yellow Perch	3.50	-5.00	10.00	5.00	-.70
Carp and Sucker	4.00	-2.00	10.00	5.00	-.20
White Sucker	3.00	-1.00	10.00	5.00	-.51
Gizzard Shad	4.50	-8.00	10.00	5.00	-1.00
Threadfin Shad	4.50	-8.00	10.00	5.00	-1.35
Golden Shiner	4.00	-5.00	10.00	5.00	-1.10
Cyprinids	4.00	-10.00	10.00	5.00	-1.20
Smelt	4.00	-5.00	10.00	5.00	- .91
Crayfish	4.00	-20.00	10.00	5.00	- .40

FECUNDITY PARAMETERS

SPECIES	$b_{seas,t}$ fa	wi	sp	su	b_{sex}	b_{mat}
Largemouth B	.00	.00	1.00	.00	.5	.240
White Bass	.00	.00	1.00	.00	.5	.265
Walleye	.00	.00	1.00	.00	.5	.430
Sunfish	.00	.00	.50	.50	.5	.015
Crappie	.00	.00	1.00	.00	.5	.050
Catfish	.00	.00	.00	1.00	.5	.510
Northern Pike	.00	1.00	.00	.00	.5	1.700
Rainbow trout	.00	.00	.00	.00	.5	.200
Brown Trout	.00	.00	.00	.00	.5	.200
Kokanee Salmon	.00	.50	.50	.00	.5	.200
Lake Trout	.00	.50	.50	.00	.5	.300
Smallmouth Bass	.00	.00	.70	.30	.5	.250
Striped Bass	.00	.00	.00	.00	.5	.500
Longnose Gar	.00	.00	.20	.80	.5	.300
Bullhead	.00	.00	.30	.70	.5	.280
Yellow Perch	.00	.00	1.00	.00	.5	.150
Carp and Suc	.00	.00	.60	.40	.5	.250
White Sucker	.00	.00	1.00	.00	.5	.250
Gizzard Shad	.00	.00	.60	.40	.5	.200
Threadfin Sh	.00	.00	.30	.70	.5	.100
Golden Shine	.00	.00	.70	.30	.5	.003
Cyprinids	.00	.00	.80	.20	.5	.002
Smelt	.00	.00	1.00	.00	.5	.100
Crayfish	.00	.00	1.00	.00	.5	.020

FECUNDITY PARAMETERS (cont'd)

SPECIES	b_{wtyos}	$b_{fec,0}$	$b_{fec,1}$	$b_{wlfl,0}$	$b_{wlfl,1}$
Largemouth Bass	.0025	32000	1.00	1.0434	-.086950
White Bass	.0025	2000000	1.00	1.0434	-.086950
Walleye	.0025	100000	1.00	1.0714	-.071430
Sunfish	.0500	200000	1.00	1.0213	-.042550
Crappie	.0500	300000	1.00	1.0714	-.071430
Catfish	.0025	6000	1.00	1.1111	-.055500
Northern Pike	.0025	35000	1.00	1.0434	-.173900
Rainbow trout	.0025	5000	1.00	1.0000	.000000
Brown Trout	.0025	5000	1.00	1.0000	.000000
Kokanee Salmon	.0025	1500	1.00	1.0000	.000000
Lake Trout	.0025	6000	1.00	1.1000	-.055000
Smallmouth Bass	.0025	20000	1.00	1.0600	-.070000
Striped Bass	.0025	200000	1.00	1.0000	.000000
Longnose Gar	.0025	5000	1.00	1.0430	-.086000
Bullhead	.0025	19000	1.00	1.0400	-.086900
Yellow Perch	.0025	250000	1.00	1.0210	-.425500
Carp and Suc	.0025	250000	1.00	1.0430	-.869500
White Sucker	.0025	100000	1.00	1.0430	-.869000
Gizzard Shad	.0025	400000	1.00	1.1500	-.050000
Threadfin Sh	.0025	400000	1.00	1.1500	-.050000
Golden Shine	.0025	100000	1.00	1.0430	-.869500
Cyprinids	.0025	100000	1.00	1.1500	-.050000
Smelt	.0025	800000	1.00	1.0210	-.042000
Crayfish	.0050	10000	1.00	1.3000	-.050000

OTHER PARAMETERS

SPECIES	brec,0	b_{wtjuv}	$b_{lnwt,0}$	$b_{lnwet,1}$
Largemouth B	300.00	.6000	-5.70	3.40
White Bass	5000.00	1.5000	-5.20	3.00
Walleye	4000.00	2.1000	-4.90	3.00
Sunfish	100.00	.1000	-5.30	3.20
Crappie	50.00	.5500	-5.40	3.20
Catfish	3000.00	1.0500	-5.30	3.30
Northern Pik	5000.00	2.6000	-4.80	2.90
Rainbow trou	1000.00	.7000	-5.00	3.00
Brown Trout	1000.00	.7000	-5.00	3.00
Kokanee Salm	1000.00	.5000	-5.00	3.00
Lake Trout	1000.00	1.0000	-5.00	3.00
Smallmouth B	300.00	3.0000	-4.68	2.91
Striped Bass	3000.00	3.0000	-5.00	3.00
Longnose Gar	5000.00	1.0000	-6.00	3.00
Bullhead	1000.00	.3000	-4.71	2.92
Yellow Perch	1000.00	.0200	-5.00	3.00
Carp and Suc	5000.00	1.0000	-5.00	3.10
White Sucker	1000.00	1.7000	-4.80	2.90
Gizzard Shad	5000.00	.0100	-5.00	3.00
Threadfin Sh	5000.00	.1000	-5.00	3.00
Golden Shine	3000.00	.5000	-4.80	3.00
Cyprinids	3000.00	.5000	-4.71	2.73
Smelt	1000.00	.2000	-4.50	2.90
Crayfish	3000.00	.2000	-4.80	3.00

