Completion Technical Report

A MODEL FOR OPTIMIZATION OF SOCIO-ECONOMIC FISHERY VALUES ON THE RIO GRANDE IN NEW MEXICO

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ABSTRACT

This report describes a mathematical model which simulates sport-fish production, yield, and economic value in the Rio Grande basin of New Mexico. The model links hydrologic, biologic, and economic components into a mathematical representation of fisheries habitat, fishery dynamics, economic benefits, and income generated by sport-fishing in New Mexico. The model has a research version programmed in FORTRAN and a user-friendly version programmed in APL.

The hydrology component is based on time-series correlations of U.S.G.S. data for inflows and outflows of a series of 19 river-basin segments which represent 8 reservoirs and 11 connecting reaches in or near the mainstream Rio Grande. It spans the period 1976 to 1984 and operates on the principal of mass balancing of water and material (suspended solids, total phosphorus, total nitrogen) in each of the 19 river segments. The hydrology component simulates material concentrations, water surface areas, water volumes, discharges, and changes in water elevation at two-week intervals for all 19 segments. These model outputs are accessible to the user and provide inputs for the biologic and economic components. Short-term predictions can be updated with the most recently determined data obtained from U.S.G.S. monitored stations.

The biologic component operates with inputs of area-depth-capacity data, water volume, water discharge and fluctuation, mean total phosphorus, total nitrogen, and total suspended solids from the hydrology submodel. It also requires inputs of mean seasonal solar radiation, water temperature, concentration of allochthonous suspended organic matter in the inflow, carbon-nitrogen ratio of allochthonous suspended solids, fish density and mean biomass per age class for each basin segment, and the

fishing effort estimated by the economic component, stocking, history and harvest regulation. The biologic component is basically a process model which simulates productions of phytoplankton, zooplankton, zoobenthos and fish. For reservoirs, fish biomass and density are simulated by size group over any one to five-year sequence selected from the time period simulated (1976 to 1984). Fish dynamics in reservoirs are predicted for nine groups of functionally similar species (guilds): crappie, sunfish, whitebass, blackbass, catfish, walleye, northern pike, carp and suckers, and trout (including salmon). A population model is used which distributes predicted fish-food production among fish guilds according to types of food eaten, habitat preference, and food consumption rates. Total fish production alone is simulated for connecting waters.

Fish biomass for each segment is output from the biologic component that serves as input for the economic component. Also, the water-surface area of reservoirs and the discharge of connecting waters required inputs for the economic component from the hydrology component. The economic component also requires for input basin estimates of travel cost, segment elevation, basin segment access, the alternative water bodies available, and other measures of basin segment quality. The economic component estimates, for each of the 19 segments, the fishing effort in angler days, the economic benefits derived by New Mexico anglers, and the income and employment generated in each of the counties in the basin. Multiple-regression techniques are used to develop an angler demand schedule. The fishing effort estimated in the economic component serves as input for the biologic model where it contributes to the estimation of fish survivorship and production.

Model users have numerous entries to model outputs and for simulating management decisions. In the user-friendly version the user can enter the model and obtain output on reservoir surface area, reservoir volume, water levels, discharge in connecting waters, total plant production, allochthonous loads of suspended organics, zooplankton production, zoobenthos production, total fish production, fish guild density by size class, fish guild yield by size class, fish guild surplus yield by size class, economic benefits to New Mexico anglers, and county income generated. The model users can modify water volume flowing through the basin by month, water stored in each reservoir, water discharged through connecting waters, material concentrations (suspended solids, total phosphorus, total nitrogen) in the water, site access, and site quality. Modifications of the historic record are simulated for periods of 1 to 5 years for individual water segments or combinations of water segments up to all water segments in the basin. Both FORTRAN and APL versions of the model are designed to run on IBM microcomputers or compatible hardware. Linkage with mainframe capability will decrease processing time. Depending on the dimensions of analysis and output desired, running time on the microcomputer is from a few minutes to several hours. Use of a mainframe reduces running time to about 1% of microcomputing time. Advances in microcomputing expected in the next year should reduce running time to speeds comparable to mainframe times.

The appendix includes FORTRAN and APL Programs and a complete mathematical documentation of the model [FORTRAN version].

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INTRODUCTION

Motivation for Model Development

Sport-fishery management in the arid west is complicated by water scarcity and extreme water fluctuations. In this region as in New Mexico water rights are property rights which may be sold at the owner's discretion. Water in New Mexico is an adjudicated right administered by the State Engineer (1953, 1966), and development or use of a water right may not impair existing water rights. Virtually all of the surface water in the Rio Grande Basin has been appropriated, with a series of reservoirs providing storage for those appropriated waters. The operation of the reservoirs and distributaries is regulated by international treaty and state compacts to assure that all owners get their appropriated share. Because irrigation accounts for 85 percent of the consumptive use in New Mexico, agricultural needs generally determine water management. Flood control is a major secondary consideration. Agencies responsible for managing fisheries are asked to optimize sport fishery values within the context of water ownership, limited water supply, and legal obligations.

Appropriated water may be used for recreation without water rights ownership as long as the use does not impair the water rights of existing owners. But because modification of existing water storage and delivery routines usually changes water loss rates, any modification requested for recreation must be accompanied by proof that downstream water rights will not be unimpaired. Alternatively, private or public interests may purchase and manage specifically for recreation. Yet, water purchased for recreational use has been limited, partly because recreational water values have not been credibly established through the market system.

Only in the last two decades have advances in natural-resource economics allowed credible valuation of non-market goods, such as recreational waters for sportfisheries resources.

Natural and anthropogenic constraints not only affect the value of goods and services produced by water in the river basins of New Mexico, they also affect the ability to predict future values. The Rio Grande usually receives 80 to 90 percent of its water from snowmelt in the San Juan and Sangre de Christo Mountains of southern Colorado and northern New Mexico. Because snow accumulation and snowmelt can be estimated in advance of its availability downstream, the amount of water transferred between reservoirs and stored in the six mainstream reservoirs of the Rio Grande Basin for the year following snowmelt is also reasonably predictable. Withdrawals from storage are highly predictable because all water is appropriated and must, by law, be beneficially used. Therefore changes in total reservoir volume and mean discharges through reservoir connecting waters are usually predictable for the next year. The exact timing of seasonal changes in discharges and water level is less predictable because of the uncertainty in the weather that controls snowmelt. Less certain still are the large and random year-to-year fluctuations in surface-water production. From 1890 to 1935, for example, water production varied between 1.4 billion m^3/yr and 5.7 billion m^3/yr (NRC 1938). The inherent uncertainty of water availability over the long-term introduces fundamental constraints into any water management forecasting.

The effects of compacts, treaties and other obligations are superimposed on these natural fluctuations. These cause water levels to increase in some reservoirs while they decrease in others, and the pattern can change from year to year depending on the timing and amount of runoff. Changes in water level in excess of five meters are common during spawning of fish. In some reservoirs, the past maximum annual mean water volumes have exceeded minimum annual mean volumes by more than ten times.

Although the resulting water dynamics are complex, modern computers can track past and present changes and predict future changes. The Department of Game and Fish sought an organizational and predictive tool to help contend with the exceptional spatial variation and instability found in New Mexico waters. The tool they sought was a sport fisheries-management model which could be used to increase the year-to-year reliability and quality of fisheries resources and the cost-effectiveness associated with fisheries management. In 1979-1980, a New Mexico State University research team was contracted by the New Mexico Department of Game and Fish and the New Mexico Water Resource Research Institute to assess the feasibility of modeling sport-fisheries for management purposes, including economic valuation in the Rio Grande basin of New Mexico (Cole et al. 1980). As a consequence of that study, a five-year project was proposed with the major objective of completing the model described in this report.

Fisheries Management Needs

The sport-fisheries management model was developed to address three general management needs for the New Mexico Rio Grande Basin:

1. Data Management and Research Application - A mechanism was needed to organize research efforts and results into a more orderly and more useful process that more effectively addressed management problems.

2. <u>Communication</u> - Credible measures of economic values for use in water-related decision making were needed for more effective communication among management agencies and resource users. Better estimates of the sport-fishery recreational benefits and costs associated with alternative resource-management decisions were needed to contrast with values of other water uses.
3. <u>Prediction</u> - A tool was needed to predict the consequences of alternative management decisions through mathematical simulation of system operation. Perhaps the greatest imperative for model development was the need for a mechanism that could be used to budget and process massive amounts of information for predicting consequences of management alternatives before costly, real-world changes were initiated.

Within the context of these general needs, the model addressed the following fishery management needs:

1) Estimating when, how, and where to stock fish for effective benefit to New Mexico anglers and effective distribution of sport-fishery generated income to different parts of the Rio Grande Basin.
2) Estimating the effects of introducing or removing species on existing fish populations and related fishery values.
3) Estimating when, where, and how to effectively restrict or expand fish harvest.
4) Estimating the effects of altered concentrations of nutrient and suspended matter on fish production, yield, and values.

5) Estimating the effects of altered water levels on fish production, yield, and value.
6) Estimating when, where, and how habitat modification, including redistribution of water, would help influence sport-fishing values.

Specific Objectives

The following specific modeling objectives were met during model development:

1) Hydrologic and biologic simulation of the reservoirs and connecting waters in the New Mexico Rio Grande Basin mainstream, including the Rio Chama.
2) Simulation of fish population dynamics for common fish groups easily recognized by the average angler (e.g. sunfish, black bass, crappie, catfish, trout, walleye, white bass, northern pike, and "others").
3) Simulation of angler fishing effort at all sites in the Rio Grande based on angler responses to fish density, site quality, waterbody size, access to water, travel cost, availability of alternative fishing sites, and climatic conditions.
4) Model responsiveness to changes in water-level fluctuation, nutrient loading, and changes in light transmission caused by suspended matter.
5) Model responsiveness to the effects of altered harvest regulations and stocking.

6) Model responsiveness to those introductions or deletions of fish species already present in the system (e.g. a species in the Rio Grande Basin may be newly stocked in a specific location).

7) Prediction of economic benefits and regional county income derived from sport-fishery management decisions.

8) Model prediction for a five-year period — for the first year based on updated snowmelt forecasts and for the next four years based on historical runoff conditions.

9) Prediction of mean annual fish yields by recognized fish population groups defined in objective 2.

10) Development of a user-friendly interactive version of the model that is easily used by management personnel.

11) Documentation of model structure including English, mathematics, FORTRAN, and APL versions.

To meet management needs, the model was designed to simulate: (1) the hydrologic component which determines water levels, nutrient concentrations, light penetration and temperature (Figure 1); (2) the biologic component determined by light, nutrient, temperature, water-level fluctuation and other interacting factors, which collectively generate fish biomass; and (3) the economic component, which results partly from angler harvest and partly from other variables that collectively determine visitation rates of anglers in various parts of the basin. Using the simulted river basin model, with appropriate recognition of its power and limitations, users can make management decisions and determine their impact on the modeled fisheries, including their economic impacts.

The sport-fishery management model is designed to enhance analysis of options available for the Rio Grande Basin mainstream reservoirs and connecting waters, including: (1) improved prediction of those water fluctuations that cause fish reproductive failure, changes in productivity, or imbalances among predators and prey, and adjustment through stocking and regulation; (2) development of alternative water-management plans that increase the probability of fish reproductive success and reliable fish yields without interfering with the water rights of others; (3) assessing the value of water for improved fisheries and, where justified and affordable, purchasing water to alter fluctuations in mainstream reservoirs or to transfer water to more manageable reservoirs off the mainstream; and (4) influencing policy or program decisions that affect the water quality or structure of the river system.

A predictive model was needed to develop options in the most cost-effective way. Recreational fishing has been estimated to generate local income worth more than $120,000,000 annually in New Mexico (U.S.F.W.S., 1982) with less than optimum fish habitat. The potentials for sport fishing to increase angler benefits and regional income stimulated the development of this model.

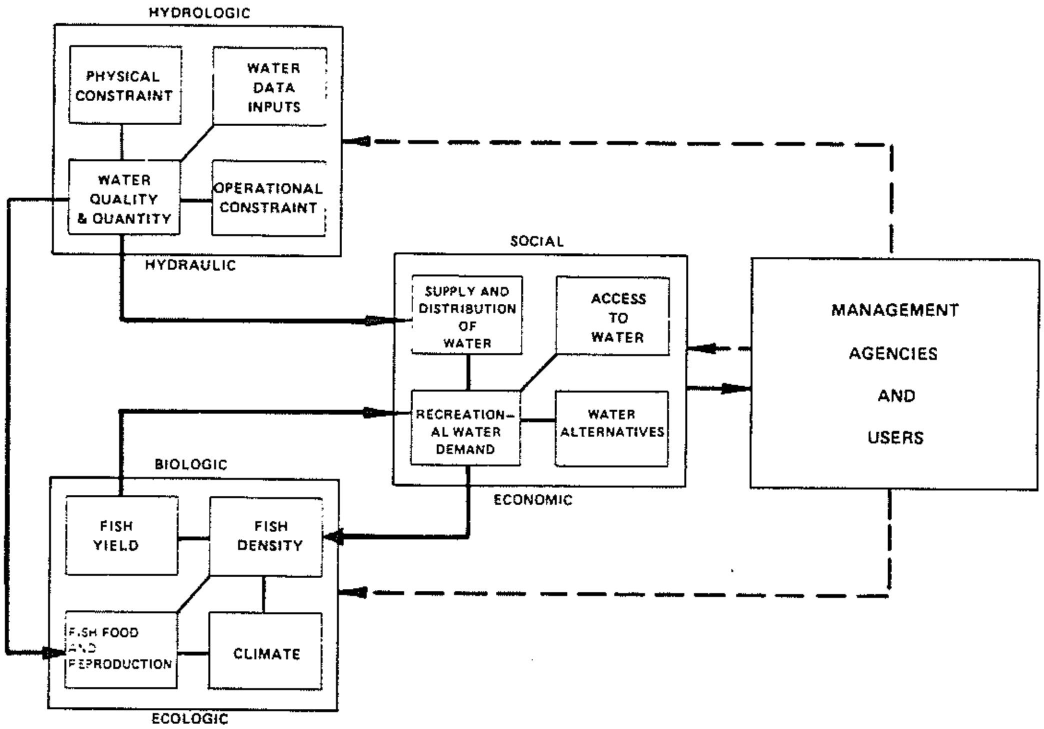


Fig. 1. Overview flow of model interactions among the major components and the model user.

THE RIVER BASIN

Hydrologic

Original Conditions

The Rio Grande begins in the San Juan Mountains in southern Colorado, flows through New Mexico and forms the border between Mexico and Texas as it proceeds to the Gulf of Mexico. Figure 2 shows the upper basin of the Rio Grande in Colorado and New Mexico. The Rio Grande has one large tributary, the Rio Chama, in the upper basin.

Much of the original character of the Rio Grande Basin can be deduced from more recently determined data (U.S.G.S. 1980–1983), (Cole et al. 1985). Water in the Rio Grande Basin is, as it was in its original state, derived mostly from snowmelt in the higher mountains of Colorado and New Mexico, augmented by summer storms. Highest flows occur in late spring and lowest flows are in fall and winter. In its pristine state, the ratio of daily high to daily low flows each year often exceeded 1000:1 or more. Extremes in flow were compounded by severe drought in some years and flood-generating precipitation in other years. Variability in the annual runoff was least in the northern mountains and greatest in the southern desert lowlands. High mean annual flows were about five times the low mean annual flows in the main river (Figure 3). Although the river is third longest in the United States its average discharge is much less than many of the shorter rivers that occur in wetter regions.

The Rio Grande watershed has a higher mean slope than most other large river systems so water in the pristine river, before impoundment, ran off quickly compared to rivers in wetter parts of the county. Except for lateral ponds, the entire river above Texas was replaced with

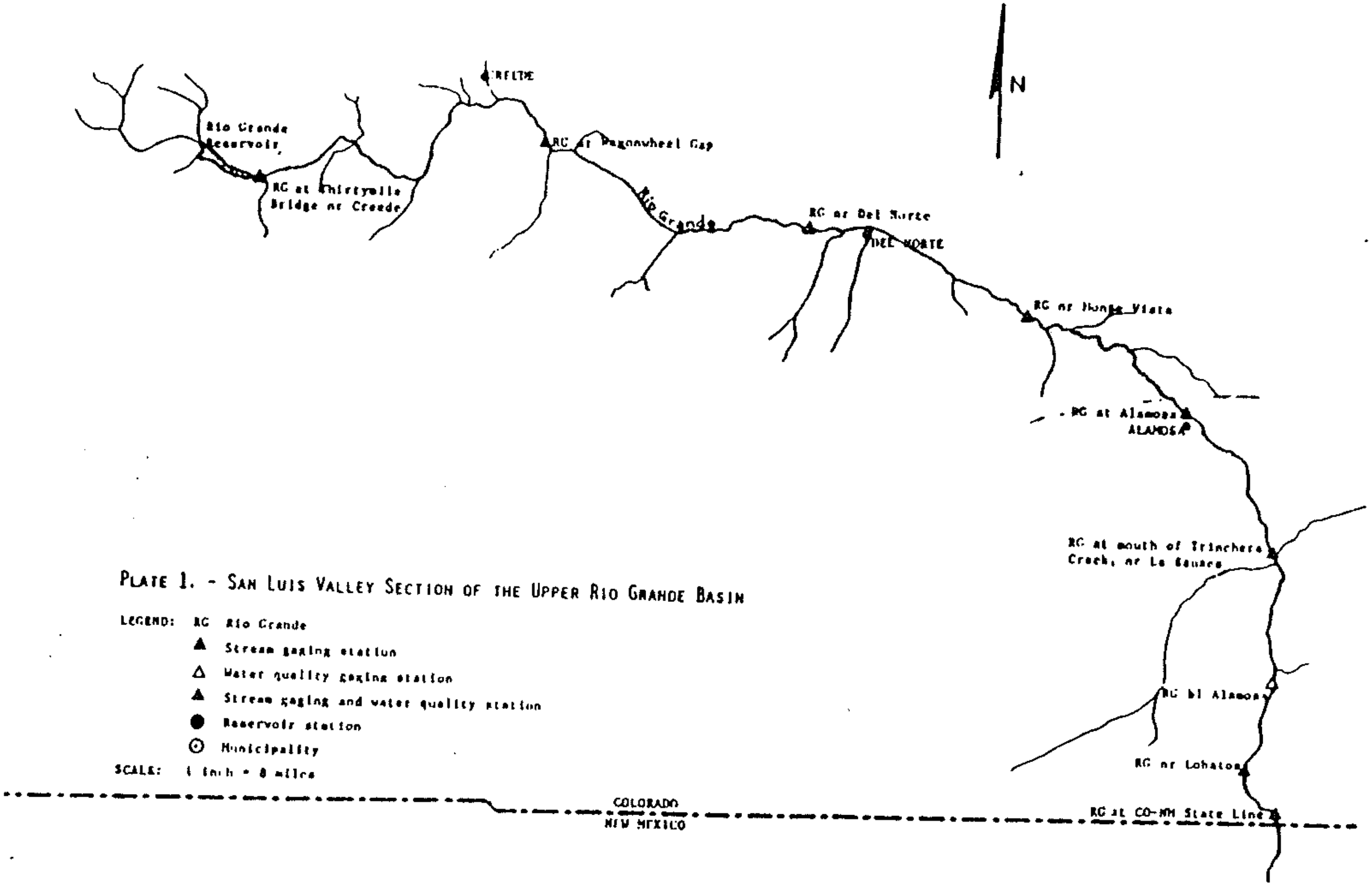
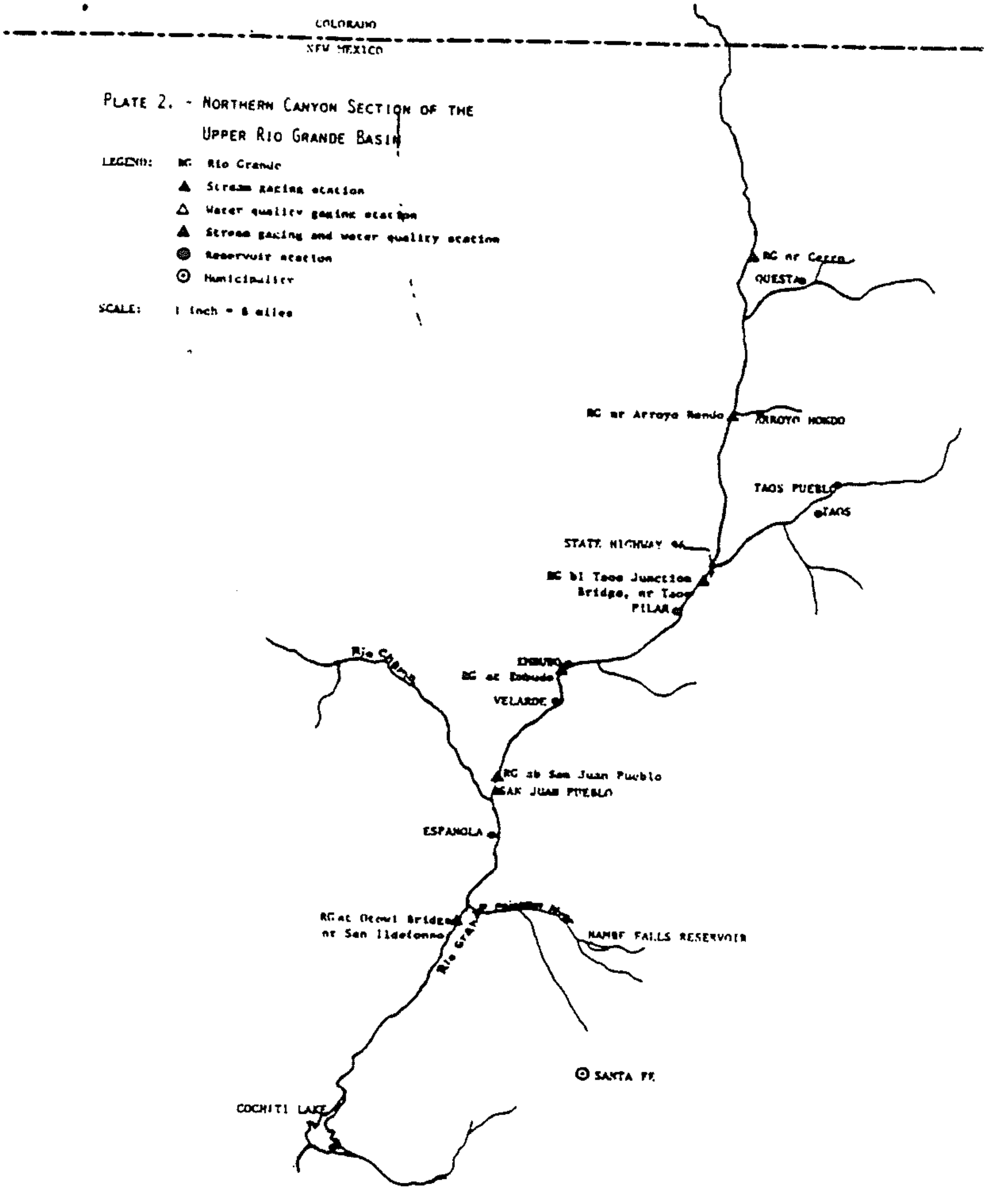


Fig. 2. Map of the Rio Grande from headwaters in Colorado to the Texas border



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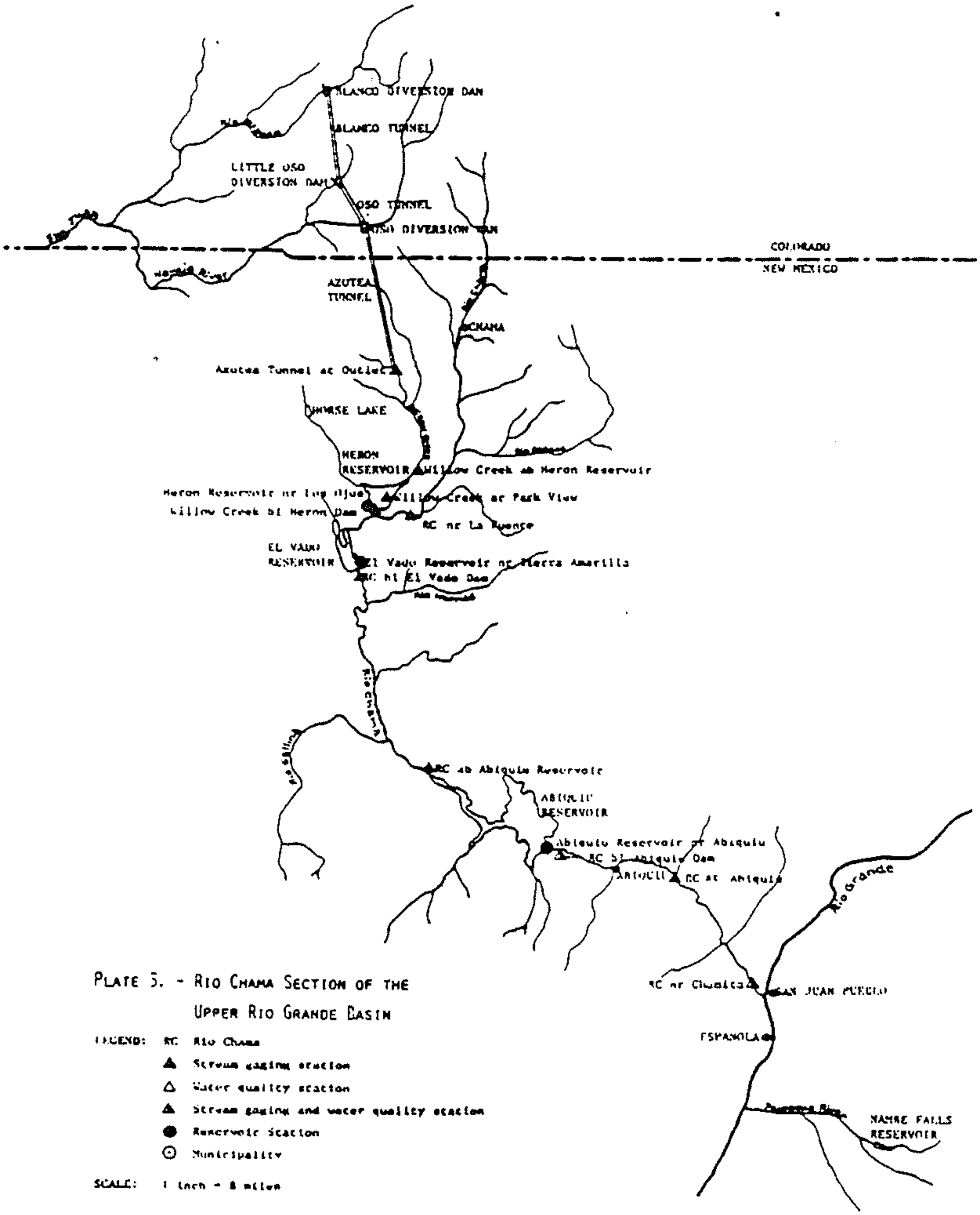