HARVEST MODEL PARAMETERS

SPECIES	b_{ctblty}	b_{mnctch}	b_{ctcomp}
Largemouth B	.000500	220.00	.0000
White Bass	.000400	220.00	.0000
Walleye	.000650	250.00	.0000
Sunfish	.000010	150.00	.0000
Crappie	.000060	190.00	.0000
Catfish	.000100	200.00	.0000
Northern Pik	.000500	300.00	.0000
Rainbow trou	.000450	180.00	.0000
Brown Trout	.000450	180.00	.0000
Kokanee Salm	.001000	180.00	.0000
Lake Trout	.000010	300.00	.0000
Smallmouth B	.000500	220.00	.0000
Striped Bass	.000010	300.00	.0000
Longnose Gar	.000000	99999.99	.0000
Bullhead	.000100	200.00	.0000
Yellow Perch	.000650	200.00	.0000
Carp and Suc	.000005	200.00	.0000
White Sucker	.000005	200.00	.0000
Gizzard Shad	.000000	99999.99	.0000
Threadfin Sh	.000000	99999.99	.0000
Golden Shine	.000000	99999.99	.0000
Cyprinids	.000000	99999.99	.0000
Smelt	.000001	150.00	.0000
Crayfish	.000000	99999.99	.0000

Biological Streams Model

Overview

This model determines productivity (gr C./m^2/day) of between reservoir river reaches. It uses a one kilometer segment and half month time interval as its basic unit. Simulating the entire reach involves determining productivity for every kilometer segment and doing this for every half month time period during the time frame wanted. There are three input sources that drives the model. Every reach has one file whose values are consistent throughout time. These are seasonal solar radiation, length of reach, average elevation of the first kilometer segment of the reach, whether or not carp are present, and particle size and riparian carbon loading for every kilometer segment of the reach. A "hydrology" file contains values that change during each time period which are the date of the period, number of days during the period, stream width, stream depth, river velocity, river flow,average slope, and concentrations of suspended solids, nitrogen, and phosphorus. A third file originates from the biology model of the water unit immediately upstream (river or reservoir). It contains temperature, oxygen content, and organic carbon concentration of the inflowing water for each two week period.

The model is based on a one kilometer segment and a half month (hydrology model) time step. The productivity of nine cells are computed for each segment. Before these can be computed changes in temperature and oxygen must be known. Temperature of the segment approaches ambient air temperature and oxygen content approaches saturation. In addition, a portion of the allocthonous carbon loading is exported into the next segment. It is because of these changes that the model is run for every kilometer segment. The result of the model will be a temperature, oxygen content, carbon export and system productivity for each kilometer segment and half month period.

This model integrates with downstream water bodies by providing the temperature, oxygen and carbon content of water leaving the reach and entering the reservoir or river reach immediately downstream from the reach of interest. It also provides the economic model with a measure of average game fish biomass for that segment. To save space, user output will be certain averages of these productivities.

This description will first describe how temperature, oxygen changes as you go downstream segment by segment. Then it will describe the calculations to determine productivities of the system for each kilometer segment. Carbon export into the next segment is discussed after system productivity. The last item will be interface to the user and integration with other parts of the RIOFISH model.

Model Description.

For all cases, the subscript "i" will be the index referring to the stream segment, the subscript "in" refers to the incoming water (inputs) and the subscript "out" will refer to model outputs (outgoing water). The subscript for time will be omitted since refers to a single time step. A value with no subscripts indicates that this is constant throughout the reach. The hydrology inputs are:

DATE - hydrology model's date
NDAYS - number of days during the period
WIDTH - width of stream (feet)
DEPTH - average depth (feet)
SLOPE - average slope
SS - suspended solids (mg/l)
P - phosphorus concentration (mg/l)
N - nitrogen concentration (mg/l)
VEL - velocity (ft/s)
FLOW - average river flow during period (cfs)

Temperature / oxygen model inputs are:

$TEMP_{in}$ - Temperature of water entering reach (Cent.)
OXY_{in} - Oxygen of water entering reach (mg/l)
C_{in} - Carbon content of incoming water (mg.l)

There is also a stream segment data base that has:

AMBL - seasonal ambient light radiation (Kcal/m^2/day)

note: it is assumed that the value used in the equations below is the proper seasonal value even though AMBL is not explicitly written as depending the particular time step (DATE).

YACARP - indicates if detritivore fish exist
BELEV - elevation of first kilometer segment (feet)
LEN - length of reach (kilometers)
$RIPIN_i$ - riparian load for each segment (gr C/m^2/day)
$PSIZE_i$ - particle size (mm).

River production is divided into nine cells. These are:

RET_i - allocthonous carbon retained
$PRIM_i$ - Primary production
$INVGR_i$ - invertebrate grazers
$INVDT_i$ - invertebrate detritivores
$VTDT_i$ - vertebrate detritivores
$CVTINV_i$ - cold water vertebrate invertivores
$WVTINV_i$ - warm water vertebrate invertivores
$CPISC_i$ - cold water piscivores
$WPISC_i$ - warm water piscivores

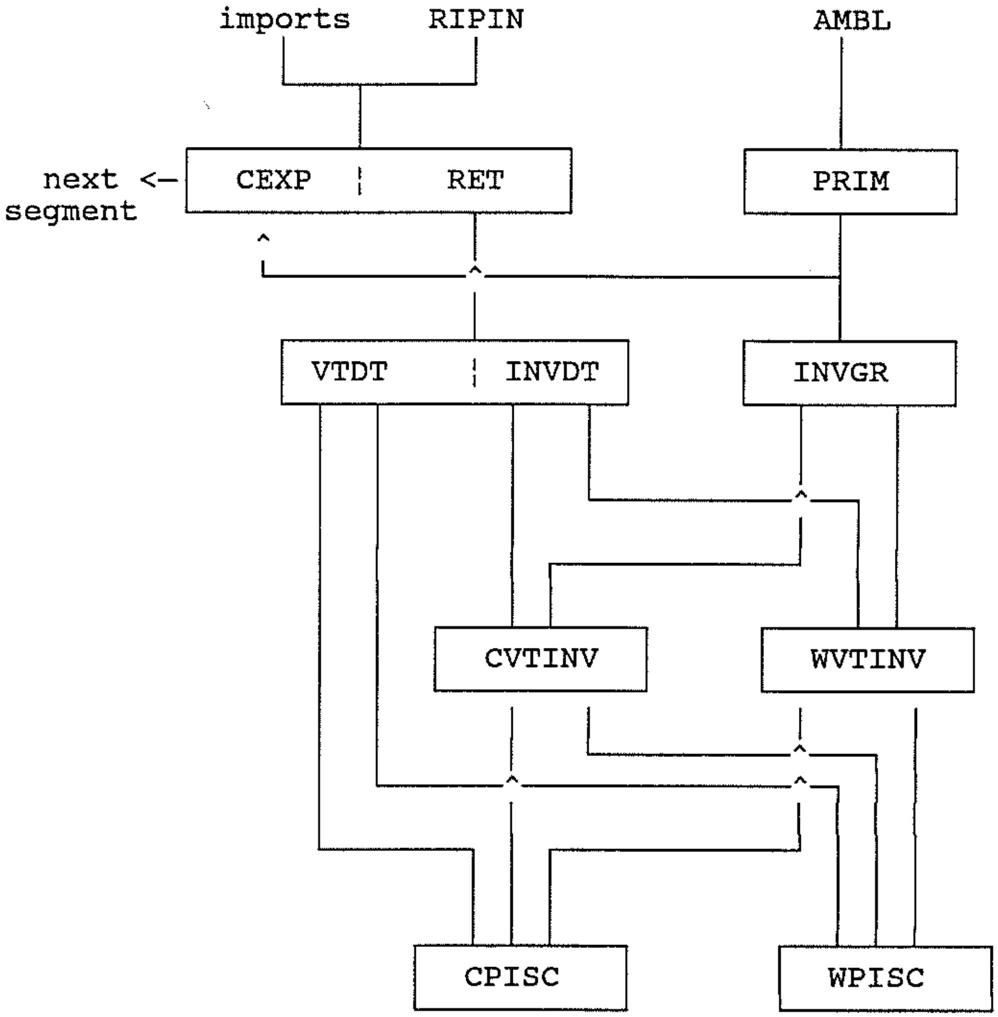
where all production values are in gr C./m^2/day. Other computed values are:

$CEXP_i$ - Carbon export (mg/l)
$ELEV_i$ - Elevation at the i'th segment (feet)
$TEMP_i$ - Temperature (centigrade)
OXY_i - oxygen content (mg/l).

Computed values used for other models in RIOFISH are:

$TEMP_{out}$ - Temperature of water leaving reach (Cent.)
OXY_{out} - Oxygen of water leaving reach (mg/l)
C_{out} - Carbon content of water leaving reach (mg.l)
ECNFSH - average biomass of fish for year (Kg/Ha/year).

The system can be represented in the following diagram:



In this diagram the lines between cells refer to efficiencies and the dashed bars separating a cell represents a fractioning of that cell into two components.

In order to compute production at a particular segment i, the change in temperature and oxygen downstream is computed. Since these approach an equilibrium based on elevation, the equations begin with the elevation at segment i. Since each segment is 3208.8 ft long elevation at segment i is

$$ELEV_i = ELEV_{i-1} - SLOPE * 3208.8$$

with the initial elevation being given as input ($ELEV_1$ = BELEV). Water temperature approaches air temperature exponentially at a rate inversely related to water velocity giving

$$TEMP_i = tamb_i - (tamb_i - TEMP_{i-1})*\exp[-334.85/VELOC]$$

where $tamb_i$ is air temperature which was described in the reservoir temperature model. It is a function of $ELEV_i$ and DATE. The value $tamb_i$ is restricted such that it is never less than freezing (0 degrees). The initial temperature, like elevation, is given as input ($TEMP_1 = TEMP_{in}$). Oxygen approaches saturation summarily. If $o2sat_i$ is the computed saturation at $ELEV_i$ and $TEMP_i$ then

$$OXY_i = o2sat_i - (o2sat_i - OXY_{i-1})*\exp[-422.45/VELOC].$$

Again, the initial oxygen value is given as input ($OXY_1 = OXY_{in}$).