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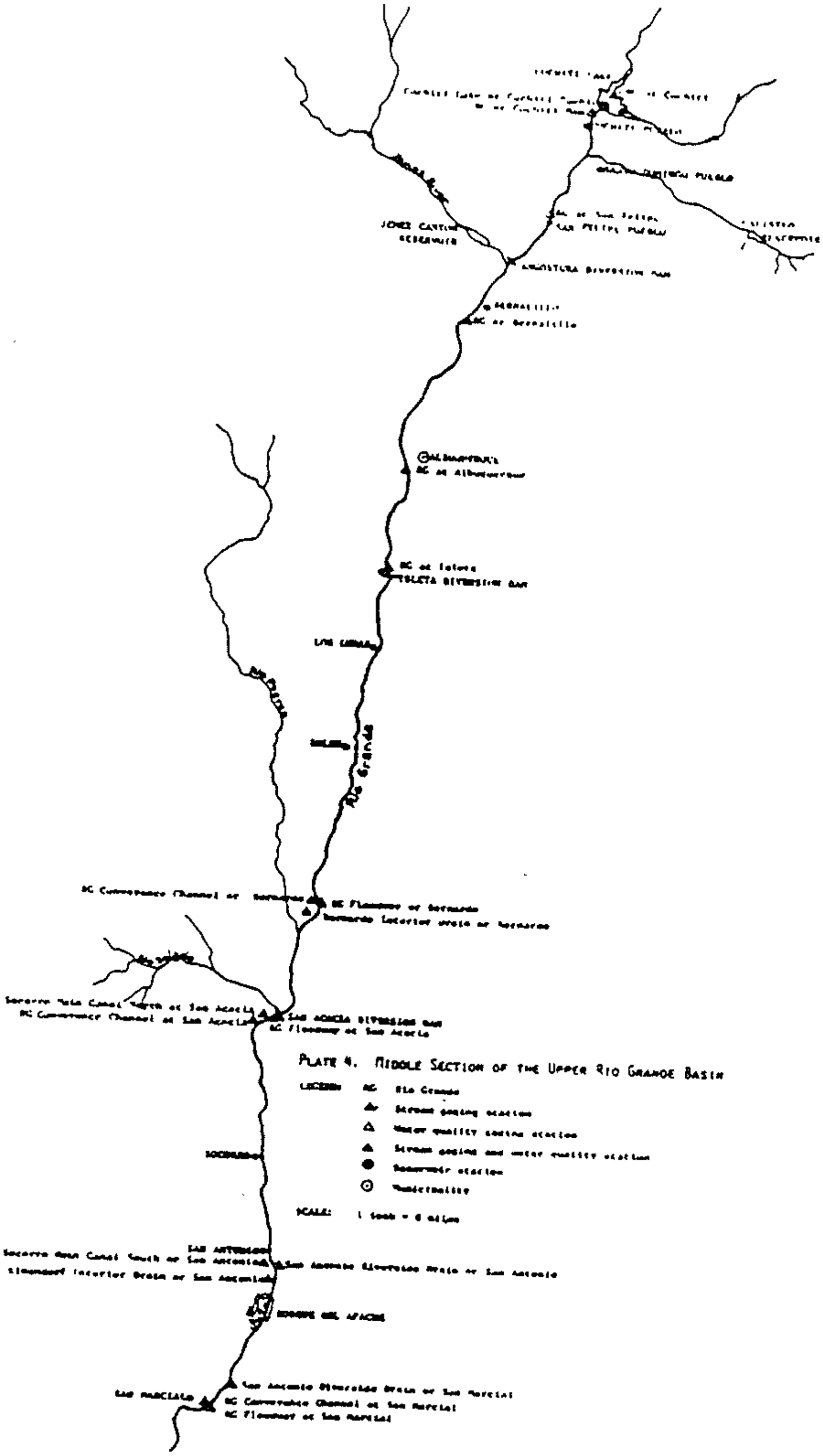

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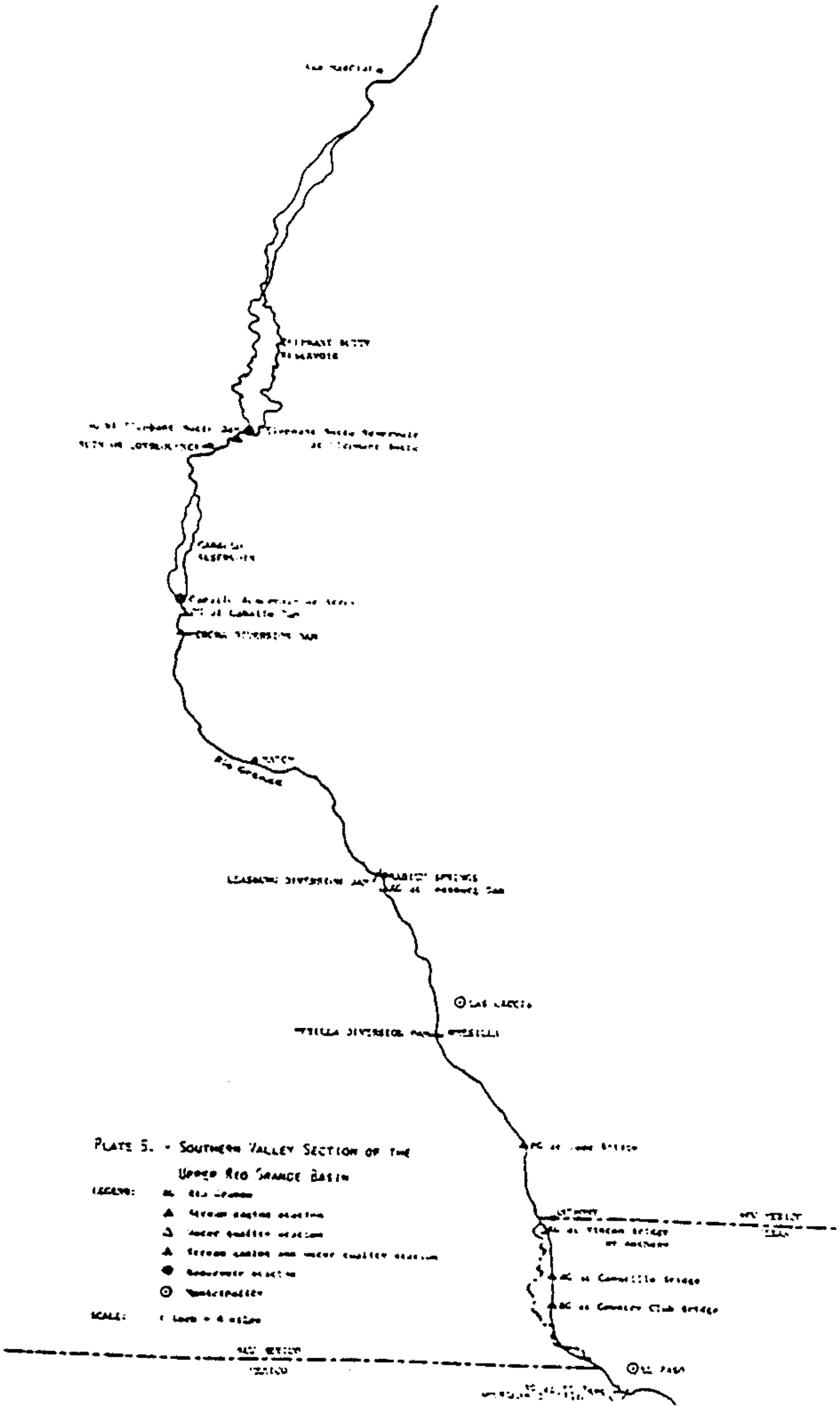

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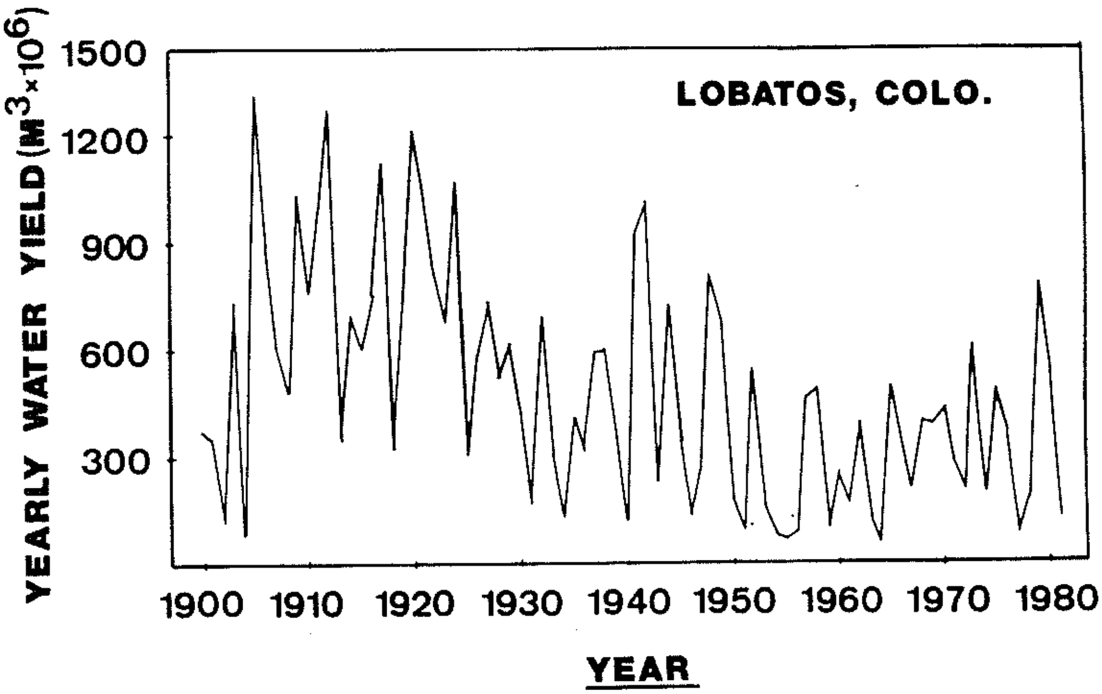

Fig. 3. Discharge in the Rio Grande at Lobatos, Colorado from 1900 to 1980.

new flow within a month. The slope is greatest in high mountain tributaries and least in the main reach, which passes through a series of low-slope river "valleys" formed behind erosion-resistent rocky ridges. These valleys (e.g. Espanola, middle Rio Grande, Hatch, Rincon and Mesilla) have accumulated deep, fine alluvium over which pristine river velocities slowed and the channel meandered widely. In the gorges between the valleys, slopes were steeper and velocities increased, sometimes torrentially during seasonal floods. Many of the small tributaries to the main river also pass through series of alternating alluvium-filled valleys and rocky gorges, but on a smaller scale.

Prehistoric river widths and depths were determined by channel erosion during high runoff, and the amount of discharge that remained above the river bottom during low flows. In the low-slope valleys during low-flow periods, the river braided over shifting, sandy bottoms, but much of the surface flow disappeared in many stretches leaving shallow flows, shallow lateral ponds and sloughs. Much of the river's flow sank into the permeable alluvium caught in the valleys and accumulated in groundwater basins behind transverse ridges of impermeable rock. Reaches over bedrock maintained their flow more constantly through drought because of the impermeable substrate. Extensive marshes and woodlands (bosques), mostly of cottonwood, occupied the alluvial flood plains (Metcalf 1969). These probably acted like natural reservoirs to hold back snowmelt and dampen flow variation in the lower river. The flows were stable enough for towns like Mesilla and Albuquerque to be built nearby.

The physical and chemical erosion from the watershed caused great loads of of suspended and dissolved materials which in turn influenced light penetration, inorganic nutrient availability to aquatic plants, inputs of terrestrial organic matter, and distributions of aquatic organisms. Material loads in the river flow were higher than river systems in wetter climates because of greater erosion from steep slopes in the watersheds. Freezing, thawing, and gravity moved boulder and cobble from canyon walls into mountain tributaries and the rocky gorges of the main river. Substrates composed of boulder and cobble provided relatively stable habitats for bottom invertebrates and were particularly suitable for spawning of salmonids and other species associates. Less stable bottoms occurred in the valley reaches, where fine sands and gravels shifted under all but the lowest flows. Except in the lateral ponds and sloughs, these areas were less productive and less suitable for spawning of certain fish than in the gorges and tributaries.

During high flows, suspended solids, eroded from the watershed, greatly restricted light transmission. Although this suspended matter carried some inorganic nutrient, most nutrient remained unavailable for plant production during high flow because of low illumination, snowmelt temperatures, and abrasion by shifting sediments. Concentrations of dissolved solids and nutrients were least during snowmelt runoff. Available nutrient concentration and light transmission increased as water levels receded to base flow and groundwater sources increasingly predominated. Therefore, light transmission, nutrient availability, and temperature favored plant production mostly in late summer and early fall, wherever substantial water remained above ground and substrates were stable enough to support plant growth.

Evidence described in Metcalf (1969) indicates that widespread livestock overgrazing starting the eighteenth century greatly increased erosion rates and the fluctuation of flows. The river became more turbid and choked with fine sands and silts. As the lateral ponds and marshes were filled for agricultural use, the river flood plain became increasingly prone to flooding. The extent of these effects have not been well documented.

Except for the snowmelt period, water temperatures in the pristine Basin were controlled mostly by air and groundwater temperatures which averaged about 10 C higher in the low desert than in the high mountains. Temperature was affected by riparian vegetation, which shaded more stream surface in the smaller, higher tributaries than in the main river. During low flows in the desert reaches, intermittent pools and lateral ponds reached 30 C during summer afternoons and diurnal temperatures fluctuated up to 15 C. Waters in the main river valleys rarely froze for more than a few days.

The original oxygen concentrations varied slightly with altitude. Although colder water holds more oxygen than warmer water, the higher elevation of colder tributaries mostly counteracted temperature affects. Consequently, oxygen concentrations were similar throughout the basin. Oxygen concentration probably remained close to saturation throughout the river during high flows but fluctuated around 100% relative saturation during low flows as a consequence of high stream community metabolism. Extreme pH fluctuations were rare because most of the larger waters in the basin were buffered by moderate to high carbonate concentrations during low flows.

Prehistoric modification of the Basin by humans amounted to small diversions for irrigation. Increasingly large diversionary systems were built and much of the riparian vegetation was removed during the eighteenth and nineteenth centuries (Sorensen and Linford, 1967). Since the turn of the twentieth century, five mainstream reservoirs, three large off-stream reservoirs and many pilot channels, diversion dams, and drainage canals were built in the New Mexico Rio Grande Basin. Table 1 summarizes operational information about these reservoirs. The first (1915) and largest reservoir built in the Basin is Elephant Butte Reservoir, located in the lower main river (Figure 2). Its construction was followed by construction of El Vado, Caballo, Jemez Canyon, Abiquiu, Heron, Galisteo, and Cochiti reservoirs. Heron (just off on Willow Creek), El Vado and Abiquiu are at the highest elevations in the Rio Chama subbasin; the other three reservoirs are at lower elevations along the main Rio Grande. Two other reservoirs are located just off the mainstream below Cochiti reservoir. Galisteo is managed solely for sediment and flood control with no permanent storage. Jemez Canyon Reservoir retains a small amount of water.

These large reservoirs are now managed for multiple-use with priorities established for irrigation and flood control. Present management of the reservoirs profoundly affect riverine biological communities. Because most water enters the state from northern tributaries and most water is used for irrigated agriculture along the mainstream valleys up to 600 km further south, reducing water loss during transfer is a priority concern. The Rio Grande is an imperfect and incompletely described fluvial system; much of the mainstream channel leaks into subsurface groundwater or evaporates and fails to reach surface-water users farther downstream. Also much of the water is lost as a natural consequence of irrigation use. The peak channel discharge is attained near Albuquerque (58,000 m^3/day) and decreases by 78% before it reaches Texas. About 19

Table 1

Location, year built, capacity, purpose and managing agency for large Reservoirs in Rio Grande Basin of New Mexico

Reservoir	Stream	Initial Year	Current Capacity (millions m^3)	Primary Purpose	Agency Operator
Heron	Interbasin transfer & Willow	1970	482	Water transfer	Bureau of Reclamation
El Vado	Rio Chama	1935	236	Irrigation	Bureau of Reclamation
Abiquiu	Rio Chama	1936	1,457	Flood Control	Corp of Engineers
Cochiti	Rio Grande	1973	607	Flood Control	Corp of Engineers
Jemez Canyon	Jemez River	1953	211	Flood Control	Corp of Engineers
Galisteo	Galisteo Creek	1970	107	Sediment Control	Corp of Engineers
Elephant Butte	Rio Grande	1915	2,532	Irrigation	Bureau of Reclamation
Caballo	Rio Grande	1938	398	Irrigation	Bureau of Reclamation

percent of the annual discharge at Albuquerque is water transferred into Heron Reservoir from the upper Colorado River Basin (0.13 x 10^9 m^3/year). Partly to offset leakage and high evaporation rates, most water is moved during the spring runoff period at the highest rates allowed by supply and the channel capacity of the river and parallel irrigation channels. Much of the river below Cochiti Dam has been modified to expedite water delivery and to restrain the river from meandering over adjacent agricultural land. In the allvial valley downstream from Cochiti Dam, most water now flows through dredged irrigation channels except during the peak runoff.

Elephant Butte and Caballo reservoirs, which lie in the low, Chihuahuan desert, have more combined storage capacity than the combined capacity of all other reservoirs in the mainstream Rio Grande and Rio Chama of New Mexico. But, surface evaporation rates are nearly twice as great at Elephant Butte and Caballo reservoirs than at Heron and El Vado reservoirs, so storage in Elephant Butte and Caballo reservoirs costs more in evaporative loss. The cost is at least partly offset by the fact that Abiquiu and Cochiti Reservoirs as flood control reservoirs are maintained at low fractions of their maximum volumes. All of the reservoirs drain from near bottom to enable maximum use of water within the reservoirs. Release gates move water rapidly through the system during the spring and summer irrigation period and, for the most part, are closed during the cool, dry season. Tailwater river channels are managed to move water rapidly; therefore, some channels are periodically deepened mechanically or by hydraulic scour.

Most of the reservoirs have been built in rocky narrows where much of the pristine river bottom that maintained year-round flows is now inundated and no longer available for most stream organisms. Groundwater levels have changed because of dam construction and groundwater use. Therefore basal flows in the remaining river channels may be more or less than they were in the pristine watershed, depending on locations. The city of Albuquerque for example, must purchase surface water (interbasin transfer from the Colorado Basin) to offset anticipated groundwater depletion. The relationships between groundwater and river flow are among the least understood hydrologic processes in the basin.

The natural lateral ponds and sloughs have been eliminated through agricultural development, except for areas difficult to farm or protected in wildlife refuges. Levee construction, channelization and discharge control have nearly eliminated the maintenance of remaining lateral ponds by seasonal flooding. The few remaining lateral ponds are maintained by natural seepage or by artifically delivered water contained diked areas. Several wildlife management areas near Belen, Bernardo and San Marcial use old lateral-pond depressions for temporary and permanent flooding. Dikes have also been constructed in two waterfowl management areas to increase the total surface area that can be flooded. A small fraction of river flow is delivered to these management areas mostly to sustain over-wintering birds.

Neither the entire system nor any reservoir in the system is being managed for constancy of water levels. Cochiti Reservoir is one of the more stable reservoirs, only exceeding 6 million m^3 storage during the snowmelt runoff. Minimum pools are maintained in most other reservoirs for sediment control or recreational use, but water levels change mostly in response to irrigation and flood control needs, as indicated in figure 4 for Elephant Butte Reservoir.

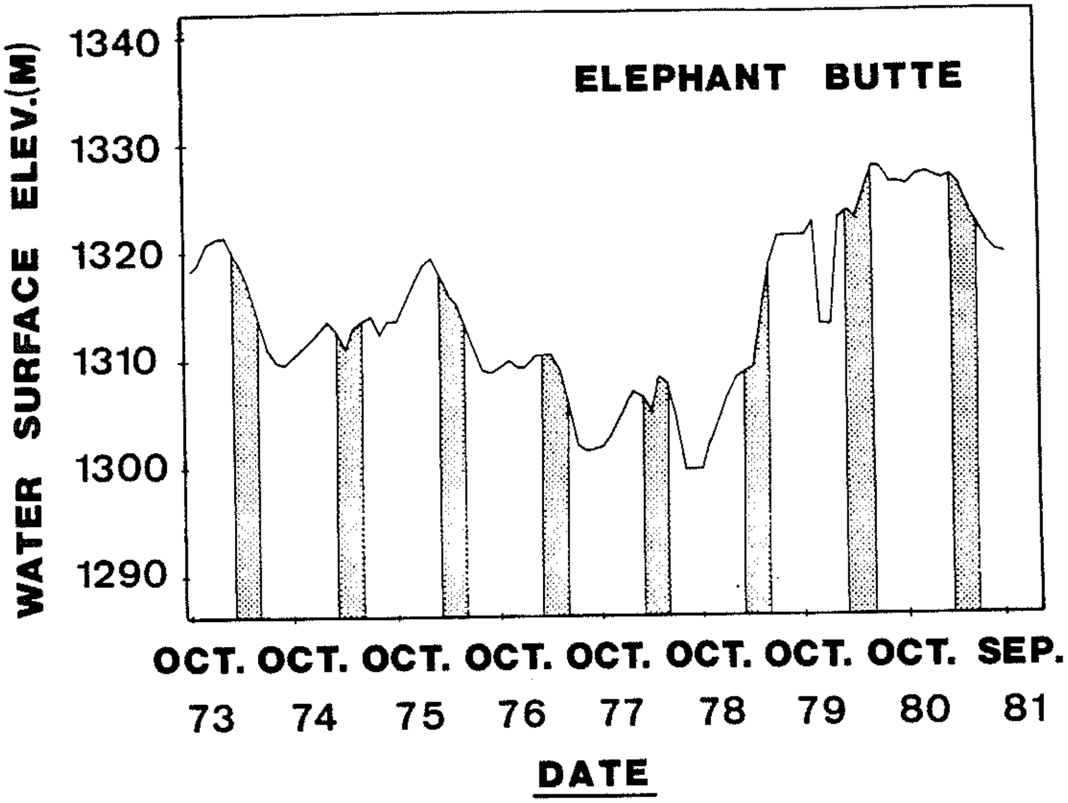

Fig. 4. Water level fluctuation in Elephant Butte Reservoir from 1973 through 1981. The stippled portion indicates spawning season for most fish.

Extreme and random, year-to-year fluctuations preclude accurate annual runoff prediction in the river (figure 3). For any given year, however, because snowmelt provides most water, the amount of water available may be reasonably predicted several months in advance. In the lower river, irrigation demands usually begin about mid-March and remain fairly constant until mid-September. The irrigation season overlaps the period when snowmelt and summer storms contribute more than over 90 percent of the reservoir water. Because snowmelt usually contributes little before April, there is often a period in early spring when water levels in the southern reservoirs are lowered because irrigation demand exceeds inflow. As snowmelt occurs, the reservoirs usually go through a period when inflows exceed outflows and water levels rise, sometimes as much as 20 cm/day. Then, in summer, water levels again decline, although this trend may be briefly reversed by exceptional summer storms. However, the year-to-year variation during fish spawning, mostly in spring, can be great at a reservoir like Elephant Butte (Figure 4).

At most reservoirs, little more than seepage is allowed downstream after mid-September and water levels tend to stabilize. At Elephant Butte Reservoir, for example, water is usually released during winter for hydroelectric power production, usually causing mid-winter declines of levels in Elephant Butte Reservoir and increases in Caballo Reservoir.

As a consequence of management for water conservation and irrigation delivery, tailwater discharges are extremely variable. During fall and winter, seepage may allow as much as 0.5 to 1.0-m^3/sec flows in contrast with irrigation deliveries of more than 50 m^3/sec during spring and summer. During high runoff years, the allowed discharge is up to 150 m^3/sec in the lower river. Low winter flows meander over the bottom of the dredged river channels or occasionally pool in depressions, particularly just below dams. Generally, mean depths are shallow and pools and riffles are poorly developed because the flow tends to spread over instable fine sediments in most areas. During irrigation, river channels and canals are close to bankfull, average 1- to 2-m deep, and flow rapidly and uniformly with little pool or riffle development.

Surface erosion in the watershed probably has increased because of land-use practices, but channel erosion has declined with engineered stabilization of the system. Much of the watershed has been intensively grazed and logged, starting in the eighteenth century. Elephant Butte, Abiquiu, and Cochiti Reservoirs are filling with sediments more rapidly than the other mainstream reservoirs because larger portions of their watersheds are particularly erodible. The capacity of Elephant Butte Reservoir declined 20 percent in 50 years (Jensen 1971). Jemez Reservoir and Galistea Reservoir, on side tributaries, were both constructed for sediment control as well as flood control. Further control of intermittent tributaries with particularly high sediment inputs has been considered for the Rio Puerco, Rio Salado and Rio Gallinas. Turbidity in connecting waters and reservoirs is greatest during high-water runoff when material loading is high. Upon entering the reservoirs, flows of the silt-laden tributaries tend to sink rapidly and often form density flows along the bottom which sometimes carry turbid inflow waters intact to the reservoir discharge (Jester et al. 1969). Water volume in the reservoir greatly influences the quality of tailwaters but even clear tailwaters rapidly gain suspended matter, turbidity and nutrients from tributaries as they proceed downstream.

Total plant-nutrient concentrations and light transmission are associated with the concentrations of suspended materials. Therefore complex intreactions between light transmission and nutrients determine levels of plant production (Jester et al. 1969 and Bolin 1985). Much of the nutrient entering a reservoir settles with the suspended solids and remains trapped in bottom substrates. Turbidity variation is often dramatic in the large reservoirs where the greatest light limitation occurs near the tributaries. In tailwaters, light, temperature, and scouring limit aquatic plant production primarily during May and June when discharge is high. Therefore, these months typically have lower productivity than expected from the solar energy available.

Water development has affected the thermal characteristics and oxygen dynamics of the basin. Thermal characteristics of the reservoirs are determined mostly by exchange rate, storage volume, and air temperature. Mean depth and air temperature are important determinants of a reservoir's tendency to thermally stratify. The shallower reservoirs, with low hydraulic retention, tend to be more uniformly mixed than the deeper reservoirs, with higher hydraulic retention. Among the extremes in the Rio Grande system, Cochiti is deep for the surface area developed and Caballo is shallow. Few reservoirs in New Mexico always remain stratified throughout the summer period because bottom drawoff rates for irrigation draw cool bottom water off faster than stratification occurs. The cool hypolimnetic (bottom layer) water is drawn away leaving gradually declining temperatures from top to bottom. In the lower-elevation reservoirs during summer, the mean daily temperature at the bottom reaches 20-27 C, although maximum daily temperature at the surface may reach 30 C. In the montane reservoirs, mean daily temperatures are 6-7

C less. Summer tailwaters tend to be cooler than equilibrium conditions allow and warming proceeds to equilibrium within a few kilometers flow from the reservoir.

During winter, few of the large reservoirs freeze completely over for long periods. Heron and El Vado may be frozen for two months or more when little water is stored, but Caballo and Elephant Butte rarely have ice and mix continuously from top to bottom during winter. Winter stratification probably occurs under ice in the reservoirs at high elevations.

Oxygen depletion occurs at least periodically during the summer in some of the reservoirs, with or without stratification. Oxygen concentrations as low as 1 to 2 mg/liter (about 15 to 25 percent saturation) have been measured in the bottom drawoff from Elephant Butte, which in turn can cause low oxygen in the tailwaters for several kilometers downstream during the summer. The large reservoirs in the Rio Grande Basin have fairly high concentrations of dissolved carbonates and pH fluctuations are minimal.

Biological

The prehistoric Rio Grande was unsuitable habitat for many aquatic organisms with narrow tolerances to temperature or water-level fluctuations and in addition, much of the main river was isolated from areas with relatively rich biotas by arid vastness. Therefore, species diversity was lower than in most river basins in the North American temperate zone. The Rio Grande's riparian vegetation and fish are most fully described and are related to the biotas of the Mississippi River and to a lesser extent to the Colorado river basins. Many of the larger, non-flying, native organisms appear to have colonized the Rio

Grande via upper tributaries by stream captures or transfers. A few species could have traveled through the Gulf of Mexico and entered the Rio Grande from its mouth. Most of the small, native organisms, such as insects, flew or were carried by wind (most often as eggs).

Before human impact, the main river in the alluvial valleys was mostly unsuitable for attached bottom algae because of shifting sandy bottoms. But at the rocky gorges or outcrops, attached bottom algae were the most important sources of energy in food chains leading to fish. Phytoplankton were never very important in the main river channels because of high exchange rates and turbulent flows. Phytoplanktonic algae may have been seasonally more important wherever slack water occured in summer and fall, when turbidity and exchange rates were low. Large aquatic plants also were scarce throughout the river system except in lateral ponds and sloughs. Extensive sloughs of emergent aquatic plants occurred in the valley bottoms of the larger tributaries and the main river was interspersed with cottonwoods and other trees. Riparian vegetation was a major source of organic detritus entering food chains leading to fish in the sloughs, ponds and river tributaries.

The original invertebrate fauna reflected the instability of the uncontrolled river system. Small zooplanktonic forms, including Cladocera, Copepoda and Rotifera, were unimportant in the turbulent main channel but most likely became, as they do now seasonally abundant in lateral waters or in beaver ponds. The flying insects were the most diverse group among bottom organisms. Large, non-flying invertebrates were much less diverse but sometimes locally abundant, especially near reliable springs. Invertebrates were least diverse and sparse in the unstable sandy meanders of the main river and most abundant in riffles of the rocky gorges and in the permanent slough and ponds parallel to the main river.

Native fish of the Rio Grande were primarily in the Salmonidae, Catostomidae and Cyprinidae but also included Centrarchids, Ictalurids, Poeciliids, Anguilids, Acerpensids, Clupeids, Lepisosteids, and Characids (Hatch 1985). Cutthroat trout (Salmo clarki) inhabited at least the upper tributaries and main river of northern New Mexico and many reaches further south that were maintained by cool groundwater. Most sucker species were particularly common in those permanent riffle-pool habitats maintained in the rocky canyons of the main river. Some may have occurred in the larger lateral ponds but the group was primarily river adapted. The minnows were usually associated with moderate flows in riffles and pool edges and probably tolerated ponded conditions better than others, but this group also was adapted for flowing waters.

Shovel-nose sturgeon (Scaphirhynchus platorynchus) and American eel (Anguilla rostrata) had been observed as far north as the Albuquerque-Santa Fe area before Elephant Butte Dam was built, so large migratory fishes were capable of traversing the river from lower reaches.

Some 26 species of fish, most with Mississippi River affinities, are though to have been native to the Rio Grande of New Mexico (Hatch 1985). Of these, 10 are now extirpated and the status of an additional four species has declined severely. Several of these species are piscivorous. Native piscivores may have been restricted to cutthroat trout, American eels and, possibly Mexican tetras (Astynax mexicanus) from Mexican river systems.

A few species of turtles managed to move up the river to New Mexico where sloughs and beaver ponds were probably the preferred habitats. Numerous species of aquatic birds used the flooded sloughs and beaver ponds although water often was low during peak, spring migrations. There probably was considerable summer use by wading birds and nesting waterfowl when sloughs were water-filled. Wintering areas probably were less dependable but were used in the lower Rio Grande. The beaver (Castor canadenisis) was common along the banks of sloughs and river channels and influenced the structure of riparian communities through its selective feeding. Large ungulates undoubtedly occurred there and had some affect on riparian communities.

Many large aquatic organisms have been introduced by humans. Among plants, salt cedar, Tamarix, is the most obvious because it has displaced native plants in riparian zones. Russian olive was introduced above Elephant Butte Reservoir. Of the aquatic invertebrates, non-native crayfish (Astacidae) and the Asiatic clam, Corbicula sp., are among the more obvious introductions, although other invertebrates may have been introduced inadvertently. Introduction of fish are best known; many introduced species are from the Mississippi drainage. Extant introduced species of fish in the Rio Grande of New Mexico include 29 species (Hatch, pers. com.). Several non-native centrarchids and perchichthyids were introduced from Mississippi River or Great Lake waters. Most introduced, cold-water fish were originally from the Great Lake or Columbia River drainages, including salmonids, esocids and percids. Because introductions have been mostly for sport or food, only seven non-game species have been introduced to the Rio Grande.

Riparian vegetation has been much reduced in the valleys because of livestock grazing and clearing for crop culture. Although older, riparian forests remain intact along unfarmed tributary valleys, young cottonwoods and willows are scarce in most places along much of the main river. Because old trees are now dying, major changes in riparian habitat may occur during the next few decades if there is no human intervention. Salt cedars have moved into much of the Rio Grande at lower elevations. This tree may not be as desirable as other riparian species because it grows in dense and uniform stands, casts minimal shade on river water, and has questionable nutritional value for aquatic organisms. Salt cedar also transpires water, but the effectiveness of phreatophyte control in generating increased volume flow of water is uncertain.

Phytoplankton have become much more important in the ecological energetics of Rio Grande habitats as a consequence of impoundment. The predominant forms are poorly known but where they have been studied they are those expected for nutrient-rich alkaline waters (Sanchez 1971, Cole et al. 1985). Because water levels tend to fluctuate rapidly during the growing season, attached algae and macrophytes contribute relatively little to primary production anywhere in reservoirs. However, during periods of relative stability, macrophytes may rapidly colonize as Jensen (1971) observed in the delta at the upper end of Elephant Butte Reservoir. Littoral zones (illuminated bottoms) in stable waters are usually more productive than open waters because of production of rooted and periphytic plants (Wetzel, 1982). In Rio Grande reservoirs, the opposite may be true because total plant production may be inhibited by water fluctuations.

Attached bottom algae are more important producers in tailwaters, particularly during low flow over rocky substrates. Rooted aquatic plants and attached algae may be abundant in lateral lakes and artificially flooded depressions adjacent to the Rio Grande. Few aquatic plants of any kind survive the shifting bottom in the main stream, but are common along the edges of any irrigation canals that retain stable flows all year.

Seasonal variations in plant production are not well described for the river system. In most of the temperate-zone locations previously studied (Wetzel 1982), plant production is usually a function of complex interactions among light transmission, temperature, nutrients and herbivore consumption. Because Rio Grande reservoirs receive cool, turbid snowmelt waters in late spring, peak primary productivity tends to occur before and after snowmelt in early spring and mid-summer. Although early spring and late summer may be the best illuminated times, nutrients are relatively scarce because of rapid sedimentation in the reservoirs at those times.

Zooplankton are more important now than in the pristine state because they abound in the impounded waters. Bottom invertebrates that feed on organic sediments occur in reservoir sediments and may be more widespread now than in the past.

In flowing tailwaters, the predominant invertebrates are flying insects and molluscs. The great seasonal fluctuations in discharge, from summer irrigation flows to winter groundwater seepage, inhibits production of invertebrates. Both zooplankton and zoobenthos collectively consume phytoplankton and detritus from upstream. Even for large reservoirs, detrital inputs contribute a large fraction of the total plant material available as food for zooplankton and zoobenthos.

In the higher-elevation reservoirs, salmonids and catostomids predominate. Centrarchids, percicthyids, ictalurids, clupeids and carp, Cyprinus carpio, are most abundant in the lower reservoirs. Most native cyprinids and catostomids are scarce in the reservoirs, perhaps because they are better adapted for flowing waters and are more vulnerable to predation in reservoirs.

Because many species rely on the littoral zone for spawning, the timing and rates of water-level change are crucial for determining reproductive success. Many species spawn in the littoral zone at temperatures that occur when water levels are changing rapidly, so their reproductive success is variable. Some species can spawn in deep water (ictalurids and gizzard shad) or tributaries (percichthyids, salmonids, catostomids and carp) and thus suffer lesser impacts from water-level fluctuations.

In connecting waters between reservoirs, fish depend on large pools or downstream reservoirs for refuges during low flows. Reproductive needs are sporadically satisfied for tributary spawners if irrigation flows coincide with sexual maturation. But much of the connecting waters are of limited use for spawning because substrate quality or water velocity are inappropriate or inadequate. Most native species of fish are scarce in connecting waters.

Other Vertebrates

Because of human effects, most dabbling waterfowl and wading birds may be less common than in the pristine watershed although diving ducks are probably more common now because reservoirs and refuges provide concentrated over wintering — perhaps too concentrated to avoid catostrophic epidemics. Certain turtles may have also benefited from larger water bodies. Aquatic mammals probably are less abundant now, partly because riparian vegetation and macrophytes have been reduced and premanent flows are more likely to be interrupted.

Angler-Attributes

The people who recreate at reservoirs and connecting waters in the Rio Grande basin were sampled in summer 1981 to develop a demand schedule described for the economy component of the model. From that data a profile of users emerged. The sample included 870 recreationists of which 347 claimed that angling was their primary activity. Among the anglers 79 percent of the Basin visitors were from New Mexico. A large fraction of the out-of-state visitors were from adjacent states, particularly Texas. The use by non residents varied depending on site. Caballo Reservoir, was fished mostly by people from El Paso, Texas (Table 2). Generally, the farther from Texas a site was located, the greater was the resident use. A small exception to this rule occurred in the northern part of the basin at Heron Reservoir and the upper Chama River.

The trip costs varied mostly in relation to the distance traveled to the site. The distance traveled indicates where most visitors lived. Cochiti Reservoir, for example, was greatly used by people nearby in Albuquerque and Santa Fe. Elephant Butte reservoir was used by a combination of people from Albuquerque, Las Cruces and El Paso, Texas. Heron reservoir and the upper Chama were used mostly by people in the Albuquerque and Santa Fe area but also attracted people from a greater distance. The cost per mile traveled tended to increase with distance traveled, indicating a longer, more expensive stay for longer trips.

Anglers claimed to have fished different lengths of time per day at different sites. The average ranged from 3 hrs/day at the lower Rio Grande River below Elephant Butte to 8 hrs/day at Heron Reservoir. It averaged about 5 hours for all sites sampled in the Basin.

Table 3 indicates how New Mexico anglers (non-residents excluded) are distributed with respect to population distribution in New Mexico. By deduction Cochiti and the lower Chama are visited mostly by people from the Albuquerque area. A relatively small percentage of people from Albuquerque go to Elephant Butte which is apparently more attractive to people from Las Cruces and other smaller towns in the southern half of the state. Most of the New Mexico anglers at the lower Rio Grande and Caballo Reservoir are from Las Cruces, but substantial number of users are from nearby rural areas.

The educational level and income of anglers was similar to that of the state's populace as a whole. They had completed a median 11.7 years of education and had a median income of $23,800.

The favorite fish of the sampled anglers was trout (64 percent) followed by blackbass (11 percent), sunfish (10 percent) and white bass (4 percent). Other fish comprised the remain 11 percent. Table 4 indicates the relative percentage of anglers who had caught fish in one or more categories when questioned in summer 1981. That sample indicates that anglers had not quite attained their desired catch of trout at sites where trout were available (Heron and lower Chama Reservoirs). At warm water sites, where no trout were available, the expected demand was 30.5 percent for blackbass, 28 percent for sunfish, 11 percent for white bass and 11 percent for others (crappie, catfish, walleye, northern pike, carp and suckers).

Table 2

Angler residency, distance traveled, travel cost and fishing time spend per day at selected sites in the Rio Grande Basin.

Site	Non Resident Angler (%)	Median Trip Cost ($)	Median One-Way Distance Traveled (miles)	Angler Time At a Site (hours)
Heron Reservoir	10	70.00	165	8
Upper Chama River	4	100.00	160	5
Lower Chama River	0	100.00	150	6
Cochiti	7	12.00	46	6
Elephant Butte Reservoir	34	55.00	115	4
Lower Rio Grande River	50	25.00	60	3
Caballo Reservoir	76	50.00	100	6

1. Below El Vado Reservoir
2. Below Elephant Butte Reservoir

Table 3

Percentage of New Mexico resident anglers from areas of different population size visiting selected sites in the Rio Grande Basin

Site	250,000 - 1,000,000	50,000 - 250,000	15,000 - 50,000	Towns Under 15,000 or Rural Areas
Caballo	0%	60%	9%	40%
Cochiti	79%	7%	3%	11%
Elephant Butte	17%	38%	31%	14%
Heron	32%	36%	25%	7%
Lower Chama	86%	0%	14%	0%
Lower Rio Grande	0%	77%	8%	15%

Table 4

The percentage of anglers who had caught one or more kinds of fish on the day surveyed (Summer 1981)

Site	Trout	Black	White	Striped	Pike	Walleye	Crappie	Sunfish	Catfish	Other
Caballo	0	0	9	0	0	0	0	0	18	9
Cochiti	0	0	14	14	0	0	0	22	32	11
Elephant Butte	0	23	25	9	0	0	5	9	9	18
Heron	29	0	0	0	0	2	0	0	0	14
Lower Chama	57	0	0	0	0	0	0	0	0	43
Lower Rio Grande	0	8	12	0	0	4	0	4	24	12

The average capture of blackbass and sunfish was less than desired, according to ranking of favorite warm water fish. All other fish were caught in excess of their expressed desirability. Certain sites were better at meeting demands than others with Elephant Butte perhaps the best suited to meet demands. Catfish apparently were in low demand but were caught by a large fraction of the anglers. The "other species" in Table 4 must, by deduction, be comprised mostly of carp and suckers and their catch rate was much higher than the demand.

In summary these data collectively indicate that anglers cannot be easily categorized in terms of population distribution, education, income, or other characteristics. They appear to represent a cross section of the State's populace and comprise about 23 percent (based on USFW 1982) of the state population as a whole. In 1980, about 200,000 anglers lived in the basin and about 40,000 out-of-state anglers visit the basin to fish. This implies that at least 20 percent of the income generated by angling is derived from outside the state. Based on USFW (1982) data, and assuming that the Rio Grande basin has proportional fishing effort compared to the rest of the state, angling generates about $80 million in local income annually, with nearly $17 million generated by out-of-state visitors. Very few New Mexico anglers fish elsewhere according to USFW 1982.

PAST RELEVANT RESEARCH

Hydrologic Model Research Review

Numerous reservoir "models" have been developed for various purposes over the last 20 years of computer aided hydrologic simulation. All of the models are based on a form of the conservation of mass (mass-balance) equation, which in effects says "you can only break even." Probably the most widely disseminated generic type of model in this genre is that developed by the U.S. Army Corps of Engineer (COE). Their models represent the espanding state-of-the-art in modeling of reservoir-stream systems. They are however, big "number-crunching" entities that require fast mini- or main-frame computers for their applications. Were this not the case, one or more of these models would have been attractive as a basis for further modification in this study.

One of the oldest models issued by the COE was developed by the Hydrologic Engineering Center (HEC) at Davis, California. This model was numbered HEC-3 and was originally released in 1968 and subsequently updated (e.g., USACOE 1974). This model simulated reservoir operation for water supply, recreation, low-flow augmentation, hydro-power, and navigation. This model, like subsequent models, allowed the user to model serial or parallel systems of reservoirs by specifying reservoir contents or flow constraints and denoted where those constraints existed in the system. This model was set up and run for the Rio Grande Basin for all six major reservoirs over a five-year period in order to have a "feel" for the least complex model of its type. It is comprehensive, but it is not easily applied by a manager with no modeling or computer experience.

Another model of this type was developed specifically for Pacific NOrthwest conditions by USAED (1975) and is referred to as the SSARR (Stream Flow Synthesis and Reservoir Regulation). This model not only considers streamflow and reservoir operation but also upland hydrology via rainfall-runoff and a snowmelt component. These additions make this model hydrologically comprehensive but the model was designed for the Northwest and thus has features that are not necessarilty appropriate for other areas. Water quality was not included.

The HEC-5 model (USACOE 1979) expanded upon the HEC-3 model, with flood control added to the reservoir operational constraints. This addition increased the applicability of the models but at a cost of in more computer time and storage. The HEC-5 has also been modified to HEC-5Q (USACOE, 1980) wherein water quality has been added to the HEC-5 version. HEC-5Q can consider temperature, dissolved oxygen and a combination of three conservative or non-conservative constituents depending on the dissoved oxygen computations. This model treats a reservoir as a vertically varying (layered) system with completely mixed layers in the lateral and longitudinal directions. Advection and mixing are permissable. Finite difference forms of the conservation-of-mass equation are solved for the layered system. This model presents a potential alternative for mainframe program development because it contains all of the necessary components for an expanded model.

A final COE entry into the realm of reservoir modeling is the water-quality model called CE-QUAL-RL (USA WES 1982). This model simulates 34 water quality factors but requires a massive amount of data to implement. It was only developed for a one reservoir-downstream flow sequence and thus is not as flexible in space as the HEC-5Q model. It also operates on a virtually stratified system and considers transfer between layers.

All of these models have admirable features, some of which are incorporated in the model developed for this study. In general, all of these models require storage and computational speed in exceeess of that available to the average user. Therefore, the research team followed a modeling approach that decreased computational requirements and data needs to a point that was consistent with the current knowledge of the system and available data.

Biological Model Research Review

Overview

Watt (1968) identified four types of population models, all of which have been used specifically as fishery models. They include (Type 1) models that explain change in population size based on the relationship between reproductive potential of adults in the population and the number of offspring eventually recruited into adult stock; (Type 2) models that relate the stock in each age class of a population for one or more years to the stock in one more previous age classes; (Type 3) models that explain changes in populations based on measurement of growth, natural density-dependent mortality, reproductive potential, or realized reproduction and fishery mortality; and (Type 4) models that include environmental factors that are density-independent as well as density-dependent, are open-ended instead of closed, and may consider virtually any factors determining changes in population abundance. Only the last type of model responds well to habitat changes. The first three models consider environmental factors as constants or randomized variables. Thus, for situations in which habitat effect and habitat manipulation are important aspects of modeling fish populations only the fourth type of model is satisfactory. One of the basic needs in the Rio Grande Basin model was that the fishing respond to hydrologic (habitat) fluctuations.

Most past fishery models are population based, steady-state models that generally ignore habitat variation (Schaff 1975). Most treat environmental variables as constants and simulate intrinsic population adjustments to changes in the forces of recruitment and mortality. An upper boundary for the population is often defined as an empirically determined environmental carrying capacity, while a lower boundary is some minimum stock needed for the population to recover from decline toward extinction.

Schaefer (1954) described a Type I model, sometimes referred to as the surplus-yield model (Everhart et al. 1975), which ignores differentiation of population regulators and combines growth, natural mortality and recruitment rate into a model that simply relates rate of population increase to existing population size and the maximum population allowed by the carrying capacity.

Fox (1970), Walter (1973), and others have suggested modifications that are more realistic, but all of these models work best when the variance in population abundance is caused only by variance in parent stock and is density dependent, and when the adult stock is generally homogenous in terms of reproductive rates and survival, regardless of age structure.

Royce and Schuck (1954) used a model which incorporated relationships between individual year classes and recruited stock. Although their model is responsive to variation among age classes, it assumes that the coefficients which relate stock of different age classes are constants rather than variables that respond to intrinsic factors within the population or extrinsic factors associated with environmental fluctuation. Therefore, their model basically suffers from the same shortcomings as the surplus-yield models.

Beverton's and Holt's (1957) model is an elaborate expansion of the above models that considers the yield of a recruited stock to be a function of fishing intensity, the change in numbers caused by natural recruitment, and mortality and the change in weight of surviving individuals. The model allows estimation of maximum yield per recruit through model manipulation of fishing mortality (or fishing effort, which is assumed to be a direct function) and the minimum size of fish harvested. As Watt (1968) has pointed out, the model may be very useful in certain fisheries but broad utility is limited because it assumes abiotic environmental stability and homogeneity in the characteristics of the entire population.

Ricker (1958) and others have tested the performance of steady-state models against simulated random fluctuations in certain environmental parameters to determine their ability to predict yield under randomly fluctuating conditions. Generally, the ability to predict yield was diminished, although in some instances the models remained useful predictors of yield. But many problems remain for the application of these models in highly unstable environments where there is fluctuation of density-dependent mortality factors that contribute greatly to population regulation.

Perhaps the best example in Rio Grande reservoirs is the seasonal change in nutrient concentration, water level, and turbidity. Although the general timing of changes is predictable, the degree of change and the relationship between nutrient change and water-level change can vary annually (Cole et al. 1985).

The fourth type of model, referred to here as the Habitat-Yield Model, was developed to circumvent the limitations of models that assume habitat consistency. These models incorporate functional descriptions of the environmental factors that significantly affect fish populations. The simplest habitat-yield models predict total fish yield from some profoundly effective habitat variables such as depth, temperature, or total dissolved solids. The intermediate interactions between the habitat and fish are not explicit but are integrated within the single interaction term. The habitat-yield models have been developed to satisfy the present need for predicting total fish yield in variable environments. The motivation for modeling the trophic-dynamics of ecosystems is the need to partition total fish yield into yields of species or species groups.