Primary production in a kilometer section of river is computed as in the reservoir model ignoring exchange rate. It is then modified by the log particle size in the segment by the equation:

$$PRIM_i = P_1 * (.05 + .25*\ln(PSIZE_i))$$

where P_l is primary production computed by the reservoir model with input values $TEMP_i$,SS,P,N,AMBL, and an abnormally large exchange rate.

Allocthonous load that is retained in the segment is a fraction of the total allocthonous loading into the segment. This is export from the previous segment and riparian loading into the segment. This fraction depends on particle size and velocity by the equation:

$$CRET_i = (CEXP_{i-1}+RIPIN_i)*[1-\exp[VELOC*(5.560+0.005384*SIZE_i)]]$$

Since this value is expressed per area C_{in} must be altered to provide the initial value C_0 int the proper units. (note that the initial value is indexed as a zero). This is the total mass of carbon entering the segment divided by area of the first kilometer segment i.e. $C_0=C_{in}*FLOW/WIDTH * 8.013$ where 8.013 is a conversion from the odd mixture of units on the right hand side of the equation to gr C./m^2/day.

To describe the trophic efficiencies it will be easier to define a generalized logistic function $LOGIT3(b_0,b_1,b_2,b_3,x)$ which is the logit of a cubic function of x i.e.:

$$LOGIT3(b_0,b_1,b_2,b_3,x) = \frac{\exp[\ b_0 + b_1x + b_2x^2 + b_3x^3]}{1 + \exp[\ b_0 + b_1x + b_2x^2 + b_3x^3]}.$$

Detritivore efficiency depends on oxygen concentration through this function with a maximum efficiency of fifteen percent and is represented by the equation

$$EFFDT = 0.15*LOGIT3(-22.26,10.05,-1.586,0.088,OXY_i).$$

Grazers are represented only by invertebrates and their efficiency is related in the same way to oxygen plus it is further reduced linearly (with the restriction that it cannot be reduced past a zero efficiency) by water velocity. Invertebrate grazer efficiency is:

$$\mathrm{EFFGR} = \mathrm{EFFDT} * \mathrm{maximum}(1.0\text{-}.2032*\mathrm{VELOC}\ ,\ 0.0).$$

Total detritivore production ($(\mathrm{INVDT+VTDT})_i$)depends on oxygen through the logistic function described above.

$$(\mathrm{INVDT+VTDT})_i = \mathrm{CRET}_i * \mathrm{EFFDT}$$

This productivity is partitioned between the fish and invertebrates by a fraction depending on particle size. This fraction is:

$$\frac{\mathrm{VTDT}_i}{(\mathrm{INVDT+VTDT})_i} = \mathrm{MAXIMUM}\ (0.9 - 0.002667*\mathrm{SIZE}_i\ ,\ 0.10)$$

if vertebrate detritivores are present. This is defined as zero if they are not present. Since grazers are not partitioned their productivity is simply:

$$\mathrm{INVGR}_i = \mathrm{EFFGR} * \mathrm{PRIM}_i.$$

Cold and warm water fish efficiencies are based on oxygen content and water temperature. The efficiency of warm water fish is

$$\mathrm{EFFWM} = \mathrm{LOGIT3}(-135.683,80.784,-16.094,1.073,\mathrm{OXY}_i) * (-0.4724 + 0.05280*\mathrm{TEMP}_i - 0.002667*\mathrm{TEMP}_i^2)$$

Cold water fish efficiency is computed summarily:

$$\begin{aligned}EFFCD = {} & LOGIT3(-370.211,125.844,-22.532,1.073,OXY_i) * \\ & (-0.1774 - 0.01121*TEMP_i - 0.002667*TEMP_i^2)\end{aligned}$$

Both these efficiencies have the obvious restriction that they cannot be less than zero. Game fish cells are

$$\begin{aligned}WVTINV_i &= (INVDT_i+INVGR_i) * EFFWM \\ CVTINV_i &= (INVDT_i+INVGR_i) * EFFCD \\ WPISC_i &= (WVTDT_i+VTINV_i+CVTINV_i) * EFFWM \\ CPISC_i &= (WVTDT_i+VTINV_i+CVTINV_i) * EFFCD.\end{aligned}$$

Carbon export is comprised of allocthonous loading that was not retained and inefficiency of autochthonous carbon use (EFFGR). The equation is:

$$CEXP_i = CEXP_{i-1}+RIPIN_i-CRET_i + PRIM_i*(.9-6*EFFGR)$$

This completes the description of river <u>segment</u> production during one time period. The production of the entire reach is approximately the average of all productivities. The economic model will use the average of all game fish productivities throughout time. This is

$$ECNFSH = 83* \frac{\sum_{t=1}^{24} \sum_{i=1}^{LEN} (WVTINV_{i,t}+ CVTINV_{i,t} + WPISC_{i,t} + CPISC_{i,t})}{24 * LEN}$$

where t is the index for each hydrology time period throughout the water year (24 half month periods) and 83 is an imputed conversion factor from gr c/m^2/day production to kg/Ha/year biomass. The connections to the downstream segments are the values corresponding to the last kilometer segment modelled ($TEMP_{out}=TEMP_{LEN}$, $OXY_{out}=OXY_{LEN}$). The last carbon export, though, is expressed as a loading which is converted to a concentration by the equation:

$$CEXP_{out} = CEXP_{LEN}*WIDTH/(8.013*FLOW).$$

This equation is the inverse of the equation used above to get the initial carbon loading into the river reach.