Empirical Models

A number of models that have been developed based on morphological and chemical measures of water bodies. Rawson (1952) was probably the first of several researchers who quantified a relationship between mean lake depth and fish yield among lakes large enough (over 1,185 km^2) to support commercial fish yield. Hayes (1957) also calculated a "quality index" by factoring out the affect of depth on the relative yield of fish. Rawson (1952) indirectly revealed the relationship between lake surface area and depth, and Hayes (1957) later quantified it and found a linear, log-log relationship for lakes over 0.3 km diameter. Rawson (1955) later demonstrated similar relationships for benthos and plankton.

Carlander (1955, 1977), Hayes and Anthony (1964) and Ryder (1965) enlarged upon the studies of Rawson (1952) and Hayes (1957), and incorporated chemical estimators of edaphic effects. Ryder (1965) indicated that his model was predictive as long as lakes were large (over 300 ha), north-temperate, and subjected to moderate or intensive, unrestricted fishing, but not subject to large environmental fluctuations such as "excessive pollution, high flushing rate, extreme turbidity, extreme water-level fluctuations, and extensive winter or summer kill".

Jenkins (1967), from studies of numerous midwestern reservoirs, reported that the morphoedaphic index was not as well correlated with fish yield from large reservoirs (over 200 ha) as Ryder (1965) found with large lakes. Jenkins (1967) related three measures of fish production — standing crop, sport-fishing yield and commercial fishing yield — to a number of reservoir characteristics in 46 to 121 different reservoirs using multiple-regression techniques. In one context or another, reservoir depth, age, hydraulic retention and temperature (growing season), dissolved solids (nutrients) and water-level fluctuation appeared to be involved in regulating sport-fisheries.

Variations of morphoedaphic models were developed specifically to relate nutrient concentration and phytoplanktonic productivity to nutrient input rates for lake eutrophication models. Empirical equations have been formulated to represent intensities of nutrient input that would create algal production great enough to cause oxygen depletion in the deep hypolimnetic water of many lakes (Vollenweider, 1968). Lorenzen (1972) described a more advanced series of "mass balance" nutrient models for sedimentary nutrient dynamics in lakes, particularly for phosphorus. Vollenweider (1979) revised earlier models to predict concentration of total phosphorus in lakes in various locations around the world. Bolin (1985) and Bolin et al. (1987) reviewed several variations of this type of model for predicting concentrations of nutrient and suspended solids.

Leidy and Jenkins (1977) chose to relate fish production to length of growing season for midwestern reservoirs. Even though explained in Leidy and Jenkins' (1977) analysis, growing season explained more variation in yield than depth, growing season still explained less than half of the entire variation in sportfish yield. In place of water-temperature data, Leidy and Jenkins (1974) used the number of frost-free days to develop a relationship for estimating fish production. Temperature data taken directly from reservoirs may provide better predictability for fish yield than the growing season.

Process Models

Nutrient enrichment-eutrophication models like Lorenzen's (1972) and Vollenweider's (1979), develop more detail than Vollenweider's (1968, 1975) empirical models, which relate depth, annual nutrient loading and production. More detail is required if any meaningful, temporal variation in productivity needs to be calculated, in order to predict yield of individual species of fish. For habitat-based models to have anything more than a foundational value, the habitat variables must be effectively linked to productivities of individual fish species.

Process models (or trophic-dynamic models) may be used to simulate resource production, partitioning, and transport in the ecosystem from the primary producers through the zooplankton and benthos to the fish. Process modeling, although more complex, time consuming and expensive than most simple empirical models, may be more generally applicable to different environmental conditions encountered in complex systems, and also more likely to reveal the relative importance of actual mechanisms of interaction. Simple habitat-yield models do not account for physical variation and this undoubtedly diminishes their value for similating reservoirs (Jenkins 1967). Process models are not so hampered but require much more data for the complex array of coefficients needed to accurately simulate the system.

Ecosystem process models were qualitatively conceived early in the century but most elegantly described by Lindeman (1942) who, with others since then (Odum 1957, Teal 1957, Nauwerck 1963), very generally lumped consumer organisms into trophic levels based on predominant feeding habits rather than detailed analyses of food-resource partitioning. At each level of transfer, allowances were made for "losses" to decomposers but decomposer production was not counted as a part of the trophic-level production. Estimation of decomposer production is very difficult. Therefore, it has been generally assumed to decline in proportion to the consumer production at each level without any real basis in data.

Lindeman (1942) also established a series of process efficiencies which estimated the gross partitioning of energy resource available to a trophic level into a new biomass and respiration. He introduced process efficiencies for respiration/growth, growth/assimilation, and a trophic level efficiency. Based on these efficiencies and efficiencies subsequently used by other investigators (summarized by Kozlovsky 1968), the energy passing from one trophic-level may be partitioned into amounts ingested and amounts not ingested, and therefore destined for decomposition or storage in deep sediments. Of the amounts ingested, part is egested then reingested, decomposed or stored. The rest is assimilated, then processed for growth, reproduction, respiration and excretion.

According to morphoedaphic models, shallow, eutrophic systems are more productive but less efficient in consumer-energy conversion of nutrients than are deep, nutrient poor systems (oligotrophic). This observation is implicit in the square root function applied in the model (Ryder 1965). It follows that decomposers may participate proportionately more than consumers in the energy conversion of eutrophic systems than in oligotrophic systems. The deduction that trophic-level efficiencies decrease as organic loading increases is a recurrent theme in the history of model development, and forms a basis for the biological part of the Rio Grande Basin model.

Biological studies of energy transfer through aquatic communities in a semi-tropical spring, a bog, two eutrophic lakes, and two large mesotrophic lakes seem to indicate wide variation in every conversion from primary producers to tertiary producers (where many fish are). These conversion efficiencies were 0.35 percent for eutrophic Lake Mendota and 1.4 percent for dystrophic Cedar Bog Lake (Lindeman 1942 and Kozlovsky 1968), 0.76 percent for semitropical Silver Springs (Odum 1957), 0.15 percent at eutrophic Severson Lake (Comita 1972), 4.4 percent at mesotrophic Lake Erken (Nauwerck 1963) and 0.64 percent for mesotrophic Lake Ontario (Robertson and Scavia 1979). In spite of the many sources of error which could affect the results, these few studies seem to reveal a general relationship between trophic status and energy conversion which resembles the relationship predicted by Ryder's (1965) morphoedaphic model. The two eutrophic lakes are less efficient than the less productive mesotrophic lakes. The bog is a moderately low productivity system similar to the mesotrophic lakes and its trophic efficiency is also similar. The major exception to the generality seems to be Silver Springs, a very productive flowing system with relatively high trophic efficiency. But Silver Springs is unique among the ecosystems described because it is the only flowing system and it has virtually constant and nearly optimum temperatures (22 C), nutrients, discharge and high transparency resulting in high benthic plant production. This suggests that the rate of mixing (aeration) and the abiotic stability of a system are basic effectors of energy-conversion efficiencies along with illumination and nutrients.

Still, the variability in results from these habitats is much larger than would be expected from Ryder's (1965) morphoedaphic model, even when Silver Springs is excluded. Part of the variation may arise from the assumption made in many of the studies that "herbivores" derived all of their energy from aquatic plant producers. Two other sources of primary energy are allochthonous detritus from surrounding terrestrial ecosystems and energy fixed in decomposers which incorporate nutrients from the water and "reconstitute" the nutritional value of leached detritus. Nauwerck (1963) recognized that secondary producers were converting more energy than was available from autochthonous plant production alone. Teal (1957) studied energy conversion in a small, cold spring where allochthonous tree leaves accounted for much energy input. His trophic conversion efficiency, calculated solely for autotrophic and primary consumers, was much higher than other systems with more of an autotrophic base. Therefore, in the development of trophic-dynamic models, it is important to credit the contribution of allochthonous imports in all habitats. This is true even for large reservoirs (Cole et al. 1985).

Numerous invertebrates digest and assimilate bacteria as well as allochthonous detritus and autochthonous plant material (Cummins 1979). If the allochthonous subsidy is not budgeted, conversion efficiencies will be overestimated. The affect of allochthonous inputs is likely to be greatest in waters with high exchange rates and high ratios of shoreline length to surface area.

More recent work conducted generally under the auspices of the International Biological Program has examined the relationship between intensity of energy flow through ecological systems (level of plant production) and trophic level conversion efficiency. Marine work (Cushing 1971 and Parsons 1980) indicates a real decline in efficiency from about 15 percent in low productivity marine environments to about 5 percent in high productivity environments. Similar trends are probable in fresh water but not clearly defined because of inadequate data in highly productive freshwater lakes (Blazka 1980).

The problem of specifically predicting production in complex communities has led to generations of increasingly complex, ecosystem models which define intermediate steps between inputs of light and nutrients and fish-production outputs. They operate with one day as the basic time unit and thereby predict a nearly continuous biomass changes over time. These models attempt to account for differences among species in the number of preceding trophic exchanges, metabolic efficiencies, and exploitation of resources held in common.

Among the more appropriate detailed ecosystem models for reservoir studies is one conceived for Lake George, New York and Lake Wingra, Wisconsin named MS. CLEANER (Park et al. 1979). The model is divided into a number of submodels each of which defines changes in important state variables in the trophic web which leads to estimations of fish production in three fish groups: carp-like fish, bass-like fish and bluegill-like fish.

A number of other ecosystem models of lakes have been devised which pertain to reservoir modeling in the Rio Grande and to modeling tributaries and connecting waters. Thomann et al. (1975), Thomann (1979), Canale et al. (1976), and Robertson and Scavia (1979) have devised models of pelagic-profundal zones in large lakes. Williams (1972) using Lindeman's (1942) data, devised an advanced trophic-level model. Patten et al. (1975) devised a model for a cove in a large reservoir, while Chen and Orlob (1975) described a general model which could pertain to reservoirs. Conceptually, these models are similar to the MS. CLEANER model but are not so thoroughly documented nor tested.

Although complex ecosystem models of reservoirs or connecting waters may generate accurate estimates of specific population yields, they require much information — perhaps more information than warranted for a proficient, management-oriented model. Yet, for highly unstable aquatic ecosystems, trophic-dynamic models are likely to be more accurate than simple morphoedaphic models and provide a means for paritioning yield among species groups. In a quest for a simple but comprehensive model, Regier and Henderson (1973) suggested theoretical modifications of a morphoedaphic model which may be suitable for unstable systems like the Rio Grande and includes economic value as well as yield in the outputs. The model also deals indirectly with the problem of partitioning resources among species. Regier and Henderson's (1973) modifications are based on theories of community complexity and function. Their model is of interest mainly for its potential use, because practical tests have not yet been made. According to Regier and Henderson (1973), the ratio of primary productivity to the total community biomass decreases as species diversity and community stability decrease. This implies that trophic conversion efficiencies decrease as the biomass increases and as productivity increases.

At low to moderate productivities, Regier and Henderson (1973) considered total commercial fish yield to be directly proportional to productivity and a parabolic function of fishing intensity (much like that proposed by Schaefer 1954). Because of species changes, fish yield is postulated to maximize in moderately-productive, mesotrophic waters rather than eutrophic waters. In their model, the economic value per kilogram of yield is also related to relative eutrophy of the system. The economic value of the fishing is predicted to maximize in somewhat less-productive and cooler waters than where maximum fish yield occurs.

Determining the value of recreational fisheries is more complex than that of commerical fisheries because the value of a sportfish is determined by more than availability, palatability, or each of food preparation. There does not presently seem to be any well-informed understanding of how diversity of fish yield (size and species) affects sport-fishing intensity and yield.

The approach of Regier and Henderson (1973) was to aggregate the highly subdivided concepts of trophic energetics as espoused in the ecosystem models of Park et al. (1974) and McIntire and Colby (1978) into something less data demanding and possibly more utilitarian. However the complexity of such concepts as community stability, resilence and regulation make such a model difficult to define; there has not been, as far as we are aware, substantial application of their model. However enough data have been generated by other researchers, particularly from the International Biological Program, to approach validation of some of the theory they generated. Fundamental is the underlying concept that trophic level efficiencies decrease with increasing productivity. This is theorized to occur partly because the relative availability of plant matter produced becomes less reliable with increasing productivity. Cushing (1971) and Parsons (1980) provide empirical evidence from marine ecosystems to support this argument in addition to those arguments presented earlier.

In the course of developing the biological model for the Rio Grande reservoir we sought a compromise between the simplicity of the highly aggregated approach in the morphoedaphic models and the flexibility of the more complex ecosystem models. We decided that the division of the processes should be no more than required to provide the outputs desired for management use and verification of model operation. The greatest detail was needed to predict fish population dynamics so that fish yield and fishery values could respond to changes in habitat, fish stocking, and harvest regulations. In the process, we developed detailed population models for nine "guilds" of ecologically similar species. Our foundational aim was to link population models, similar to ones conceived by Taylor (1981) and Zagar and Orth (1986), with trophic-level models so that the energy in both allochthonous and autochthonous organic matter entering the system is partitioned realistically among the guilds.

Flowing waters have received less modeling attention than lakes. Because of the importance of shade, fish production in flowing waters can be nearly independent of variations in depth and nutrient concentrations but responds to temperature change and allochthonous inputs from shore. In larger rivers, reservoirs or tailwaters, the relative impacts of depth and nutrients on fish production are likely to be greater because of the diminished effect of shoreline sources of allocthonous organic matter and shade; therefore, an index like the morphoedaphic index for streams is likely to predict fish production more effectively in large flowing waters than in smaller waters. No one seems to have published a morphoedaphic approach to predict production in flowing waters, and its suitability remains untested.

Vannote et al. (1980) formulated a qualitative precursor (the stream continuum concept) of what may eventually be a quantitative model that relates stream order to a set of biological properties including productivity. However, highly regulated watersheds may not fit a model devised for unregulated flows; therefore, the stream continuum model may have limited applicability to the Rio Grande system.

Existing habitat models are based on the distributions of velocity, depth, bottom characteristics (including banks), temperature and the total discharge. These data are integrated to assess the instream flow requirements of a variety of species (Bovee, 1978a and 1978b) and to determine the highest carrying capacity allowed for the channel shape and water available. The most complicated of the techniques estimates the relative suitability of a stream reach based on the predilection of fish for particular locations in streams. The predilection is defined for spawning adults, eggs, fry, juveniles and non-spawning adults. A probability-of-use curve is calculated from as large a number of observations in as wide a variety of flowing waters as possible. The relationship between fish carrying capacity, predicted from probability-of-use models, and actual yield has not been researched intensively.

Because neither nutrients or food is included, actual production estimation or carrying capacity is not estimated by instream-flow models.

Advanced trophic-dynamic models have also been developed for flowing waters (McIntire and Colby 1978, Boling et al. 1975), which depend more on allochthonous sources of organic matter for energy input than do reservoirs with low exchange rates. The major differences between these models and MS. CLEANER are the differences in submodels and coefficients. Community functions in stream segments are more likely to be influenced by import and export dynamics than are communities in segments of a reservoir.

Autochthonous production is mostly in the form of attached algae, rather than phytoplankton. Allochthonous detritus tends to be of larger mean particle size than in reservoirs because of terrestrial litter inputs. Reservoir tailwaters, however, are exceptional because of the detrital phytoplankton released from the reservoir. As in lake models, temperature and gas concentrations are important regulatory factors for all metabolic rates.

Stream trophic-dynamic models have not greatly emphasized fish, partly because small streams have received the most research attention. The McIntire and Colby (1978) model divides fish into riffle and pool categories. As in lake models, partition coefficients are required. Among fish, size and habitat positions may be the best way to partition energy since most species may be categorized as temporary migrants, slack water or backwater inhabitants, riffle inhabitatns, pool inhabitants, or inhabitants of pool-riffle ecotones.

The McIntire-Colby model uses a "general ecosystem" model called FLEX and is documented in the specific stream model called FLEXFORM. The transport functions are derived from recent hydraulic theory (after Leopold et al. 1964) and include terms to simulate mean current velocity, suspended load and shear stress. These are predicted from empirical constants and measures of width, depth, hydraulic radius, slope, and bottom roughness. The illumination is simulated as a function of suspended matter, absorption by pure water, and the depth. Suspended load is defined as a function of discharge but there is no density or viscosity correction term for temperature or alkalinity variations.

Inputs for the McIntire-Colby model include isolation, photoperiod, allochthonous organic matter, temperature, hydrologic parameters, light extinction data, and coefficients of energy transfer developed as fractions of transfer under optimum conditions. Competitive coefficients may also be needed. The allochthonous inputs may be divided into large refractory particles, whole leaves, leaf fragments, fine particulate material, and dissolved organic matter as modeled by Boling et al. (1975).

Economic Model Research Review

Introduction

For resources and commodoties produced and sold in the market place (e.g. agricultural goods) market prices usually assign value, and these market values form the basis for the allocation of resources. However, estimating benefits of under-priced or non-priced public recreational facilities such as sport fisheries in the Rio Grande Basin, requires either direct measurement of willingness to pay for the facilities or estimation of site demand schedules and subsequent calculation of willingness to pay. One direct approach to the measurement of willingness-to-pay for something is the Contingent Value Method. A good discussion of the Contingent Value Method can be found in Schulze et al. (1981); it will not be reviewed further here. A more widely used "indirect" approach, for estimating a site demand schedule and then calculating the willingness to pay is the Travel-Cost Method (TCM). It was applied in development of the economic model. Both methods have been recommended for use by federal agencies since 1979 (U.S. Water Resources Council, 1979, 1983). The purpose of this review is to identify past development in TCM and examine its relevance to New Mexico's Rio Grande Basin.

Essentially, the TCM is used to estimate the "price" of a site in order to determine its value under status quo and other management choices. It involves estimating a site-demand schedule using regression techniques. Some chosen measure of site visitation is specified to be the quantity of product consumed and average travel cost per unit visitation is specified as the price of the consumed product. Much of the discussion in the literature has focused on the exact form of the quantity measure (e.g. individual visits, trips, trips per capita, etc.) and the exact form for the price variable (e.g. out of pocket costs only, opportunity cost of travel time, etc.).

Three different types of management decisions stand out as suitable for valuation using the TCM: (1) the use and value contributed by recreational resources at an existing site (This value is often needed by managers to find the extent of recreation benefits lost if, for example, water were totally removed from the site), (2) the additional recreational use of a site and benefits gained from improving the quality of services offered by recreaton at the site, and (3) the additional aggregate use and benefits created by introducing one or more new sites (or loss associated with site removal).

Many forms of TCM have been developed and no one form of the TCM is best at providing a predictive tool for all of the above types of management decisions. Simple single-site models can easily apply to the first type, whereas more complicated multi-site regional models (Knetsch et al. 1976; Çesario and Knetsch 1976, Mendelsohn and Brown 1983) are required to answer the second. For the third type of decision a system of several demand equations may be preferred when several new sites are to be added to a given area (Cicchetti et al. 1976). Because of the system-wide nature of decision-making in New Mexico's Rio Grande Basin, we decided that the third approach was best for the Rio Grande study.

The data available also influences the exact form that the TCM site-demand equation takes. Specifically, the sampling procedure used and visitation patterns at the site (e.g. do recreationists typically visit more than once a year?), influences the form of the dependent variable and the kinds of variables that can be included in the equation.

Choice Theory

The earliest conceptual basis of the TCM is found in the writings of Hotelling (1947) and Clawson and Knetsch (1966). Although constancy in site fees precludes direct estimation of a site demand schedule, they recognized that the large variation in travel costs to a site from many zones-of-origin permits estimation of a demand curve. The estimate is equivalent to the site-demand curve if consumers react to higher site-use fees the same way that they react to higher, per trip travel costs.

Bockstael (1981, 1983) showed that the TCM is simply a special case of the Hosehold Production (HP) approach (Becker, 1965) in which the household members produce recreational trips and related trip quality (e.g. fish harvest) by combining their skills, purchased inputs (e.g. gasoline) and publicly provided inputs (e.g. habitat). In the HP formulation, site-quality characteristics comprise variables that can be chosen by the recreationist because quality can be determined in part by the household members.

The HP approach becomes the equivalent of the TCM when the household cannot influence the quality of recreational experience and a household's marginal site visit cost is constant. The resulting TCM demand schedule is one which each recreationist faces a potentially different supply schedule at their current per-trip travel cost. Each of the two conditions is discussed below.

First, the assumption that individuals travel cost per trip is constant is often reasonable and has been an implicit assumption of most empirical applications of the TCM. For the assumption to hold, each trip to a given site costs each household the same amount and the main source of variation in travel costs among households come from each living at different distances from the site. In other words, tavel cost is externally "imposed" on recreationists by virtue of their location in relation to the recreational opportunity. However, Ward (1984) and Brown et al. (1983) have shown that a portion of travel costs can be decided upon by the household. This finding has major implications for estimating site demand and benefits.

Second, the quality of the recreational experience on site may be outside the household's control in many recreational settings. For example, buying a bigger boat does not increase the water level or water quality in a reservoir for fishing. Having a better kayak does not improve the river for rafting, which is determined by nature or by reservoir operational decisions.

In summary, measurement of recreational benefits under conditions of externally managed quality and constant per trip travel costs can be carried out using the TCM. When one or more of these conditions do not hold the analyst may need to modify the simple TCM (e.g. Ward 1984) or use a more general HP approach (Bockstael and McConnel 1981).

Managers often wonder why economists "count" the unpriced benefits consumer surplus for outdoor recreational services but do not count similar benefits for marketed commodities. Burt and Brewer (1971) explained the phenomenon. Essentially, introduction or removal of a recreational site generally creates a relatively large price reduction for people who live close to the site. This price reduction is typically a free (unpriced) benefit. Most watershed-management decisions change the supply of market good (e.g. cattle) that are traded in national or international markets and there is no perceptible change in price. With no change in price, society's willingness to pay for the marketed good is limited to the change in receipts existing (price times change in quantity) after production costs have been subtracted. There is no gain in unpriced benefit. However, if the project of land-use decision is large enough to change the price of the marketed good produced in the watershed (e.g. reduce the national average price of cattle) then the consumer surplus for that marketed good also must be included.

Definition of Site Use (Quantity)

Several different measures of the quantity of on-site recreational consumption have been used in past research. These include visits, trips, and visitor days. As discussed by McConnel (1975), the household decision-making process implied in the TCM requires each round trip to reflect one unit of consumption. When using travel cost as a price, the only logical unit of consumption is a trip or visit to the site. Travel cost cannot be meaningfully assigned on a per visitor day basis of trip when the trip itself is the main decision.

In their TCM demand schedules Clawson and Knetsch (1966) used visits per capita (of total population) from zones of visitor origin, rather than absolute visits, as the measure of recreational quantity consumed. That approach has become known as the "zonal" or "aggregate" method because recreationists living at similar distances from a site were grouped into zones (e.g. one or more contiguous counties). To adjust for differences in population sizes of the zones, or counties around the site, absolute aggregate visits were divided by the total population in the zones. If this adjustment for population is not performed, a false positive relationship can result between total visits and price, especially if the largest population centers are located farther from the site.

A researcher who employs zonal averaging typically assumes that all site visitors from a given zone have similar tastes and preferences. The use of total visits per capital as the dependent variable accounts for both the probability of participation and the number of trips. It does so by estimating only one coefficient for the interaction of both variables to account for both decision processes. This approach is simplistic; more recent methods employ probit and logit analysis to model these two decisions independently (e.g. Hanemann 1981).

A related statistical problem, often associated with any sort of per capita specification of the dependent variable, occurs when the units of aggregation (here the zones) have radically different bases of aggregation. Zones of origin can have populations ranging from a few thousand to several million which can introduce non-constant error variance (heteroskedasticity) into site-demand schedule (visit predictions) estimates. Suggested corrections include specifying population as an independent variable (Knetsch et al. 1976). weighting the observations by square-root of the population (Bowes and Loomis 1980), and selecting a functional form which minimizes the effect of inconstant error variance (Vaughan et al. 1982 and Strong 1983).

The zonal TCM has serious limitations that result from the loss of information incurred by aggregating data and the inability to separate out the influence of travel time from monetary travel cost or participation. Useful information is often lost in the aggregation by using zonal average income, average price of substitutes, average tastes and preferences, and average site-use determinants. As Brown and Nawas (1973) point out, estimates of the travel cost coefficient from zonal models are often statistically imprecise and therefore leads to inaccurate estimates of the price coefficient which is used to compute benefits of various management decisions.

It is important to adjust the price coefficient to properly account for the influence of travel time. In the zonal TCM adjustment this is difficult to accomplish because aggregating recreationists by similar travel distances tends to create a high correlation between travel cost and travel time. Thus, attempts to adjust for the separate influence of travel time on the number of trips taken, by including a separate variable, often meet with frustration.

Brown and Nawas (1973) and Martin and Gum (1974) developed the "individual observations" TCM approach to contend with inability to measure the effect of price on visitor participation. In their approach, the quantity consumed by recreationists is defined as the number of trips taken per year or season by each household and the sample size equals the sum of all households sampled. This quantity is regressed against the household's individual monetary travel cost, travel time and socioeconomic characteristics. Because there is no aggregation, correlation between travel cost and travel time is reduced and the separate effects of price and other variables on visits are more effectively measured.

Two difficulties emerge with this disaggregation. First, when a typical recreationist only takes one trip a year (as in the case of fishing for a unique species), it is impossible to estimate a disagregated TCM demand schedule because each individual's visits per season do not exceed one. Second, the role of distance in influencing probability of participation is ignored. The disaggregated approach models only those visit rates by households which have already made the decision to visit and underestimates in crease in aggregate visits with provision of a closer, similar site. Underestimation happens because prospective potential site visitors have necessarily been excluded from the on-site sample. Brown et al. (1983) have shown that when the proportion of non-participants increases with distance from the site, the TCM based on individual observations overstates the benefits.

Solutions to this problem of omission of non-participants bring us to the current state of the art in defining the quantity variable. Brown et al. (1983) proposed maintaining the individual observations for independent variables but divided each individual's trips by their "share" of their zone's population. This method appears to combine a good feature of zonal TCM (unbiased benefit estimate) with the best features of the individual-observation TCM (statistical precision in price-parameter estimates).

Alternative corrections include sequentially estimating two equations: (1) probability of participation (such as using probit analysis) and (2) individual-observation TCM equations conditions on actual participation. These two functions can then be linked sequentially to calculate a consumer surplus, reflecting the influence of both functions. Similarly, a multinominal logit model could be estimated. In it the probability of participation and number of trips taken becomes part of a nested decision process (Peterson et al. 1982, Hanemann 1981).

Definition of Price

Early applications of TCM specified transportation cost per round trip, excluding travel time, as the price variable. However, Cesario and Knetsch (1970) recognized that more distant recreationists visit a site less frequently than recreationists living closer to the site because of the joint and compounding effects (costs) of transporation expenses and travel time. The opportunity cost of extra travel time acts independently of transportation expenses to inhibit visiting of more distant sites. When opportunity cost of travel time is left out, visitation incorrectly appears to be quite sensitive to the travel-expense price because all of the observed decrease in visitation is falsely ascribed to transportation expenses alone. This results in estimation of a biased price coefficient that is too price sensitive and underestimates site benefits.

Correction for this potential source of site under valuation has taken several forms. Because of the correlation between transportation expenses and travel time in the zonal model, a separate variable for travel time to the moneyequivalent transport cost to arrive at a total travel cost. The approach appears appropriate but resulting benefit estimates depend on the specific value of the travel time chosen.

Since Cesario and Knetsch's (1970) suggestion, much effort has been applied to estimating the value of travel time (Cesario 1976 and Strand 1981; Ward 1983; Smith et al. 1983). Currently, many analysts rely on travetime values derived from commuting studies like those summarized by Cesario (1976), and use a value of onethird to onehalf the wage rate as the value of travel time for recreational travel can be found in McConnell and Strand (1981) and Ward (1983). They inferred the value of travel time from visitors' willingness to trade off travel cost and travel time. While their results are specific to samples, they concluded that 33 percent is a conservative percentage of the wage rate to use for valuing travel time.

There has also been discussion in the literature about whether the opportunity costs of "on site" time need be included in the price variable or incorporated into the regression. According to McConnell (1975) the opportunity cost of on-site time should be included in the price variable and failure to do so will underestimate benefits. Knetsch and Cesario (1976) believed that on site costs should be excluded. Wilman (1980) developed amodel showing the necessity of including on-site time under certain circumstances. Smith et al. (1983) also suggested the importance of including on-site time. Recent work by Ward (1984) demonstrated the need to account for on-site time in determination of the trip cost when all or part of the on-site time is a choice variable and varies with distance.

No concensus exists about the exact form for inclusion of on-site time and whether it should be valued differently from travel time. While there is clearly an opportunity cost to time on site, it is precisely this time that produces the enjoyment desired by the recreationist. One way to account for differences in on-site is estimating different demand equations for trips of different length (Miller and Hay, 1984).

Congestion and Other Quality Measures

During the late 1960s, crowding at recreational areas sparked emthods to employ the TCM to properly estimate demand and benefits of congested recreational sites. Smith (1975) examined the difficulty in the context of wilderness areas where the level of congestion and hence quality of the recreational experience varied over a period of data collection.

McConnell (1980) and Anderson (1980) showed that the TCM can be used to construct a congestion-"constant" demand curve. They argue that it is from this demand curve that the benefits of the site under current level of congestion are correctly measured. To find the net willingness to pay, congestion must be held constant at the current level when calculating the area under the demand curve. When congestion varies over the sample period, it may be necessary to include a "shifter" variable to account for changes in congestion. Alternatively, it may be possible to estimate demand curves for weekdays, weekends and holidays if congestion is homogenous within but not among visitor categories.

Congestion is one of many sitequality determinants. Other quality measures include harvest success in fishing or hunting (Mendelshon and Brown 1983; Donnelly et al. 1984), water quality (Smith et al. 1983), and recreational site size (Knetsch et al. 1976). Attempts to include site quality have generally required modifications of the simple TCM. Instead of developing single-site models in which site quality remains constant, multi-site models have been estimated. Multi-site models can be single-equation models which incorporate the influence of substitutes as shifter variables, (Cesario and Knetsch 1976; Vaughan and Russell, 1982). Alternatively, Medndelshon and Brown's "Hedonic TCM" rearranges the entire TCM problem from "many origins to a singe site" into a "single origin selecting among many sites." Their approach uses travel cost to estimate willingness to pay for characteristics of a site such as scenery and fish harvest in the first stage. In the second stage, a demand curve for the characteristic is estimated using each origin's price of a characteristic and quantity of characteristic consumed. The hedonic TCM approach is claimed to be a compromise between a Household Production approach and the simple TCM (Mendelshon and Brown 1983).
In some cases direct incorporation of site characteristics (such as air quality or visibility) into the TCM can be quite difficult. In these cases where the proposed level or type of quality is outside of the range of observed visitor experience, methods that directly assess willingness to pay, such as the Contingent Valuation Method, may be more applicable.

Substitutes

Economic principles suggest that price and availability of substitutes are important demand (visitation) determinants. If the price of a site and the price of substitute sites are positively correlated, then omission of substitute site price will result in estimation of a more price-insensitive inelastic demand schedule than the "true" demand schedule (Caulkins, Bishop and Bouwes 1984). The recreationist benefits derived from this demand schedule will be an overstatement of the true benefit. Essentially, the overstatement results from falsely ascribing reductions in visitation at hgiher travel costs to an inelastic demand for the site rather than to the true effect of a higher price of substitutes faced by more distant origins.

Much effort has gone into incorporating substitutes into the TCM demand curves. Burt and Brewer (1971) and Cicchetti et al. (1976) use a system of multiple-site demand equations. The price of both the targeted site and cross-price effects of other sites are included in the target site each demand equation. A management decision that introduces or deletes a site is treated as a price change. Introducing a new site is viewed as lowering the price of its best substitute for all zones of origin closer to the new site.

Often, approaches that rely on a system of multiple-site demand equations suffer from a high degree of multicollinearity between the target site's price and prices at other sites (e.g. visitors who live a long way from one recreational site may live a great distance from all recreational sites). Knetsch et al. (1976) addressed these problems by using an "index" value as a measure of substitutes. They use the ratio of site quality of the substitute site (e.g. surface acres, fish harvest, etc.) divided by distance from the origin to the substitute site. For higher values of this ratio for a given origin-substitute site combination, the substitute site is aid to be more competitive to the study site.

Limitations of TCM

Because the TCM measures a site's price by its travel cost, recreationists on multi-destination trips must be excluded. It is incorrect to ascribe the entire travel cost to any one site for the visitor on a long vacation, who visits many recreational sites. Doing so will result in overestimation of site benefits (Smith and Kopp 1980; Haspel and Johnson 1982). Such vacations, in fact, produce a joint product in which ascribing portions of total travel cost to any site necessarily involves arbitrary cost allocation. Haspel and Johnson (1982) have provided one plausible cost allocation for recreational trips to Bryce Canyon National Park. In practice, most researchers limit their TCM analysis to single-destination users and, if necessary, generalize these results to all users.

The TCM is limited to measuring the on-site recreational benefits provided by a site or facility. The benefits estimated from TCM do not include any option values for future use (Bishop 1982) nor any "existence" values (Randall and Stoll 1983), or other "off-site" values. In other words, the TCM does not reflect the value associated with potential visitors "just knowing it is there." For designated wilderness areas, Wild and Scenic Rivers, and unique wildlife species (e.g. bighorn sheep or whooping cranes), off-site benefits may be equal to or greater than the recreational benefits (Walsh et al. 1984 Brookshire, et al. 1982 Stoll and Johnson, 1984). For many types of commonly available recreational sites including most fisheries, the omission of off-site user benefits is probably not very significant. However excluding off-site values, as was done in the sport-fishery management model for the Rio Grande Basin, probably results in a small underestimate of resource value.

Conclusions

The TCM has evolved into a diverse set of techniques for estimating visitor demands schedule for and benefits from on-site management decisions. The simplest version of the TCM uses transportation cost as the price variable and some measure of per capita visitation as the quantity variable to trace out a demand schedule. Much research has refined the price variable to include travel time, and sometimes on-site time. Shifter variables reflecting site quality (e.g. congestion, harvest, etc.) and substitutes have lined the TCM more closely with economic concepts and expanded the type of resource allocation decisions to which the TCM could be applied.

Federal agencies under the auspices of the U.S. Water Resources Council often use the TCM to estimate benefits of recreation gained or lost because of resource development. Agencies such as the U.S. Forest Service and Bureau of Land Management, which require estimates of net willingness to pay for resource allocation decisions, are also turning to TCM estimates.

However, several issues remain less than satisfactorily resolved. These include valuation of travel time in the zonal TCM, treatment of on-site time and incorporation of substitutes and site quality into TCM demand curves. Total concensus on some of these issues has yet to emerge.

METHODS

Model-Development-Strategy

Philosophical Foundation

The type of model to be developed and the strategy to be used in development were evaluated. During the modeling feasibility study conducted in 1979-80 (Cole et al. 1980 the team took a holistic approach to develop a model that could (1) organize past data collection as much as possible into a meaningful whole, (2) guide new data collection to improve model performance, and (3) mathematically simulated those relevant aspects of the Rio Grande Basin that could be used to analyze sport-fishery management problems in the basin. Agency planners perceived the model as a mechanism for integrating fishery science and fishery management more effectively than in the past. In meeting that objective, the research team defined the terms fishery science and fishery management much like Lackey (1975) who wrote: "In the broad sense fishery science is the study of the structure, dynamics and interactions of habitat, aquatic biota and man and the achievement of human goals and objectives. Management is the analysis and implementation of decisions to meet human goals and objectives through use of the aquatic resource." Therefore, the model needed was one that could simulate interactions among habitat (hydrology), aquatic biota (biology) and economics so that the mathematical simulation could be manipulated to analyse the consequences of management decisions about the aquatic resource. The model was to be a cost effective management tool, used for predictions. Within that context, the model was to be useful for guiding future research toward more complete understanding of the ecosystem and, also guide fishery management decisions.

Identification of Management Problems.

The method used to develop the model was a generally accepted process similar to the one reviewed by James and Burges (1982) and shown in figure 5 from Orlob (1975). First the quantities that were important to the user had to be identified so that the model size and detail could be conceptualized. The intended users who sponsored model development wanted much flexibility in potential model use because of unforeseen predictive needs for management purposes. For example, if an agency proposed to build a dam anywhere in the Rio Grande Basin, fisheries managers wanted to know how that subsequent reservoir operation would influence sport-fisheries? Or if an agency proposed significant changes in land management practices or waste disposal somewhere in the system managers how would want to know how those changes would influence sport-fisheries? Other needs were more obvious. How, for example, should regulations and stocking practices be modified, if at all, under anticipated fluctuating water conditions? Based on discussion of the perceived uses, the research team chose a model that met the objectives defined in the introduction.

Associated with the need for model flexibility was a need for a spatially comprehensive model. The intended model users had an imperfect idea of which part of New Mexico would first require modeling attention, but decided that the most densely populated river basin, the Rio Grande Basin, would be an appropriate start. The selection of a spatially large-scale model, with the funds available, placed limitations on modeling detail. In an alternative approach, which was discussed and rejected, a certain segment of the basin was to be chosen for detailed modeling attention, with the intent of developing greater accuracy in

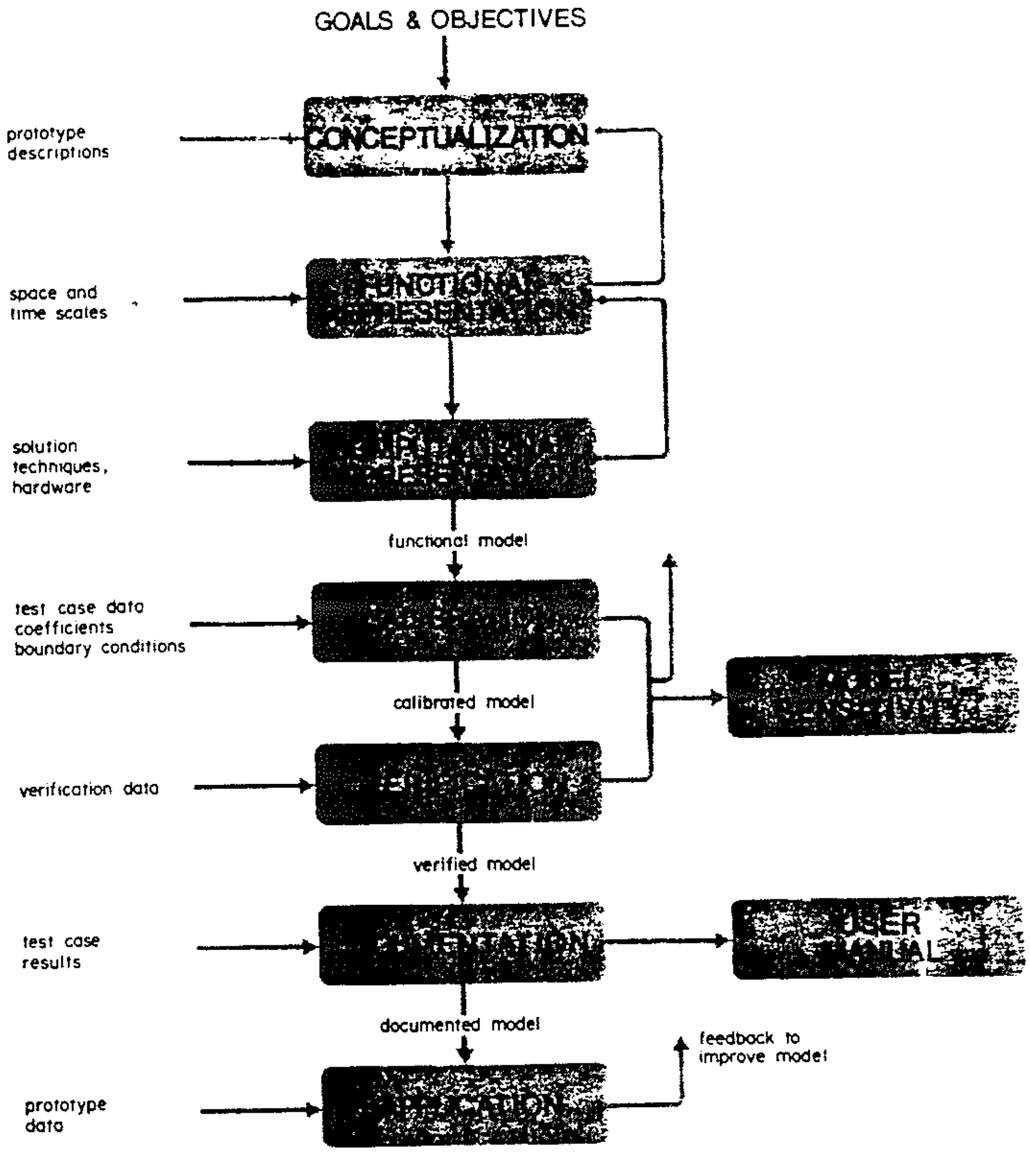

Fig 5. The general process used to develop, validate and apply a model (from Orlob 1975).

the resulting spatially restricted model than would be feasible for a model of the entire basin constructed in the same time period with the same funding.

After deliberation, the researchers and sponsors together decided to include the following model components: All reservoirs in the system because they depended on hydrologic knowledge elsewhere to simulate the operation of a single reservoir realistically. If water redistribution in or out of any mainstream reservoir were to be realistically simulated, all other reservoirs acting to provide or receive water had to be included.

The values of fisheries in "competative" water bodies, which could serve as alternative fisheries, had to be included to estimate fishery values reaslistically. Economic values were expected to be influenced by factors other than fish yield (such as proximity of the water to large cities; consequently fishing could sometimes become the major source of fish mortality. Because anglers were expected to make their site selections partly on the basis of alternative site availability, the complex interactions among anglers and fish had to be simulated within a large enough geographical area to include numerous fishing-site alternatives. A large river basin was thought to be the smallest reasonable area to model realistically.

Because it had broader applicability to solution of management problems, a large basin provided a research tool which, through sensitivity analyses, would help in model refinement once the model structure was first developed.

In addition, with the operational constraints inherent in management agencies in New Mexico there was more likelihood of organizing data collection for monitoring model predictions for a large management area than there was in concentrating effort in a small area.

Within the Basin, the mainstream river was identified for modeling attention, with greatest focus on the reservoirs. Connecting waters were collectively considered less valuable as sport-fisheries and, therefore, of secondary concern in this particular model's development. Because of its comprehensiveness and holistic approach, the model was conceived to be a continuously evolving model, in the sense of O'Neill (1975), which upon completion, would be used to organize future data collection made in routine agency operations into a continuing refinement of model structure. This should also result in a continuing refinement of management utility as data accumulation improves the accuracy of model prediction. The model was designed to be most suitable for large-scale management decisions (e.g. where to concentrate fish management attention, how to design the most suitable long-term harvest and stocking strategies, where if possible to redistribute water, how if possible to redistribute flows to encourage more spawning). Although the model is also designed for more specific predictions of responses of individual water bodies to various water-management alternatives, the accuracy of those predictions is expected to be less than for the system as a whole. Agency decisions about the specific needs for accuracy in the future will determine which specific water bodies should receive the most research attention for model refinement. The model was designed to help with that aspect. If, for example, the model indicates that a particular Basin segment contributes a disproportionately high amount of sport-fishery benefit to New Mexico anglers, but the coefficient or input data are exceptionally uncertain, that site may deserve more research attention than a segment with lower benefits and more certainty in the coefficient and input data.

As indicated in Figure 5, once the research team and sponsors together identified the geographical area and model outputs the research team developed flow charts for a prototype model were developed to identify the necessary components of the system (Cole et al. 1980). The prototype model was used to guide model development but many specific alterations were made as equations were selected for model construction. The equations were assembled into a computational representation and coefficients for the equations were selected from local data sources obtained in the Basin and from scientific literature. The model was calibrated with incorporation of the best data available that provided the best model fit to observed values in the system. At the end of the five year project period calibration was considered completed *de facto* because the model can be improved through further research. This was decided based on the generally accepted approach described by O'Neill (1975) who emphasized, for those inexperienced in modeling methodology and model use, that successful modeling is a continuing process, rather than an end in itself, and it should be valued as much for its organizational and communication purposes as for its predictive purposes. However, to force periodic evaluation of the process, O'Neill (1975) emphasized that periodic documentation of successive versions of the model is needed. The first complete documentation was planned for five years after model initiation in summer 1985.

The five-year modeling objectives did not provide for complete verification. The research team believed that with the funds available and the scale of modeling required that data searches for structural development and calibration would take the entire five year period. Calibration studies and some verification of the biological parts of the model were completed under separate contract obligations reported in Cole et al. (1985). As a consequence, the modeling process as defined by Orlob (1975) and James and Burges (1982) was not complete for the final project report because verification was not included in the five-year segment. The model documented in the form of this report then is likely to be altered by complete verification of the model.

Any further data can be used to to validate model performance. Because uncertainty is represented in statistical variance in all aspects of the modeling process (model structure, stochastic simulations, calibration data and test data) test data will only by small chance exactly fit model prediction. The amount that the test data proves different from prediction will provide model users with an improved sense of model utility. The test data then can be used in the model to refine and calibrate it more precisely.

Specific Model Types Used

Among the modeling strategies available as described by James and Burges (1982) were (1) process models (e.g. food conversion efficiencies times food available generates fish production in the prevailing environment), (2) regression models relating major spatial-inputs to model outputs (distance, size, elevation, and fish biomass collectively determine angler visitation); (3) time-series models, which seek to correlate outputs with past temporal events (e.g. next month's discharge is correlated with last month's discharge during snowmelt); and (4) a statistical optimization model in which a totally integrated, multiple-regression model is calibrated for delivering the one "optimum" output condition (e.g. simulation of a specific set of conditions in the Basin which would produce some predetermined "optimum" fish value generated).

Three of the four modeling strategies are used in various parts of the model. The statistical optimatization model was not used because it was too specific, to rigid and could not deliver all desired outputs. Another limitation was inherent in the necessary definition of a preconceived optimum output value. The conditions which maximize fishery resources in the Rio Grande Basin are not the conditions which provide optimum economic benefit for water use in the state. Some intermediate fishery value is likely to be optimum in the context of total water use. The model users who sponsored the research needed a model that would help them to determine those intermediate values.

Process models, which simulate mechanisms and are based on a quantitative understanding of cause-and-effect sequence of process interaction, are the most flexible of models. This flexibility increases as the sub-processes within processes are increasingly defined. However, one cost of flexibility in such models is some imprecision in prediction because the processes are usually represented with globally determined data transformed into idealized mathematical logic, rather than site-specific data represented in specific multiple-regression descriptions. Inherent in the mathematical simplication of a process is the uncertainty embodied in the idealized mathematical representation of the process. Uncertaintly can be reduced through use of coefficients and structural refinements based on site-specific attributes of the basin to which the models are being applied. These empirical adjustments are often made through regression analyses, thereby producing a hybrid model.

The biological portion of the model proved to be a candidate for a process model hybridized with empirical regression analysis of data determined at sites in New Mexico. The model users, the sport-fishery management agencies, were most concerned with the responses of biological processes, (culminating in fish growth, production, and yield) to hydrological and economic variation. A process model would allow the model user to enter into the biological component of the model at a large number of points to obtain output on primary production, fish-food production of different types, fish survivorship, mortality, recruitment and growth among different populations, fish yield, and the surplus yield that remained available to anglers. Multiple-regression models were not used because they would not treat the required flexibility nearly as effectively. Although process models often cost more to develop the same level of accuracy as multiple-regression models, they have a wider range of applications. Furthermore, in this case, much of the biological process was already known and therefore process modeling was cost effective.

The desired economic and hydrologic outputs were fewer than the biological outputs, they included the fishing effort, fishery benefits, local income generated by fish, and distribution of water in the system (anticipated levels, surface areas, volumes, and discharges). Therefore, flexibility was much less a priority need and global regression approaches were viewed as reasonable modeling alternatives. In the case of modeling the economics component, processes were poorly defined and a process model, therefore, did not apply. A regression model which related spatial inputs to model outputs was used. In the case of the hydrology model, a combination of time-sequence correlation modeling (the greatest emphasis) and some process modeling was viewed as the most cost-effective approach in development of the working model for the intended purposes. The primary limitation of the regression approach is that its applicability is limited to the conditions under which the regressions are developed.

Because process models are usually developed to represent universal conditions, no management choices applied in a river basin are likely to exceed the model's capacity. However, multiple-regression models define only that part of the universe from which their data are derived. Therefore any management option that creates conditions beyond those incorporated in the regressions are not reliably predicted by the model. This limitation reduces management options. For example, the economics model could possibly predict substantial angling visits to a dry lake because no such condition is represented in the data set used in the model. Extremely small to dry lakes need to be included to accurately define the relationship between lake area and fishing effort under dry conditions. The primary advantage is greater predictive accuracy for the range of sampled conditions represented in the model.

The modeling detail needed was also defined mostly by the output requirements and flexibility. The most detail was needed for generating the highly variable hydrologic inputs to the biological and economic submodels and for the numerous potential biological outputs. Less detail was modeled where there was less variation or less user interest. The complexity used in the model was limited to that necessary to meet basic user demands settled upon for model construction. As those demands enlarge in the future, a model of greater complexity probably will be required.

User "friendliness"

Ease of model use and communication of model capability were aspects which became increasingly important as the study progressed. Although the original contract defined a working model as the final product, it became apparent that the form of the format was also important if the model was to be used. The significance of this need is summarized by James and Burges (1982): "A great deal more attention needs to be given to the technology transfer of complicated hydrologic modeling; one survey could not find one user that was able to apply a complex model successfully without first taking a course on the model from someone who was previously trained..."

Because the model users would be computer inexperienced managers, the research team redirected contract funds from the previously agreed upon FORTRAN version to develop a more "user-friendly" version of the model in APL, in addition to the FORTRAN version of the model. Both APL and FORTRAN versions are included in the Appendix. The user-friendly version does not make all possible areas of the FORTRAN version of the model available to the casual user. Selection of specific output for the APL version was based on the perceived paramount needs of the model users and the degree of model complexity that could be reasonably achieved during this time period.