For now, user outputs will be the arithmetical average seasonal productivity in each cell in three zones. THe first zone represents the first five kilometers of the reach the second zone represents the second ten kilometers and the last zone is the rest of the reach.

Economics

Angler Demand

The system of demands predicts average trips per kth zone angler (1) to the ith site and (2) to the aggregate of the ith site's substitute sites. The vector of trips to these two site types is specified to be:

$$\text{(1a)} \quad \mathbf{X}_{ik} = \{\beta_{XX}^{-1}\, \mathbf{P}_{ik}(\mathbf{P}_{ik}'\beta_{XX}^{-1}\mathbf{P}_{ik})^{-1}[\mathbf{P}_{ik}'\beta_{XX}^{-1}(\alpha^*_{ik}) + M_k]\} - \beta_{XX}^{-1}(\alpha^*_{ik})$$

where

$$\text{(1b)} \quad \alpha^*_{ik} \quad = \quad \alpha_X + \beta_{XQ}'Q_i + \beta_{XZ}'\mathbf{Z}_k$$

$$\mathbf{X}_{ik} = \begin{bmatrix} X_{1ik} \\ X_{2ik} \end{bmatrix} \quad \begin{array}{l} \text{predicted trips to the ith site from the kth zone} \\ \text{predicted trips to the sum of all substitutes for the ith site from the kth zone.} \end{array}$$

$$\alpha_X = \begin{bmatrix} -.83729 \\ (3.18)^{\dagger} \\ \\ 1 \\ (-)^{\dagger\dagger} \end{bmatrix}, \quad \begin{array}{l} \text{marginal utility of trip quantities of trips consumed at the ith site} \\ \\ \\ \text{marginal utilities of quantities consumed at substitute for ith site} \end{array}$$

$$\beta_{XX}^{-1} = \begin{bmatrix} -1.17096 & -5.12953 \\ (-4.63) & (-3.08) \\ & \\ -5.12953 & -39.38637 \\ (-3.08) & (-3.90) \end{bmatrix}, \quad \text{inverse of four elements in } \beta_{XX} \text{ matrix in utility function, equal to } \frac{\partial\left(\frac{\partial U}{\partial X_i}\right)}{\partial X_j} \text{ described in the utility function (4)}$$

$\dagger$ Student t-ratios, approximate

$\dagger\dagger$ Student t-ratio not defined.

$$\beta_{XQ}' = \begin{bmatrix} 6.7E^{-6} & .007889 & .001449 & 1.976 & 0.20544 & 0 \\ (15.19) & (2.00) & (1.49) & (11.77) & (7.63) & \\ & & & & & \\ 0 & 0 & 0 & 0 & 0 & 1.08E^{-5} \\ & & & & & (5.57) \end{bmatrix},$$

$\dfrac{\partial \left(\frac{\partial U}{\partial X_i}\right)}{\partial Q_i}$ elements in the utility function described in (4).

$$\beta_{XZ}' = \begin{bmatrix} 3.0126 & 9.4839 & 2.507 & 0.0105 & 11.687 & -0.0251 \\ (5.78) & (18.96) & (10.75) & (15.84) & (16.45) & (-15.37) \\ & & & & & \\ 0 & 0 & -0.038 & 0 & 1.488 & 0 \\ & & (-0.72) & & (27.86) & \end{bmatrix},$$

$\dfrac{\partial \left(\frac{\partial U}{\partial X_i}\right)}{\partial Z_j}$ elements in the utility function described in (4).

$$\mathbf{P}_{ik} = \begin{bmatrix} P_{1ik} \\ \\ \\ \\ P_{2ik} \end{bmatrix}$$

P_{1ik}: (round trip miles x travel cost/mile + entry fee) x .95; where travel cost/mile varies by year, and .95 is a calibration coefficient, including an opportunity cost of time valued at 1/2 the hourly wage.

P_{2ik}: $\sum_{i' \neq i} P_{1ik} X_{1ik}/\sum X_{1ik}$, i.e. a substitute site price, weighted observed visits to all substitutes for the ith sites $_{i' \neq i}$

M_k = recreational expenditure by the typical kth zone-of-origin angler, to the ith site and its substitutes defined by the recreational budget constraint $\mathbf{P}_{ik}'\mathbf{X}_{ik}$.

$$Q_i = \begin{bmatrix} (Q_{11i})^{.9} \\ (Q_{12i})^{.5} \\ Q_{13i} \\ Q_{14i} \\ Q_{15i} \\ Q_{21i} \end{bmatrix}$$

Q_{11}, average water volume acre feet, June-Aug, at ith site

Q_{12}, average biomass caught/hour of game fish, grams/hour, at ith site

Q_{13}, percentage shoreline accessible from a vehicle at ith site

Q_{14}, Lake Sumner (0-1) dummy

Q_{15}, number of concrete boat ramps at ith site weighted by spacing and quality factor

Q_{21}, number of average water surface acres at substitute for ith site, June - August, weighted by trips to each substitute for $i=i.'$

$$Z_k = \begin{bmatrix} Z_{1k} \\ Z_{2k} \\ Z_{3k} \\ Z_{4k} \\ Z_{5k} \\ Z_{6k} \end{bmatrix}$$

Z_1, dummy variable, kth angler zone < 15 miles from good fishing

Z_2, dummy variable, kth angler zone < 50 miles from good fishing

Z_3, dummy variable, numerous fishing substitutes at kth zone, accounts for light visitation at a site where other sites are comparatively closer.