Computing Hardware

At the inception of this project, the approach was to develop a model written in FORTRAN for the mainframe computer at New Mexico State Univeristy. This was to be done because the primary users had access to the NMSU facilities. The environment has since changed to one where the New Mexico Department of Game and Fish no longer has access to the NMSU facilities but now has access to mini- and micro-computers. Since 1983 a user-friendly version has been developed, written in APL, which is based useable on both a mainframe and on a micro-computer. The current FORTRAN version of the research model is also based on a micro-computer. Current system specifications for the micro-based models are: INTEL

8088 processor (IBM PC or work-a-like), INTEL 8087 coprocessor chip (extremely important for speed), a minimum 256K Bytes, McMort, or MS or PC-DOS operating system, and a hard disk (recommended because of file storage). There is no restriction on monitor type or graphics capabilities. A high-speed, dot-matrix printer is also suggested for easier model use.

MODEL DESCRIPTION

An Overview of Model Interactions

Figure 6, shows how Lackey (1975) reviewed relationships existing among all categories of sport-fishery models. The Rio Grande sport-fishery management model resembles Lackey's (1975) conception (figure 7) in that it integrates habitat (hydrology), biological process, and socio-economic fishery models into a comprehensive interdisciplinary structure. The Rio Grande model incorporates most of Lackey's (1975) categories of fishery models into a single operational unit, which provides useful outputs and access for model users at several junctures. In the Rio Grande model, habitat is defined by hydrologic functions, which are coupled with the trophic-level structure in the biology model to simulate aquatic ecosystems. Using ecosystem simulations, the model predicts changes in fish population in response to habitat changes or changes induced by biological management. Economic models join with the biology models to predict the angler effort, which feeds back to the biology model to influence fish populations.

The Rio Grande sport-fishery management model is driven by physical-chemical inputs derived from data that are routinely collected at permanent monitoring stations by various agencies, but mostly by the U.S. Geological Survey (USGS) and the National Oceanographic and Atmospheric Administration (NOAA). The effects of material flows of water, suspended matter, and nutrients on fish production, yield, and economic values are simulated, and results are made available to model users. Model users are provided with a "management capability" for modifying modeled water distribution, water quality, fish harvest regulation, stocking and other site characteristics to determine management effects on the model's

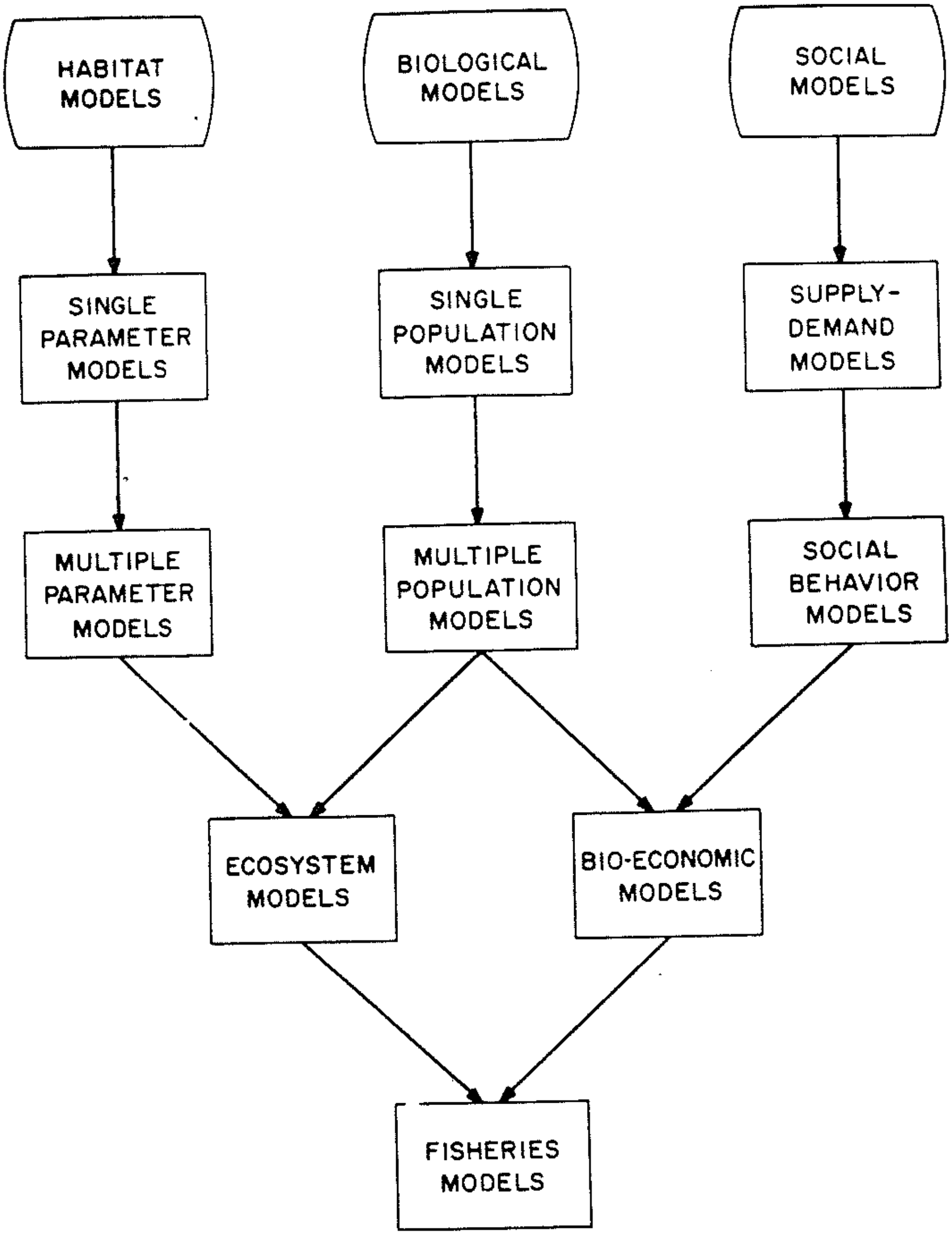

Fig. 6. The types and interactions of models that have been developed for use in fisheries management (from Lackey 1975).

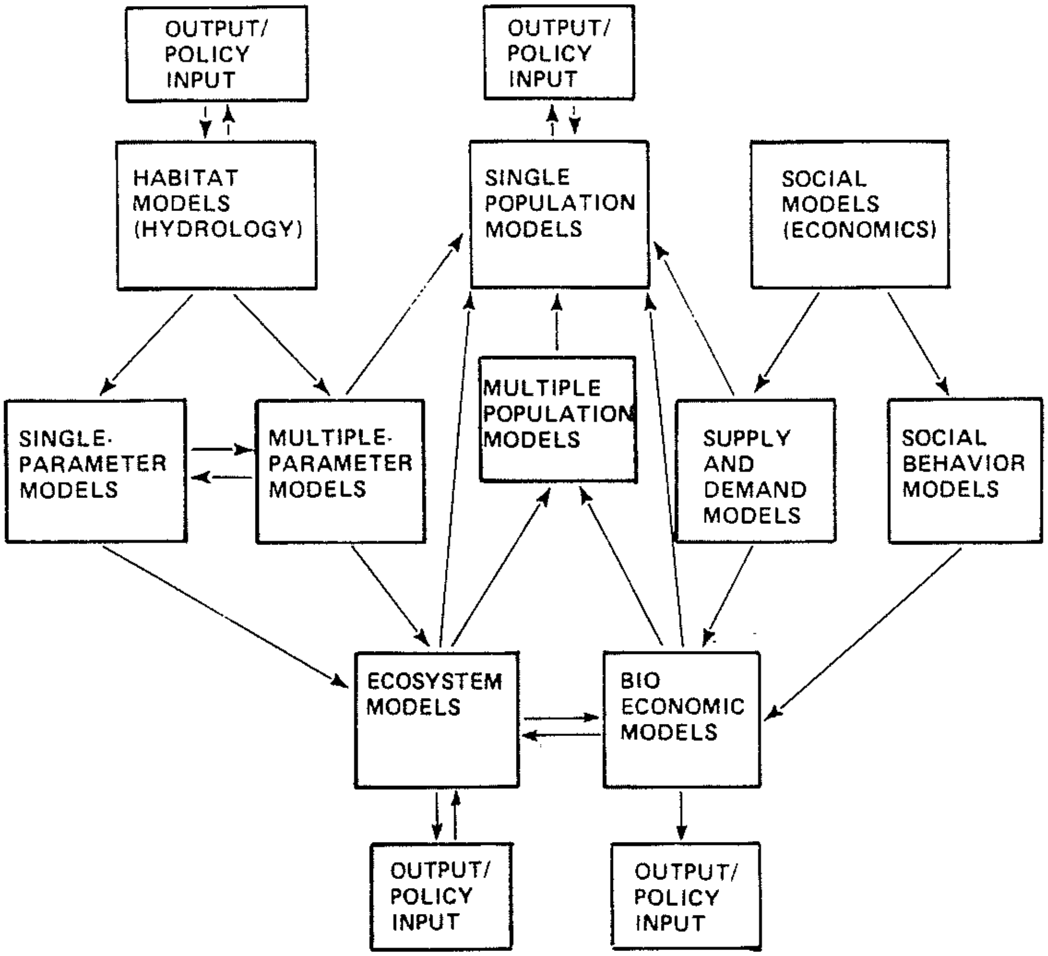

Fig. 7. Flow chart of the Rio Grande Basin Model which parallels Lackey's (1975) description (Figure 6 in this report) of models used in fisheries management. Major points of model-user entry are identified (output/policy input).

predictions (figure 1). Sport-fishing predictions include fish density, biomass, growth, survivorship, yield and economic value by group of ecologically similar species (e.g., sunfish).

The model describes all of the mainstream Rio Grande and Rio Chama basins in New Mexico (figure 8). Water input to the upper part of the basin in New Mexico is monitored near the Colorado border (Lobatos) and at the upper-most USGS station (La Puente) on the Rio Chama. Increments or deletions of water and materials are incorporated at each new monitoring station encountered with passage downstream. The basin is split into 19 water-body segments, 8 of which are reservoirs. Connecting waters are sometimes split into a degrading segment (actively eroding with large-particle substrate) and an aggrading segment (accumulating fine sediments) to reflect the differences in the more stable substrate of degrading segments below reservoirs. In the hydrologic submodels, historical data on discharge of water, phosphorus, nitrogen, and suspended matter is processed to predict time-related outputs including water volume, water surface area, water elevation, discharge, and concentrations of phosphorus, nitrogen, and suspended solids in each of the river basin segments. Mean concentrations of suspended matter and nutrients are predicted for each of the reservoirs with submodels that link loading rates to predict sedimentation. A two-week time unit is used to simulate time-related variation in hydrology.

Predicted changes in water quality and quantity serve as inputs for the biologic submodel, which also requires inputs of solar radiation and water temperature from sources elsewhere. The hydrologic inputs for short-term prediction over the next year enable stochastic predictions (some of the inputs are varied randomly so that several runs of the same

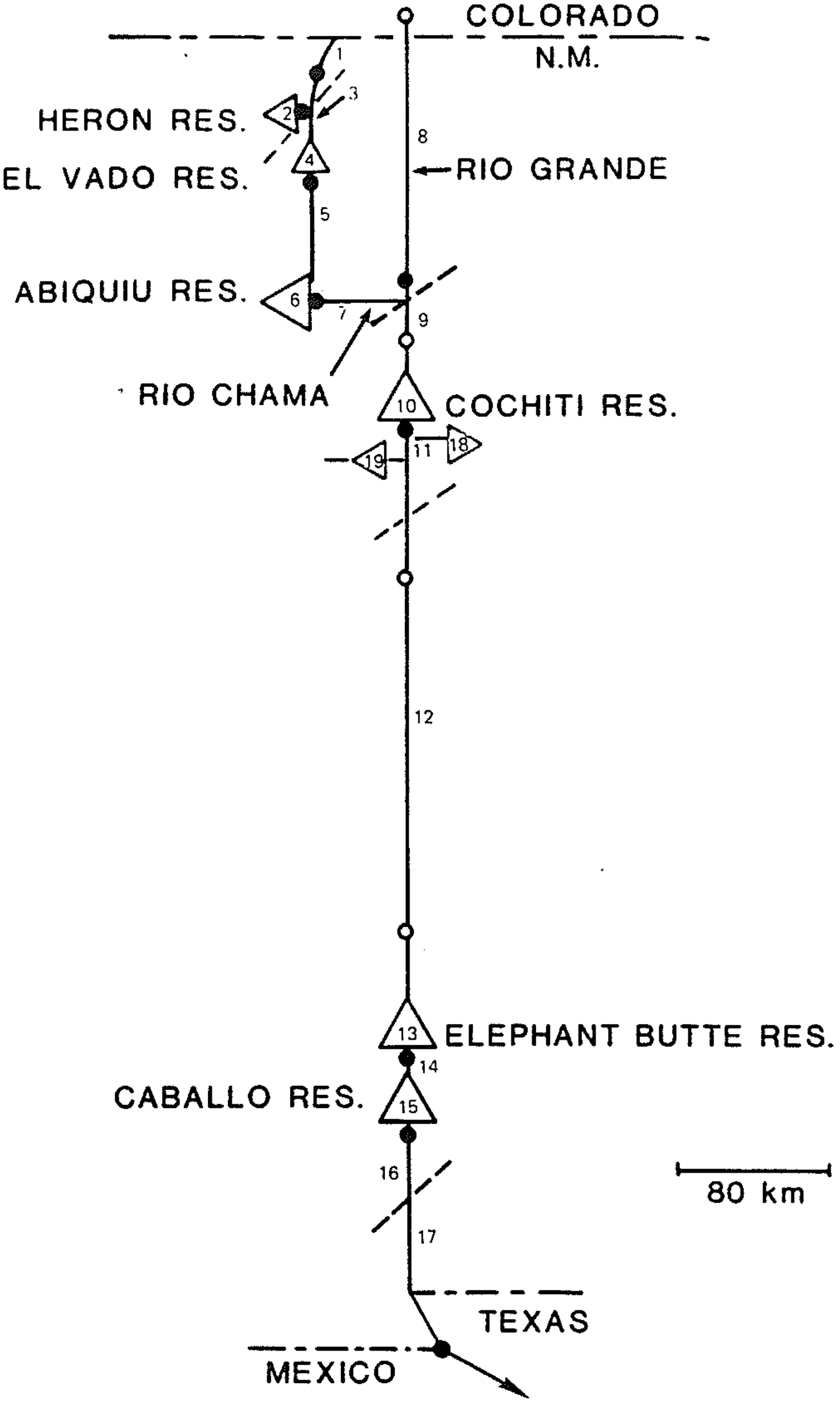

Fig. 8. Locations of the segments modeled in the Rio Grande Basin Model.

simulation will result in a range of different output values) of fish biomass and fish yield (harvest) through a series of process sub-models which simulate transfers of energy and material through the aquatic community. Annual fluctuations in fish production and fish yield are predicted from variations in water and material generated by the hydrologic submodel, climatic inputs, and variations in angler effort, the last of which is generated from the economics submodel. Biological processes are based on seasonal mean conditions.

Inputs required for the economic model include fish biomass per unit area (from the biological model), water-body size (from the hydrologic model and other aspects of environmental quality); fishing success (yield/angler day); travel distances of anglers site, access to anglers, availability of substitute water bodies for fishing, and site elevation. From these inputs, the model estimates annual sport-fishing recreational benefits and income generated in those countys nearest each Basin segment.

Simulation of flow through the Rio Grande is based on two strategies, depending on long-term or short-term modeling needs. Over the long-term, historical water and material fluctuation from 1975 to 1983 is used to simulate long-term dynamics. This form of analysis is of value for long-term agency planning which may be facilitated once agencies can accurately anticipate the range of environmental conditions that could emerge as a consequence of basin changes. For example, these changes could include water storage distributions among existing reservoirs, or the influence of new reservoirs built in the basin. Management decisions are superimposed on the historical record to estimate system responses to "what if" conditions.

For short-term questions related to when and how to stock or regulate harvest, predictions of water and material changes are based mostly on effects of snowmelt. By the end of snow accumulation in April or May, most of the volume available for storage is generally predictable, but the exact timing of the runoff is variable (figure 9). Therefore, next month's predicted runoff and the volume distributed in reservoirs is stochastically estimated. Probabilities of runoff effect on reproductive success of various fish populations are developed from simulations of temporal and spacial spawning intervals and probable rate of water-level change during those spawning intervals. Related changes in nutrient concentration and resulting changes in fish growth and survivorship also can be incorporated. In the specific description that follows, flow charts are used to help describe processes. Each unit in the flow charts is numbered to coordinate with the description below and the mathematical and program documentation in the Appendices.

Hydrologic Model Description

General Overview

Unit 1 and 2, (figure 10): The driving variable in the hydrology component of the Rio Grande Basin model is the quantity of water entering or leaving reservoirs or connecting river reaches as monitored by the USGS and other agencies. This driving variable 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 connecting waters. Both models operate on a two-week (twice monthly) time period for measured flows.

Unit 3 and 4. The reservoir submodel assumes conservation of mass.

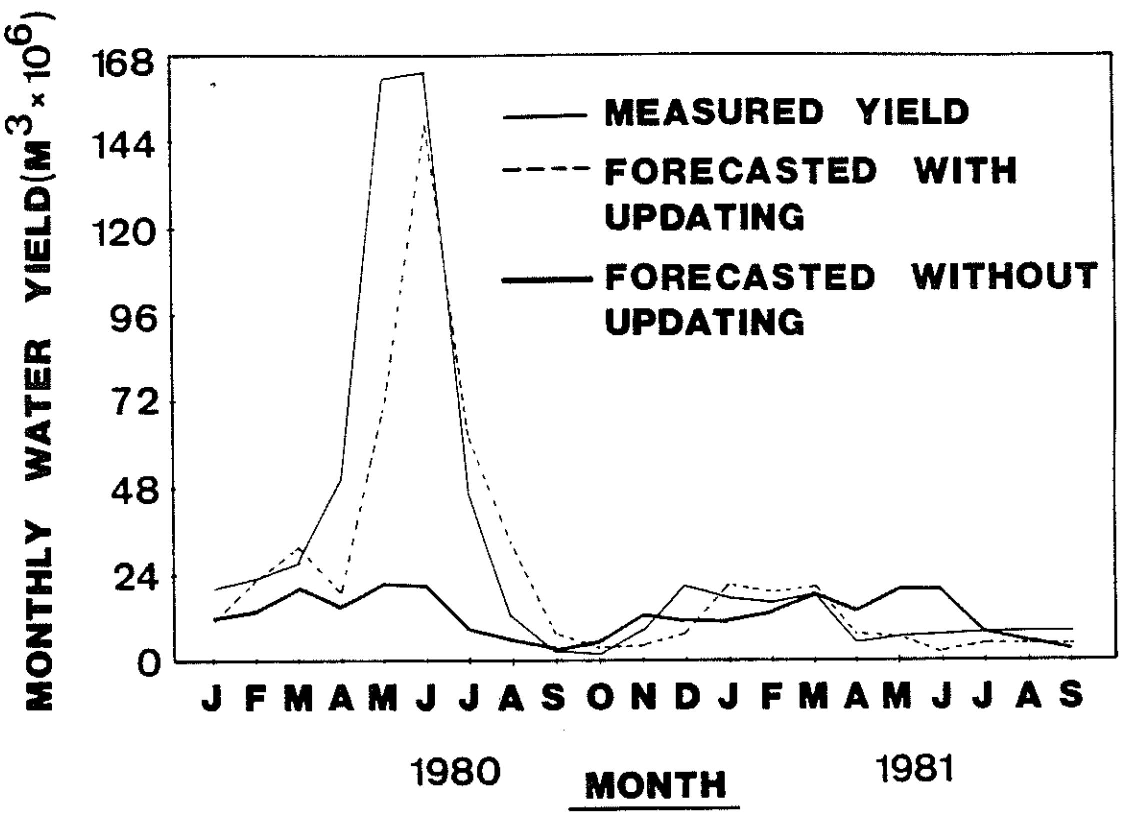

Fig. 9. Demonstration of the improvement in forecasting runoff if the input data is updated as soon as it becomes available.

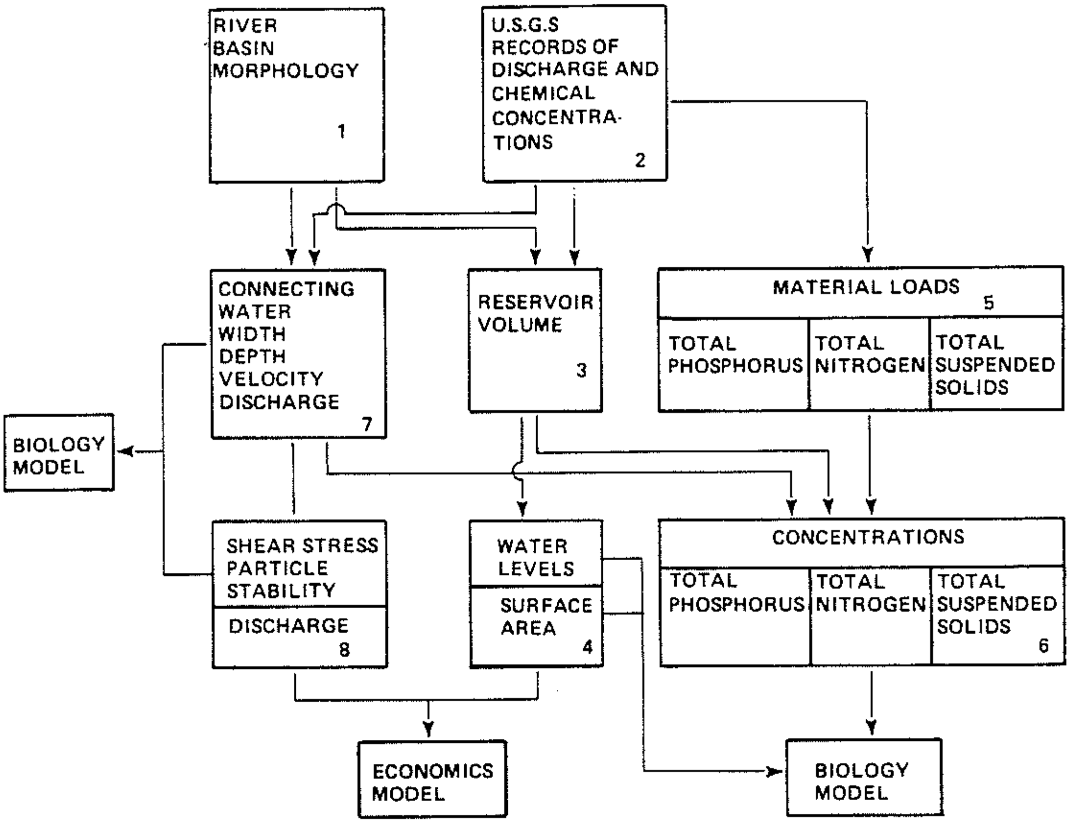

Fig. 10. Overview of the hydrology component of the Rio Grande Basin Model.

Therefore, inflows and precipitation entering a reservoir in a two-week period causes reservoir contents to increase. Reservoir releases through outflows and evaporation cause contents to decrease. An additional loss or gain may occur through reservoir leakage. Ungauged inflows and reservoir leakages can create mass balancing difficulties so that the predicted contents sometimes do not match measured contents accurately. These difficulties are particularly evident at Cochiti and Abiquiui reservoirs.

Unit 6. Loadings of total phosphorus, nitrogen and suspended sediment are included in the reservoir submodel. These loadings are estimated from U.S.G.S. data as modified by other studies (e.g., SLA 1981). 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 (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 suspended solids (suspended sediment) are either computed from empirical discharge-load relationships, or, when appropriate, are assumed to be equal to the immediate upstream reservoir 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 rates in order to analyse the effects of such management decisions on fish abundance, fish yield and fishery values. Flow charts are used to help describe in detail the hydrology submodels in figures 11 (reservoirs) and 12 (connecting waters). The detailed model description that follows is organized to match with the flow chart units.