Z_4, kth zone angler average annual expenditures on equipment

Z_5, kth zone has more than 30% retirees; (0-1) dummy

Z_6, percentage of kth zone's population living in an urban area.

Equations (1a) consist of a set of 2 equations that predict the demand for two "site types" the "own" site and the aggregate of "all other" substitute sites. Thus, sites are differentiated solely by their characteristics, and no site is a unique other than what is completely accounted for by its characteristics. The system of nonlinear equations was estimated by a seemingly unrelated regressions.

Total predicted angler days visited to each ith site are calculated by multiplying trips per angler by site and zone, X_{1ik} in (1), times average observed days per trip at the ith site, times kth zone angler population times a calibration coefficient of 1/2, then summing over zones. It is defined as

$$(2) \qquad D_i \quad = \quad \sum_k X_{1ik} \; d_i \; APOP_k \; (1/2),$$

where d_i, observed average days per trip at the ith site and $APOP_k$ kth zone angler population, and

$$(2a) \qquad (TPOP_k)(f_k) \quad = \quad APOP_k$$

where $TPOP_k$ total kth zone population and f_k, fraction of population that are anglers. In the percent implementation of the model APOP is exogenously determined for each year, based on ongoing statewide angler telephone survey data. For future versions of the model we hope to better understand how angler populations change in response to changes in management policy. As currently designed, the model may underestimate the increase in trips, resulting from a change in stocking regulations that enhances fishing and conversely, underestimate the decrease in trips resulting from a deterioration in fishing conditions.

A calibration factor is applied to total predicted angler days from (2) so that it corresponds to observed angler days by site, consistent with New Mexico Game and Fish Card Survey Data. Corrected angler days predicted at the ith site are:

$$(3) \qquad D^*_i = D_i + \Delta D_i$$

where ΔD_i is the residual difference between predicted angler days and days measured by the

Card Survey. The residual ΔD_i is partitioned out among each kth zone-of-origin proportional to each zone's D_i.

Angler Benefits

A central purpose of this model is to allow fisheries managers to assess the angler benefits of making policy changes that would change the vector of site qualities in (1b) from baseline values $\mathbf{Q}^o$ to new - policy values $\mathbf{Q}$. Another purpose is to see how the value of those quality changes are conditioned by travel cost when they vary from baseline values $\mathbf{P}^o$ to new values $\mathbf{P}$ or by angler characteristics that vary from $\mathbf{Z}^o$ to $\mathbf{Z}$. This section describes how we compute the benefits associated with changing baseline values ($\mathbf{P}^o$, $\mathbf{Q}^o$, $\mathbf{Z}^o$) to new values ($\mathbf{P}$, $\mathbf{Q}$, $\mathbf{Z}$).

Angler benefits predict per capita benefits for any time period compared to a baseline year of 1981. Statewide benefits are found by summing over zones. Benefits are only meaningfully defined "with a policy" as opposed to "without the policy." The with and without policy must be defined over the same time and space. Thus to correctly evaluate the relative payoff to anglers of any two fish management policies, PO_1 and PO_2 over the same time and space, the benefits of PO_1, relative to 1981 must be compared to PO_2 also relative to 1981. The year 1981 was selected as a convenient frame of reference and has no special economic significance.

Benefits can be evaluated by either changing the price ($\mathbf{P}$), or quality ($\mathbf{Q}$) vectors in (1). If neither a price nor a quality is changed by a policy, benefits are by definition zero.
No new variables are required to predict benefits once 1981 and new-policy trips are predicted.

Benefits are measured as a compensating variation (CV). The CV is defined as the difference between actual recreational expenditure, M_{ik} in (1) and the minimum expenditure needed to sustain original utility under new-policy prices and qualities.

For any kth zone and ith site, the recreational fishing expenditure needed to achieve 1981 level utility is computed by inverting the indirect utility function. The indirect utility function achieved by the typical angler under 1981 prices and qualities for the ith site and kth zone is defined by the following second order Taylor approximation to any utility index in prices and unpriced qualities:

$$(4) \qquad U^{\circ}_{ik} \quad = \quad \alpha^{\circ\prime}_{ik}\,\mathbf{X}^{\circ}(\ )_{ik} + .5\mathbf{X}^{\circ}(\ )_{ik}\beta_{XX}\,\mathbf{X}^{\circ}(\ )_{ik}$$

where $\alpha^{\circ\prime}_{ik}$ is defined at pre-policy levels of $\mathbf{Q}^{o}_{i}$ and $\mathbf{Z}^{o}_{k}$ and where $\mathbf{X}^{o}(\ )_{ik}$ is the result of equation (1) with $\mathbf{Q}_{i} = \mathbf{Q}^{o}_{i}$, where $\mathbf{Q}^{o}_{i}$ = baseline quality and $\mathbf{Q}_{i}$ is new policy quality; and $\mathbf{X}^{\circ}(\ )_{ik}$ is the system of equilibrium demands for the ith site and its substitute from the kth zone. The demand system $\mathbf{X}^{\circ}(\ )_{ik}$ is defined in (1) and is conditioned by the values taken on by its independent variable for 1981.

The demand system (1) is derived from and consistent with the utility function (4) and the recreational expenditure constraint.

$$(4a) \qquad M_{ik} \quad = \quad \mathbf{P}_{ik}'\mathbf{X}_{ik}.$$

The indirect utility function at 1981 reference levels can be inverted to solve for M_{ik} as a function of new policy values of $\mathbf{P}_{ik}$, $\mathbf{Q}_{i}$, $\mathbf{Z}_{k}$ and the level of (indirect) utility achieved in 1981, U°_{ik}. U°_{ik} is a function of 1981 values of $\mathbf{P}^{\circ}_{ik}$, $\mathbf{Q}^{\circ}_{i}$, and $\mathbf{Z}_{k}$.

The expenditure function needed to sustain baseline 1981 utility is solved by inverting the indirect utility function (4). It is :

$$(5) \qquad E_{ik}\,(U^{\circ}_{ik}(.);\, \mathbf{P}_{ik},\, \mathbf{Q}_i,\, \mathbf{Z}_k) \qquad = \; - \; \frac{b_{ik} + [b^2_{ik} - 4a_{ik}c_{ik}]^{.5}}{2a_{ik}}$$

where

$$(5a) \qquad a_{ik} \qquad = \qquad .5\ \mathbf{T}_{2ik}'\ \beta_{XX}\ \mathbf{T}_{2ik}$$

$$(5b) \qquad b_{ik} \qquad = \qquad .5\ (\mathbf{T}_{1ik}'\ \beta_{XX}\ \mathbf{T}_{2ik} + \mathbf{T}_{2ik}'\ \beta_{XX}\ \mathbf{T}_{1ik}) + \boldsymbol{\alpha}^*_{ik}{}'\ \mathbf{T}_{2ik}$$

$$(5c) \qquad c_{ik} \qquad = \qquad .5\ \mathbf{T}_{1ik}'\ \beta_{XX}\ \mathbf{T}_1 + \boldsymbol{\alpha}^*_{ik}{}'\ \mathbf{T}_{1ik} - U^{\circ}_{ik}$$

where $\boldsymbol{\alpha}^*_{ik}{}'$ is the value of (1b) at new policy levels of $\mathbf{Q}_i$ and $\mathbf{Z}_k$, and U°_{ik} is the pre-policy indirect utility function defined in (4), as a function of $\mathbf{Q}^{\circ}_i$, $\mathbf{Z}_k$ and $\mathbf{P}^{\circ}_{ik}$; and

$$(5d) \qquad \mathbf{T}_{1ik} \qquad = \qquad \beta_{XX}^{-1}\ \mathbf{P}_{ik}\ (\mathbf{P}_{ik}'\ \beta_{XX}^{-1}\ \mathbf{P}_{ik})^{-1}\ [\mathbf{P}_{ik}'\beta_{XX}^{-1}\ \alpha^*_{ik}] - \beta_{XX}^{-1}\ \alpha^*_{ik}$$

$$(5e) \qquad \mathbf{T}_{2ik} \qquad = \qquad \beta_{XX}^{-1}\ \mathbf{P}_{ik}\ (\mathbf{P}_{ik}'\ \beta_{XX}^{-1}\ \mathbf{P}_{ik})^{-1}$$

Per capita benefits from the kth zone associated with any policy change in $\mathbf{P}_{ik}$ or $\mathbf{Q}_i$ relative to 1981 at the ith site or its substitute aggregate can be calculated. It is

$$(6) \qquad BCAP_{ik} \qquad = \qquad M_{ik} - E_{ik}\ (\cdot).$$

where M_{ik} is actual kth zone recreational expenditure at the ith site and its substitutes, $E_{ik}(\cdot)$ is defined in (5). Benefits per capita can be computed for a policy that changes **P**'s and **Q**'s from 1981 levels at any ith site in question and/or the ith site's substitutes.

Total kth zone benefits from the policy change is found by summing over sites as:

$$(7) \qquad \text{Bene}_k \quad = \quad \sum_i (\text{BCAP}_{ik})(\text{APOP}_k)$$

where APOP_k is the estimated population of anglers in the kth zone defined in (2 - 2a). Total statewide benefits from a change in policy from $(\mathbf{P}^{\circ}_{ik}, \mathbf{Q}^{\circ}_{i}, \mathbf{Z}^{\circ}_{k})$ to $(\mathbf{P}_{ik}, \mathbf{Q}_{i}, \mathbf{Z}_{k})$ are found by summing (7) over zones:

$$(8) \qquad \text{Bene} \quad = \quad \sum_k \text{Bene}_k$$

Further Calibration

One complication arises when a kth zone's per capita trips predicted by (1) are negative. In such a case, the benefits of a quality increase or at any ith site predicted by (6) turn out to be negative, i.e., a nonsense result. To stop this from happening the following principle is applied:

If visits fall from positive to negative as a result of reducing a site's quality from 1981 levels, then we lessen the quality reduction so that visits only go zero. Then compute benefit losses based on that lessened quality reduction. Similarly if a quality improvement increases a site's predicted visits from negative to positive, then reset 1981 baseline quality so that predicted visits start at zero before increasing.

To accomplish this, two check flags are set.

Flag #1 For the 1981 year policy: Flag all zone site combinations (i,k) for which predicted per capita trips from (1), $X_{1ik} < 0$.