Reservoir Submodel

Units 9-11 (figure 11). In initiation of model operation, the user is prompted for the names of files needed to define inflows, reservoir parameters (i.e. reservoir maximum contents, minimum contents, maximum outflow rates, and pan coefficients for evaporation rates), 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. Inflows can also be modified by a flow forecasting model. These synthetic forecasted flows can be generated by a peripheral model developed during this modeling

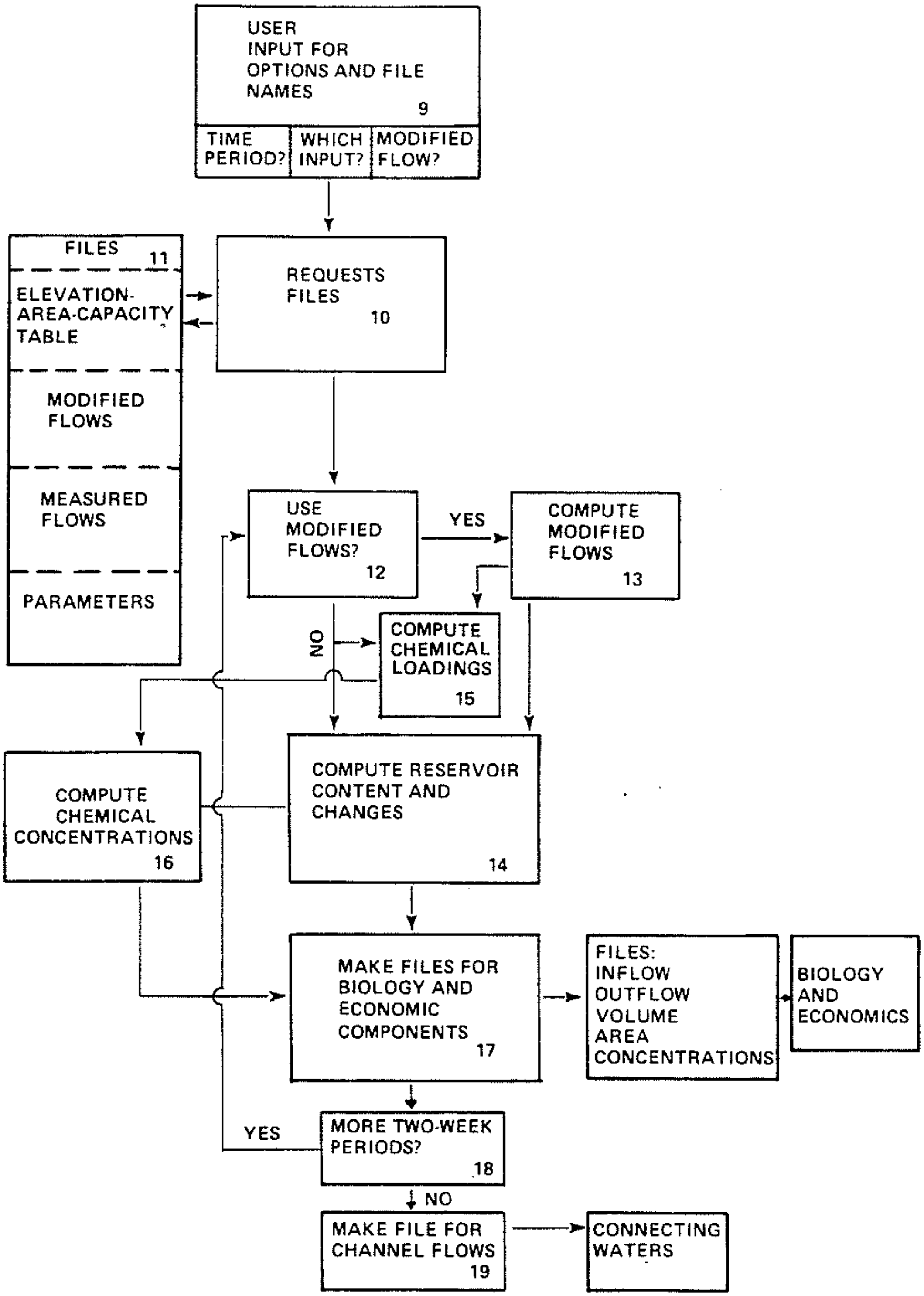

Fig. 11. Flowchart of the submodel which simulates reservoir hydrology.

effort or if the user so chooses by other models developed elsewhere. When short-term forecasting is needed for the next year or sooner, we recommend that the flow sequence be updated each month as measured data become available. This approach provides the most accurate short-term forecasts.

Units 12 and 13. The user, at this point, can select either the historical record, a synthetic 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 June flow at the Otowi Bridge gauging station was determined from nine years of flow records to be 1.083 times the combined outflow from Abiquiu Reservoir and the Rio Grande at San Juan Pueblo (where another gauging station exists). The flow records were from water-year 1975 through water-year 1983. Similar relationships were developed for each month at each reservoir inflow gauging station. With these relatonships, 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 ouflows) 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 contraints, the volume is used to compute area and elevation for other uses.

Unit 15 and 16. Reservoir inflows contain phosphorus, nitrogen, and suspended sediments. USGS data were analyzed from monitored sites to determine relationships between total load (tons/day) and 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 at some sites were estimated from those at other locations. Currently, the most complete data are from gauging stations at Otowi Bridge and San Marcial. Other sites have less data. For example, the gauging station on the Rio Chama above Abiquiu Reservoir only provides data for inflow and suspended sediment; not nutrients. Therefore relationships generated at Otowi Bridge were used to estimate nutrient loadings into Abiquiu Reservoir.

The loadings calculated for each reservoir are converted to reservoir seasonal concentrations of suspended solids, total phosphorus, and total nitrogen by equations developed by Bolin (1985). These equations use a steady-state solution to a chemical mass balance formulation — i.e. 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 independently calibrated with data for Abiquiu, Cochiti and Caballo reservoirs but not for other reservoirs in the system. Descriptions of the retention models are given in Bolin (1985), Bolin et al. (1985) and Bolin et al. (1987).

Unit 17. At this point, hydrologic files are composed for passage to the biological and economic 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 suspended sediment.

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 activity 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 10, can also be accessed by the user of the submodel for connecting waters.

Connecting-Water Submodel

The connecting-water 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 12. Differences are pointed out below.

Units 20–22. 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 suspended solids, total phosphorus and total nitrogen.

Units 23 and 24. At this point the model user chooses to use 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

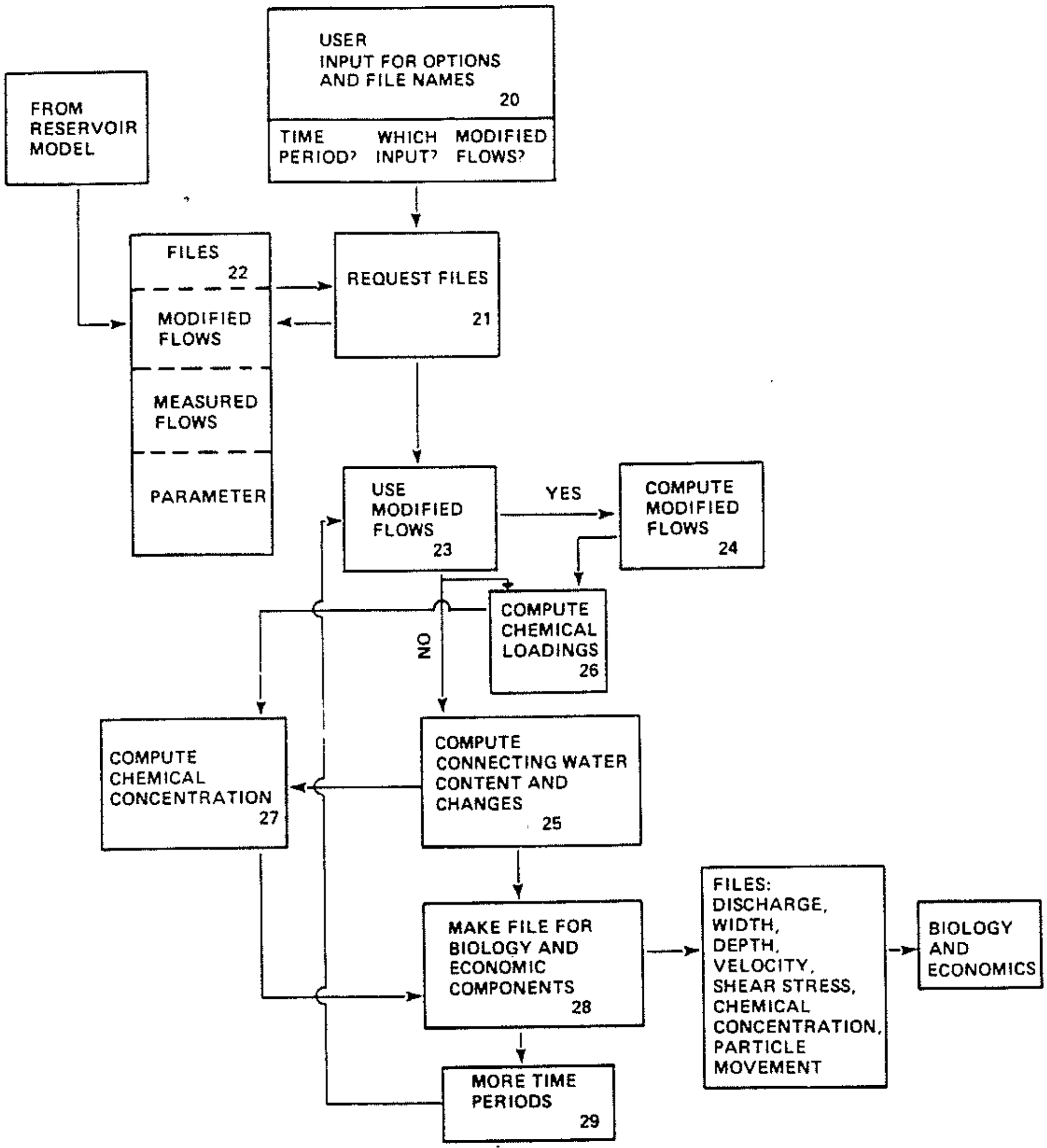

Fig. 12. Flowchart of the submodel which simulates connecting-water hydrology.

because the reach is immediately downstream from the reservoir. For reaches farther downstream from a reservoir, such as Albuquerque below Cochiti 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.

Unit 28. At this point the model creates a file for the biologic and economic components of the Rio Grande model. 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 phosphorus, nitrogen and suspended sediment.

Biologic Model Description

General Overview

The controlling forces in the biological model are inputs of mean seasonal 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 volumes of water which move through the reservoirs. Mathematical relationships are given in the mathematical appendix. Flow rates and basin morphology, interact to determine water-level fluctuation, surface area, and water exchange rates. Figures 13, 14 and 15 show flow charts of model contents that can be used as visual aids for the following descriptions of biological processes. The first part of the biology model, depicted in figure 13, applies with some exceptions to both reservoirs and connecting waters. Figure 14 describes the model used to partition energy among fish populations. Figure 15 represents additional components used in the model of connecting waters.

The Reservoir Production Model

Units 1 and 2 (Figure 13). Phosphorus concentrations are calculated as described in the hydrology section. Mean euphotic-zone (where algae have enough light to use nutrient) concentrations of phosphorus in each reservoir are calculated seasonally from loading-concentration submodels. Modifications of submodels reviewed by Bolin (1985) are incorporated to predict phosphorus concentration from phosphorus loading. The loads are estimated from discharged nutrient measurements recorded in U.S.G.S. records. These models use measures of hydraulic retention or exchange rate in days and empirically determined net sedimentation rates (Bolin 1985, Bolin et al. 1987) and reservoir depth

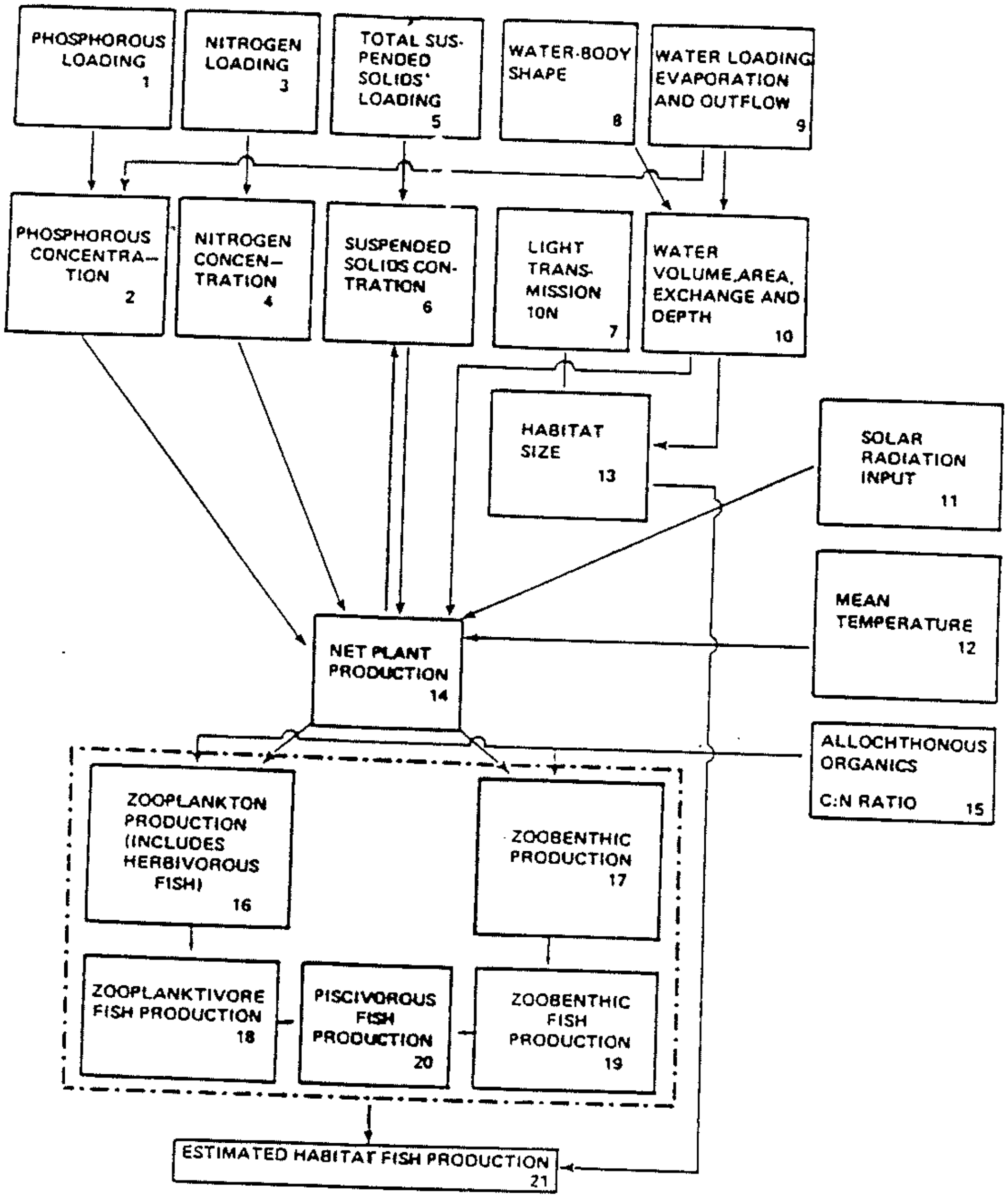

Fig. 13. Flowchart of the submodel which simulates production of fish in each habitat by feeding habit

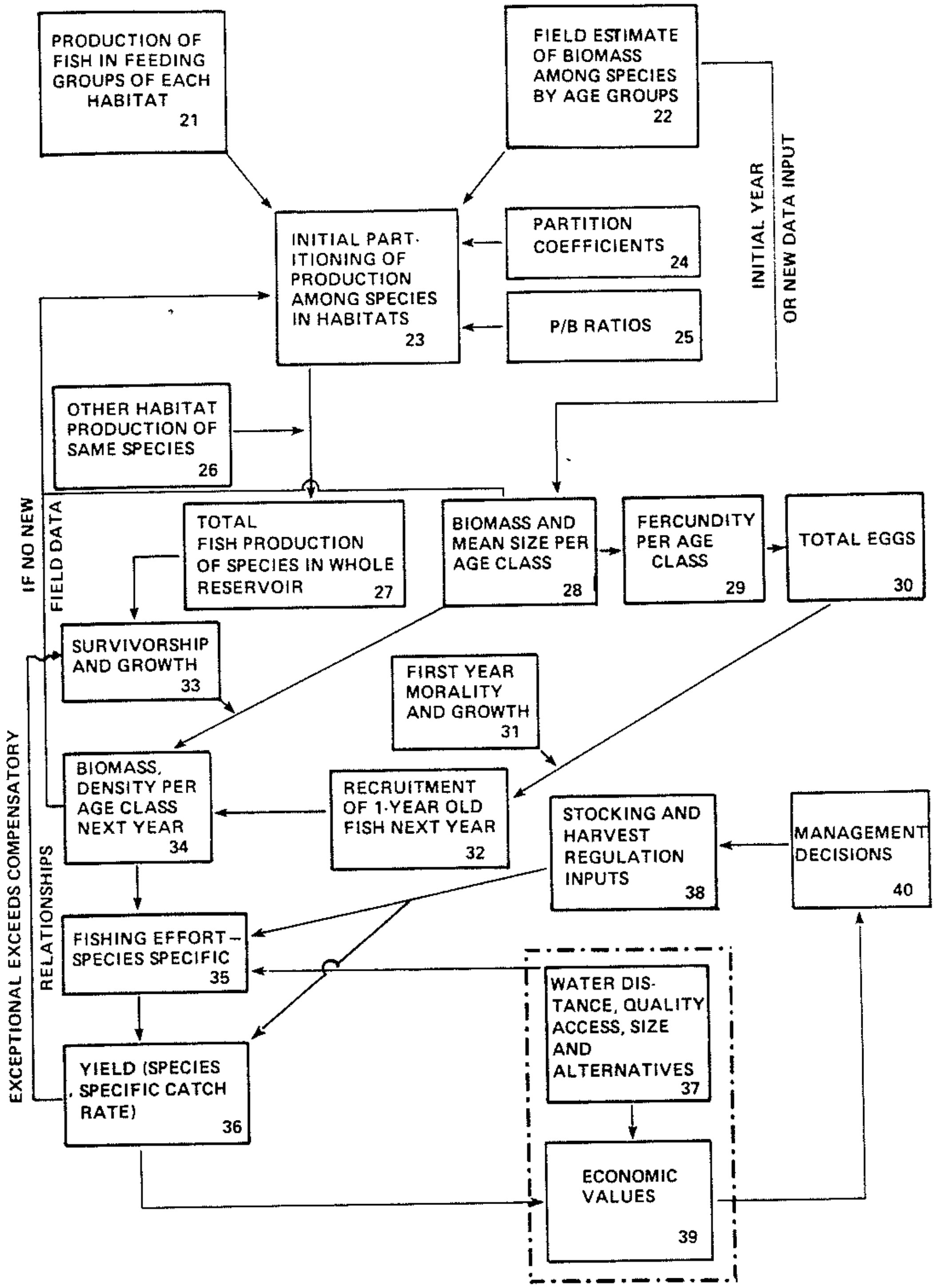

Fig. 14. Flowchart of the submodel which simulates partitioning of production among guilds of fish in reservoirs.

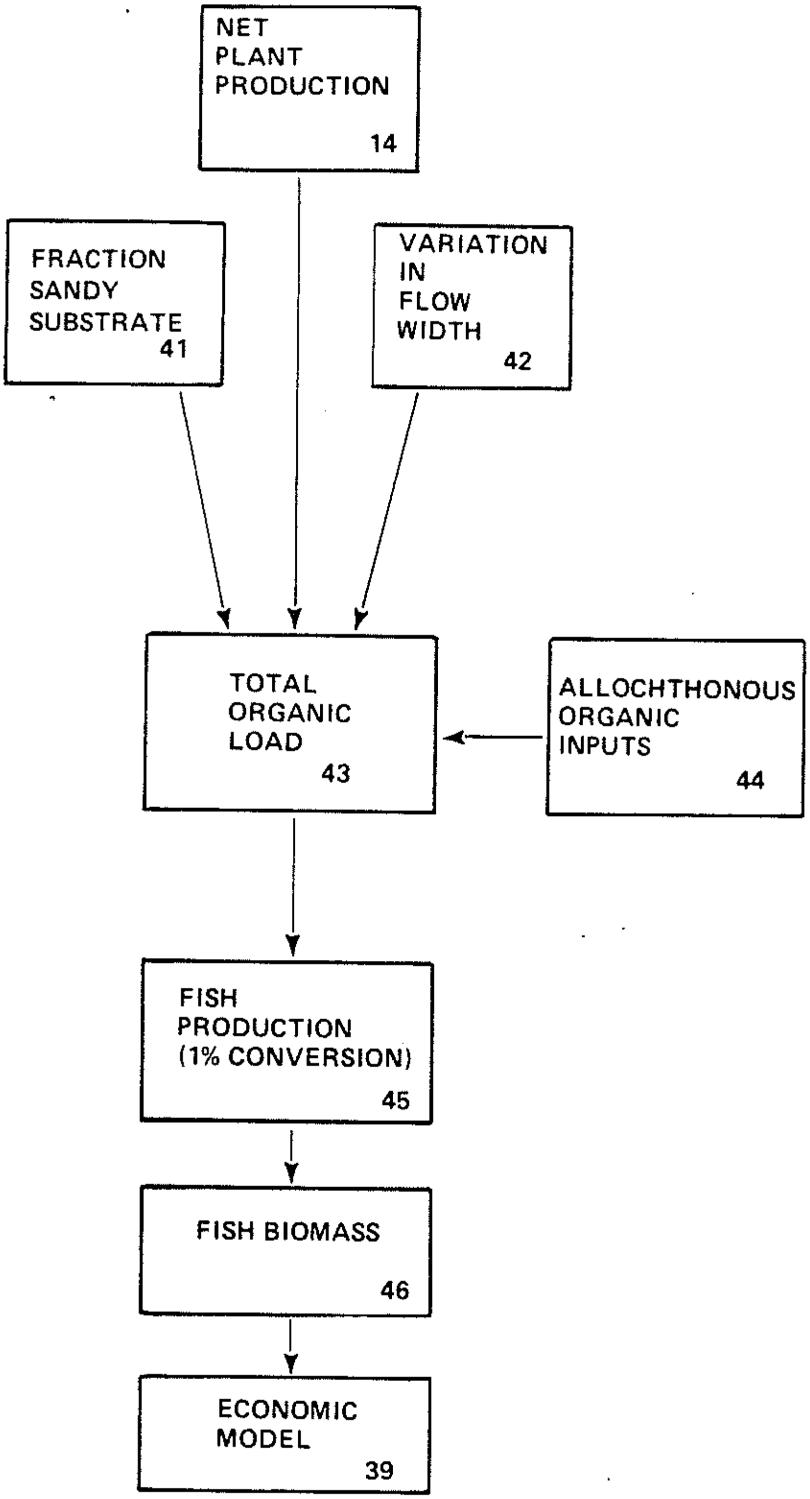

Fig. 15. Flowchart of the submodel used to predict fish production and biomass from net plant production estimation (Figure 13) in connecting waters between reservoirs.

to predict the reservoir concentration of phosphorus from the measured loadings. Data collected at Caballo, Abiquiu, Cochiti and Lake Sumner reservoirs were used to calibrate the loading-concentration models for all reservoirs in the Basin (Bolin 1985) except for Elephant Butte Reservoir, which required a separate mathematical description.

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, As for phosphorus, Elephant Butte Reservoir required separate submodels.

Units 5 and 6. Loadings of total suspended 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. As for phosphorus, Elephant Butte reservoir required a separate submodel.

Unit 7. Light transmission is determined by variation in the suspended solids generated by allochthonous (outside) loading and autochthonous 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 (see Mathematical Appendix) between suspended matter and light transmission was developed from spatially variant data gathered from three Rio Grande reservoirs (Caballo, Cochiti, and Abiquiu). Dissolved organics were assumed not to be an important variable controlling differences in light transmission in time and space within the Basin based on data from three reservoirs. Analysis of organic concentrations at USGS stations in various parts of the River Basin indicate relatively little variation in concentration of dissolved organic carbon.

Units 8 to 10. The shape of the water-body is developed from 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.

Unit 11. 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 input but the potential exists for varying this input stochastically. Light reflectance from the water surface varies from 12 percent in winter to 6 percent in summer (Cole 1983).

Unit 12. Mean seasonal water temperature is determined from weather station records of mean seasonal air temprature and empirically determined relationships between air temperature and water temperature in water bodies around the state. Except during spring when snowmelt reduces mean seasonal water temperature slightly in some reservoirs, the mean seasonal water temperature is nearly identical to mean seasonal air-temperature (Cole et al. 1985). Unlike daily temperature, mean seasonal temperature is not a function of flow because the large time interval in the season allows lags between air and water to catch up. Mean seasonal water temperature is held constant from year to year in this version of the model.

Unit 13. 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 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, 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); (4) the limnetic zone offshore where highly illuminated surface waters occur above bottom but light does not reach bottom (defined as 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 not suitable for plant productivity (defined by illumination between 1 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. Connecting waters are assumed to be entirely littoral in terms of light transmission.

The organic product of net plant production is assumed to be equally distributed among all reservoir habitats by mixing and sedimentation. All production is assumed to be phytoplanktonic with negligeable contributions of periphyton or macrophytes. Therefore the relative volume of each habitat is the important determinant of the relative contribution of plant production to total reservoir production.

Unit 14. The functions used to estimate the net plant production are based on empirical evidence from a variety of sources. First a maximum photosynthetic efficiency as calculated by Dubinsky and Berman (1981 a) and Morel (1978) was assumed to be 2 percent based on well mixed, nutrient rich lakes in tropical Africa (Westlake 1980) and marine field studies (Rhyther 1957). The maximum value appears to be between 2 and 3 percent based on the annual estimates in rich tropical lakes and maximum daily values found in several of the worlds hypereutrophic lakes (5000 to 6000 mg c/m^2/day according to Wetzel (1982) The 3 percent value was not used because ecological limitations, primarily due to inadequate mixing, are likely to make mean seasonal values somewhat smaller than values determined for a single day. Several studied lakes attain close to 2% photosynthetic efficiency on an annual basis value (Westlake 1980). We assumed that the maximum of 2 percent is reached when the lake is superenriched with all nutrient, the euphotic zone is completely mixed, the depth of the euphotic zone is determined only by the autochthononous generation of suspended and dissolved organic matter, and the temperature averages 30°C. These conditions are generally met by the tropical lakes with about 2 percent photosynthetic efficiency.