Flag #2 For the new (modified) policy: Again flag all zone site combinations (i,k) for which $X_{1ik} < 0$

There are three possibilities that can occur:

Both Flags Occur

If any zone-site combination (i,k) has both flags, then reset new Q_i back to the original baseline Q°_i. This resetting results in the new policy leaving visits and benefits unaffected compared to baseline. The theory behind this adjustment is that anglers gain or lose no benefits for quality changes at a site for which quality is inferior with and without the policy.

Only Flag #1 Occurs

For any (i,k) that has Flag #1 (new Q is better overall, as it increases X_{1ik} from negative to positive), reduce the gain in quality by resetting the baseline quality Q° so that predicted visits ≈ 0. This means resetting Q° up "toward" the new-policy Q until a Q^{mod} is found for which $X_{1ik} \approx 0$.

First, find a λ_{ik} between 0 and 1, by which we can multiply $X^{\circ}_{1ik} - X^{m}_{1ik} = \Delta X_{1ik}$ so that $\lambda_{ik}\Delta X_{1ik}$ when subtracted from new visits leaves "modified original" visits at approximately zero. Thus, if original predicted trips per capita from (1) were -1.0 and new policy visits are 3.0, then $\lambda = 3.0 / (3.0 + 1.0) = 3/4$. In general the formula is

$$\lambda_{ik} = \frac{X^{m}_{1ik}}{|X^{\circ}_{1ik}| + X^{m}_{1ik}}$$

Second, use the above λ_{ik} to shrink the $\Delta \mathbf{Q}_i$ from its actual change to a modified change $= \lambda_{ik} \Delta\mathbf{Q}_i$. This shrinkage factor is applied to all dimensions of the vector $\mathbf{Q}_i$ which is changed due to the policy. This method requires finding the "length" of each element ΔQ_{ij} for each jth dimension of the quality vector. After all the ΔQ_{ij}'s are computed, reset the original baseline quality from Q^{o}_{ij} to

$$Q^{r}_{ij} = Q_{ij} - \lambda_{ik}\Delta Q_{ij}$$

where "r" is a "reset" superscript. Do this over all dimensions (j) of quality that the policy changed. For any dimensions of the quality vector that did not change, i.e., for which $\Delta Q_{ij} = 0$, then that dimension is left alone. Some dimensions of quality may increase (e.g. more fish) while others may go down (e.g. less water). This doesn't matter. Still follow the rule: Shrink the size of all quality changes (positive or negative) by using the λ_{ik} formula.

The theory behind this follows: Anglers never actually visit any site at negative levels. But they may perceive a site's quality as being so bad that they wouldn't consider visiting it until it got a lot better. So they are not willing to pay anything for (get benefits from) further quality improvements until quality is good enough at a site for them to become positive visitors. Thus we only compute benefits from quality improvements at a site beyond a high enough quality level that pushes them into the class of a site visitor.

Only Flag #2 Occurs

For any zone site combination (i,k) that has only Flag #2, i.e., new $\mathbf{Q}$ is worse overall, as it reduced X_{1ik} from positive to negative, then we lessen the quality reduction. This means "pulling" new $\mathbf{Q}$ back toward the original baseline $\mathbf{Q}^{o}$ until finding a $\mathbf{Q}^{mod}$ for which $X_{1ik} \approx 0$.

The math follows:

First, look for a λ_{ik} between 0 and 1. The goal is to multiply the λ_{ik} by ΔX_{1ik} with the intent of reducing ΔX_{1ik} to a lesser amount $\lambda \Delta X_{1ik}$. This lesser change leaves new visits at approximately zero. Thus if original visits were 2.2 and new policy visits are - 1.1, then $\lambda = 2.2/(2.2 + 1.1) = 2/3$. The general formula is

$$\lambda_{ik} = \frac{X^{\circ}_{1ik}}{X^{\circ}_{1ik} + |X^{m}_{1ik}|}$$

Second, use the above λ_{ik} to shrink the $\Delta\ Q_i$ from its actual change

$$\Delta\ Q_i = Q_i - Q^{\circ}_i$$

to a reduced change $= \lambda_{ik}\Delta Q_i$. This shrinkage factor is applied to all dimensions of the quality vector Q_i which changed due to the policy. This method requires finding the "length" of each element $\Delta\ Q^{\circ}_{ij}$ for each jth dimension of the quality vector. After all the $\Delta\ Q_{ij}$'s are computed, reset the modified quality from Q_i to $Q^{mod}_i = Q^{\circ}_i + \lambda_{ik}\Delta Q_i$ over all dimensions (j) of quality that the policy changed. For any dimensions of Q_{ij} that did not change, i.e. for which $\Delta Q_{ij} = 0$, then that dimension is left alone. For example, if only volume and fish catch are changed by the policy, rest only those two dimensions of Q_i. Note that some dimensions of quality may go up (e.g. more fish), which others may go down (e.g. less water), the net effect still showing visits falling to negative. If this occurs, the rule above is still followed, i.e. shrink the size of all quality changes (positive or negative) toward zero. This method for resetting quality results in predicted visits going to approximately zero under reset modified quality.

Third, after going through these steps to reset quality, visits from a zone to each site and benefits accruing to a zone from all sites can be computed. For new policy quality, use the reset value of the quality vector:

$$Q^{mod}{}_i = Q^o{}_i + \lambda_{ik} \Delta Q_i$$

Benefits from the quality change are then recomputed using $Q^{mod}{}_i$ in place of Q_i in equations (1) - (8).