The effect of temperature was estimated as indicated in figure 16. The relationship is based on laboratory data, presented by Aruga (1964), which showed that the plant productivity (growth of laboratory culture) increased about 1.9 x for each doubling of temperature (C°). This relationship was also suggested by seasonal fluctuation in lakes with low introductions of allochthonous suspended solids and relatively constant seasonal nutrient concentrations over the annual cycle (e.g, Lawrence Lake and Wintegreen Lake reported in Wetzel (1982), Lake Erie reported in Marcus (1972). They typically vary from seasonal low values in mid-winter solstice to seasonally high values near summer solstice of 4:1 to 5:1 (from 4°C to 26°C); similar to the laboratory studies. Therefore that relationship was used to reduce the photosynthetic efficiency as temperature varied from the otpimum at 30°C.

Limiting nutrients could be either phosphorus or nitrogen. When ratios of nitrogen to phosphorus are more than 10:1 phosphorus is limiting. Because of extremely rapid turnovers and the fact that nearly 99% of all phosphorus is bound in suspended organic matter at any one time (Lean 1973, Wetzel 1982), total nutrient concentrations were used as advocated by Westlake et al. (1980). Figure 17 is based on Vollenweider (1979) but corrected for temperature and concentration of allochthonous suspended solids (see Mathematical Appendix) 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°C (4° in

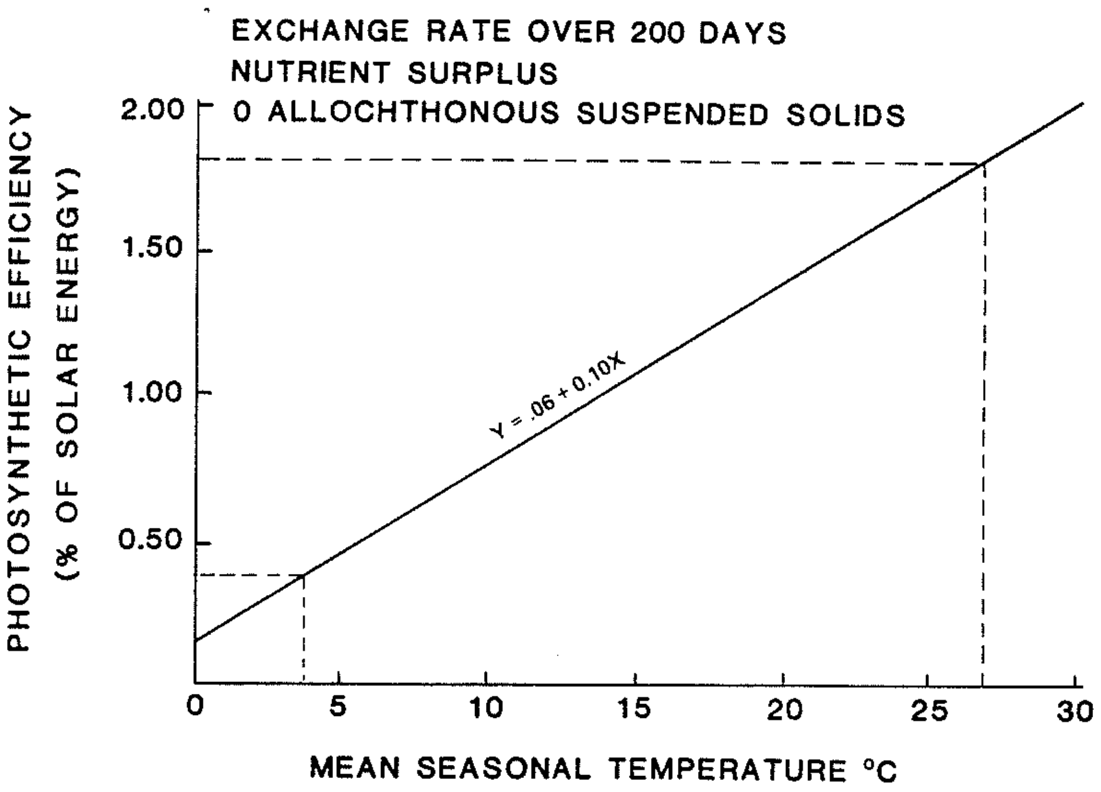

Fig. 16. Relationship of photosynthetic efficiency to mean seasonal temperature when exchange rate is low, nutrients are not limiting growth and there are no suspended solids introduced which decrease light transmission. The temperatures and expected efficiencies within the dashed lines represent ranges expected in the Rio Grande.

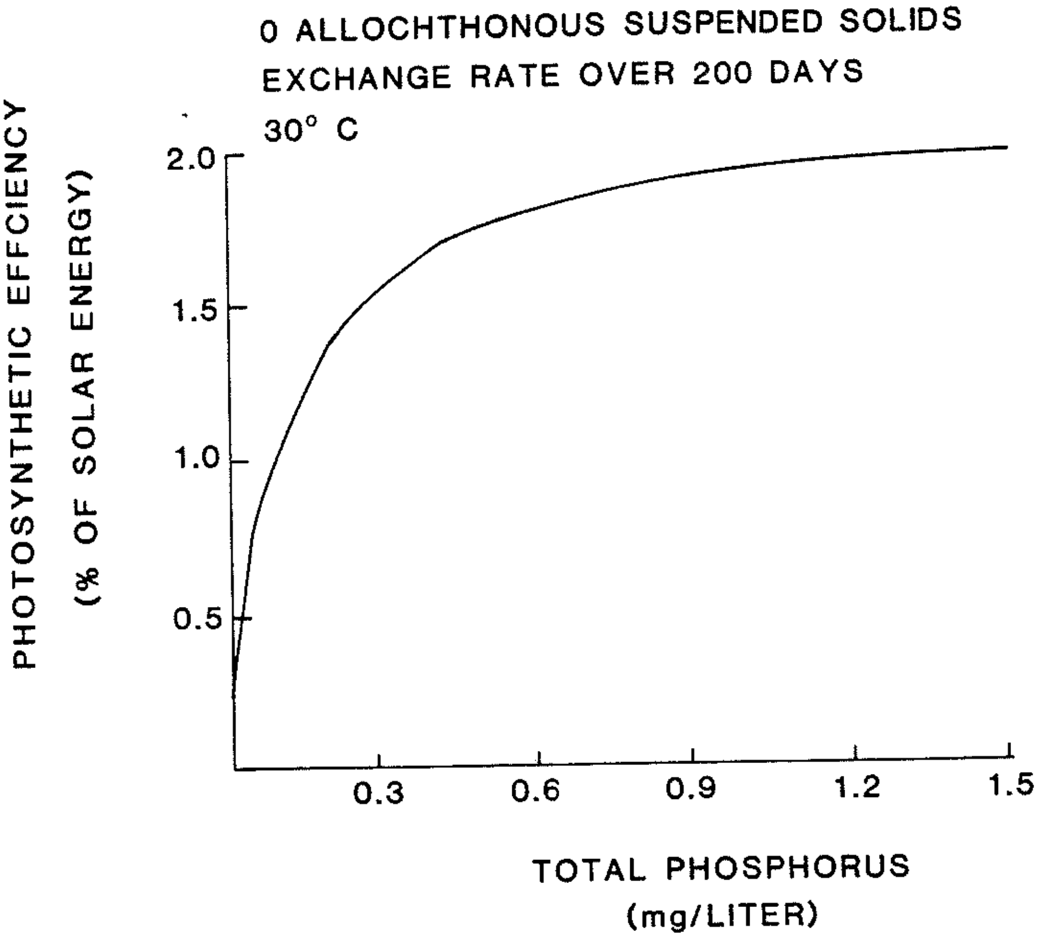

Fig. 17. The relationship used in the model between photosynthetic efficiency and concentration of total phosphorus when all other regulators of plant production are optimum.

winter to 26° in summer) and corrected his relationship upward to a 30°C optimum. We also assumed that the maximum nutrient concentration would be, at 30°C, equivalent to that necessary to sustain a 2 percent photosynthetic efficiency at the equator, resulting in a plant production about 1500 g C/m^2/year. At the other extreme, productivity was assumed to be 0 when total phosphorus was 0. Figure 16 indicates that the maximum production at 30°C (twice as high as the average 15°C) should be 1.9 times higher than 15°C if there was no allochthonous suspended solids or no limiting exchange rates in Vollenweider's (1979) lakes. In fact it 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) lakes are large and have relatively low exchange rates so 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 would be enough to cause the observed discrepancy.

Figure 18 demonstrates the effect of suspended solids on photosynthetic efficiency. It shows the relationship we used between suspended solids and the photsynthetic efficiency based on a model illustrated in Wetzel (1982) between the depth of the euphotic zone and concentrations of suspended algal solids. In developing the relationship in Figure 19 we assumed that as the euphotic zone was reduced by addition of allochthonous suspended solids, the primary productivity would be

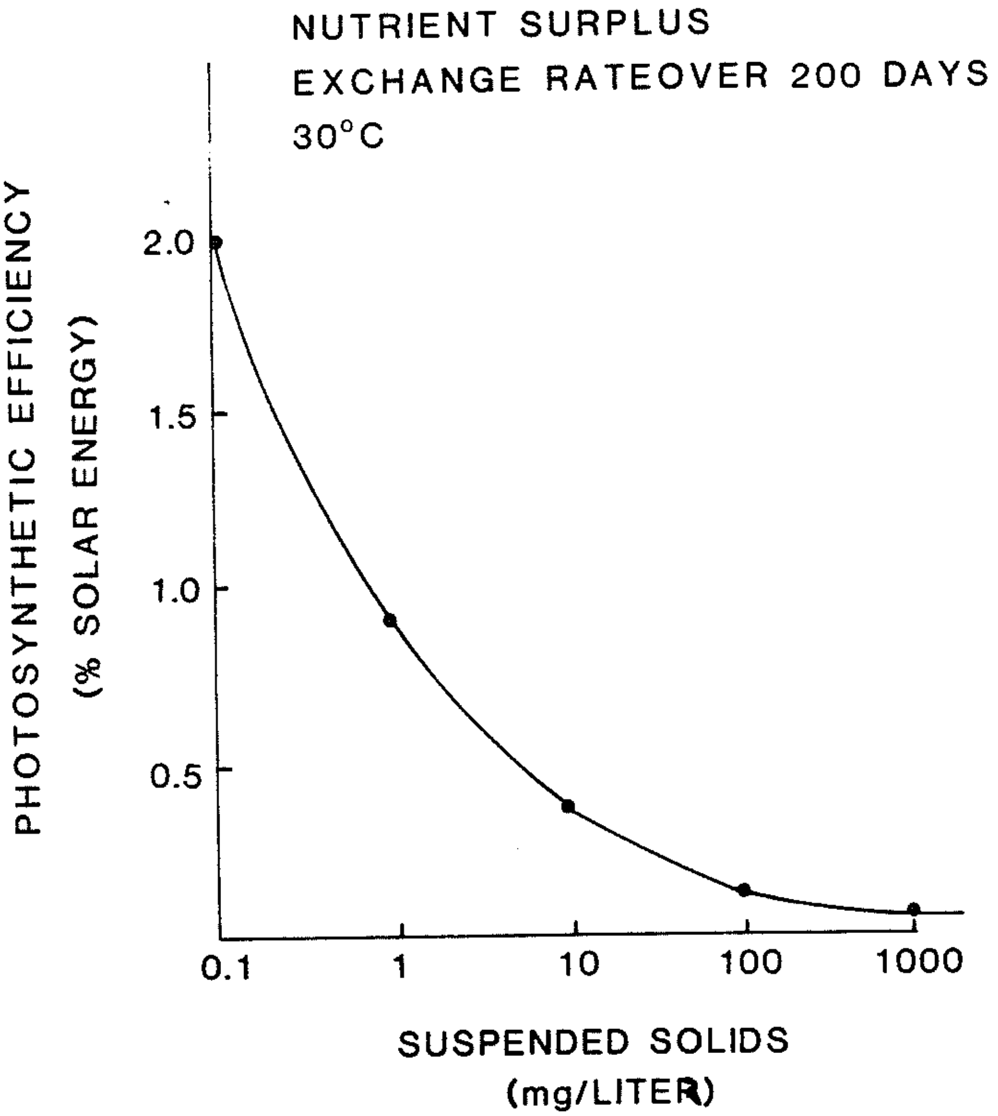

Fig. 18. The relationship used in the model between photosynthetic efficiency and concentration of suspended solids when all other regulators of plant production are optimum.

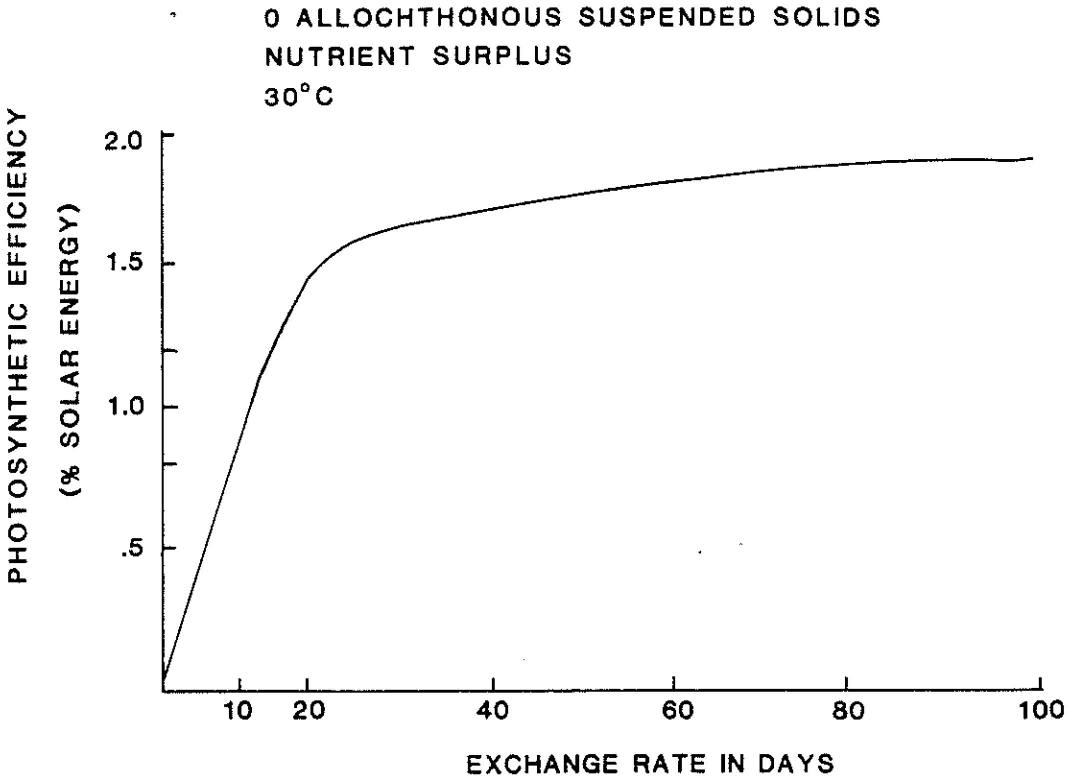

Fig. 19. The relationship used in the model between photosynthetic efficiency and exchange rate when all other regulators of plant production are optimum.

reduced in direct proportion to the diminishment of light energy available.

The last factor considered in the estimation of photosynthetic effiency was the exchange rate. In certain seasons certain reservoirs in the Basin have high exchange rates. Water in those reservoirs is completely replaced in as little as 6 days. Figure 19 represents the relationship we deduced from the following assumptions. First, in otherwise unlimited circumstances and with an initial productive mass entering the reservoir which 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 about 350 (Brylinski et al. 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 assume, regardless of the equilibrium biomass obtained that it takes 10 days to attain the equilibrium following a logistic rate of biomass to an equilibrium mass. This assumption means that the P/B ratio 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 conversion efficiency would be reduced to about 50 percent over the area of the lake involved if the exchange rates were exactly 10 days. If the entire lake exchange time were 20 days, the efficiency of conversion would be reduced for the entire time period only about 25%. As the exchange time decreases the effect of equilibration period at the upper end of the reservoir diminishes. At a 200-day exchange time we assume the effect is negligable. For exchange times shorter than 10 days the reduction is indirectly proportional to exchange time. At very rapid exchange times a reservoir resembles a river with no true phytoplanktonic productivity and too deep for periphytic production.

Unit 15. Mean seasonal loadings of allochthonus organics and ratios of organic carbon to organic nitrogen are estimated from USGS records at several locations in the River Basin. Little spatial variation occurs throughout the basin but loadings tend to be higher in the lower elevations of the Basin. For a particular season, loadings vary only with discharge because concentration is constant. Mean concentrations vary from season to season but do not vary from year to year.

The carbon:nitrogen ratio indicates the potential contribution of food energy in allochthonous material to overall fish production. In the model, the conversion of allochthonus material into herbivorous production is relatively low, about 5% when C:N ratios are high (over 20:1), and increases linearly to a maximum of 15% as the nitrogen fraction increases to a C:N ratio of 5:1 the ratio of these values approximate the observed differences in assimilation efficiency of invertebrates fed living micro-organisms with low C:N ratio and detritus with higher C:N ratios (Bird and Kaushik 1981). The allochthonous organic load and the autochthonous organic load together comprise the total organic load which serves to nourish the primary consumers, the herbivores.

Units 16 and 17. Primary consumers are assumed to be in two categories: zoobenthos and "zooplankton". In some reservoirs zooplankton are all invertebrates, but in other reservoirs a fraction of the "zooplankton" are planktivorous shad (both threadfin and gizzard shad). Planktivorous fish are assumed to take proportions of the calculated organic productions of input from algal production and allochthonous import as defined in figure 20. The function represented in figure 20 is based on the apparent relative biomass shad seem to comprise in lakes of various trophic status in New Mexico (Cole et al. 1985) up to about 400 g C/m^2/yr. Beyond that point, the model is only intuitive; based on the probability that super-enriched lakes will not support fish as efficiently as lakes of lower trophic status. This approximation indicates that shad feeding effectiveness is maximum at intermediate organic loads when particle size and abundance is most appropriate for herbivorous filter feeding. At higher organic loadings, shad abundance falls as environmental factors, such as oxygen depression, limit shad more than they limit invertebrate zooplankton. No actual data are available for high organic load lakes, thus the model needs to be empirically refined before it can be applied in such circumstance with any confidence.

Numerous community studies of ecological efficiency of the herbivorous trophic level indicate a mean trophic-level conversion (including detrital components) of about 10 percent with a range of 5 to 15 percent (Brylinski et al. 1980). However, the connection between rate of organic loading and conversion efficiency by consumers is less documented. The maximum conversion efficiency of 15% used in this model is assumed to occur at low productivity (figure 21), whereas the minimum of 5% occurs in the most organically loaded waters. This simple function used to relate herbivores and primary production is based primarily on observed relationships between primary and secondary producers in marine waters (Cushing 1971, Parsons 1980). The relationship has not been as clearly confirmed in fresh waters (Blazka et al. 1980), mostly because of vari-

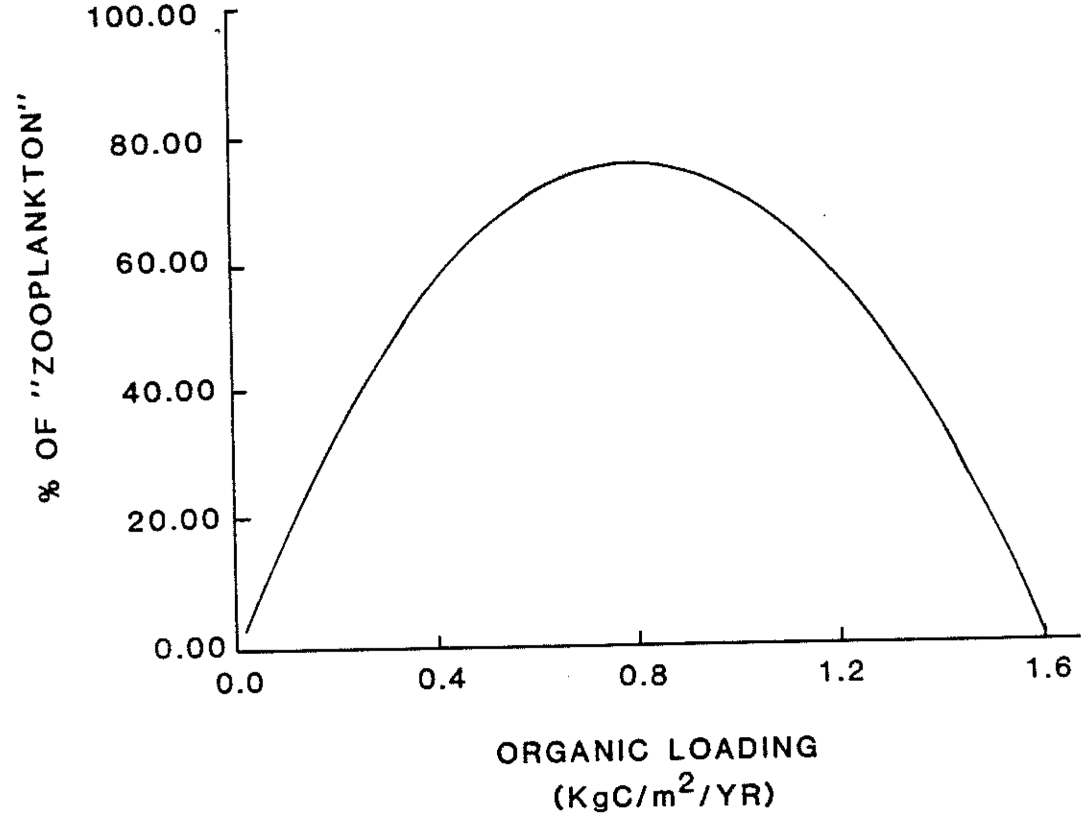

Fig. 20. The submodel used to partition plant production into herbivorous fish (mostly gizzard shad) among the total "zooplankton" according to intensity of organic loading.

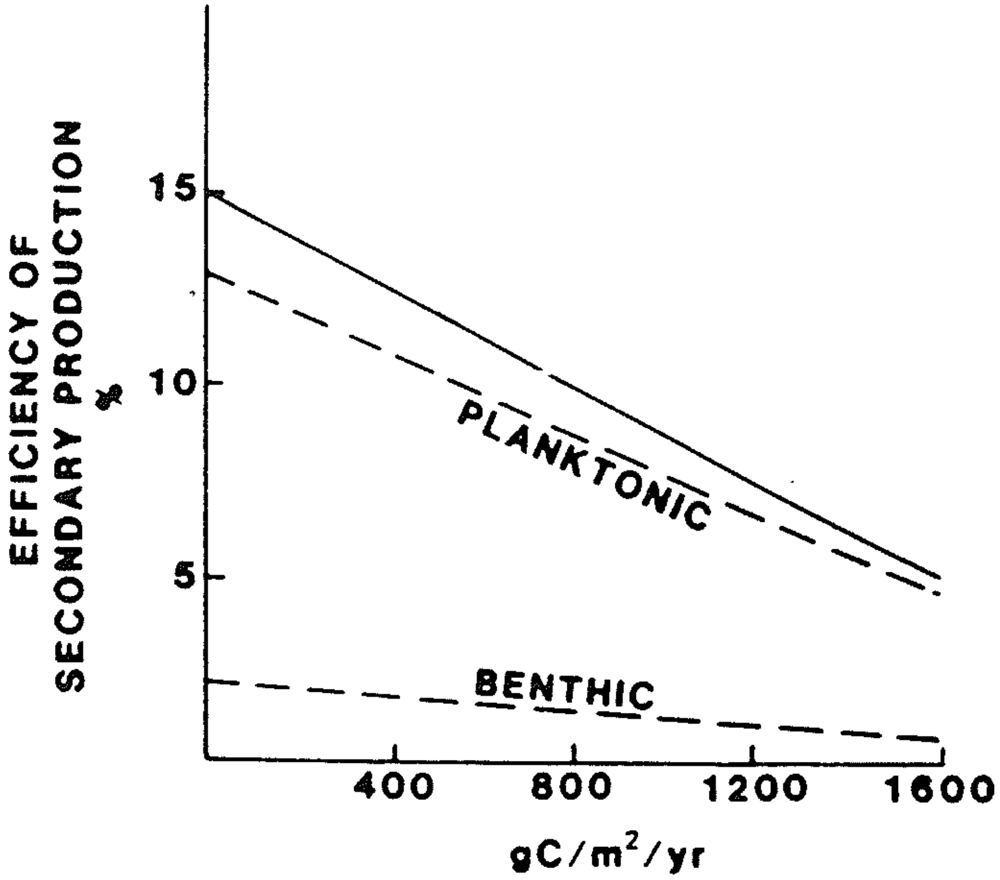

Fig. 21. The submodels used to partition organic loads among the zooplankton, zoobenthos and total herbivores.

ance and limited information in eutrophic environments. Makarewicz and Likens (1979) indicated that zooplankton proportionally increased compared to zoobenthos as organic loading increased. Data gathered by Cole et al. (1985) indicated that the relative proportion of zooplankton and zoobenthos shifted subtly as indicated in figure 21. However, the actual quantification of the relationship remains approximate. There are also logical rationales for why the herbivore efficiency in total should decrease with increased production. These rationales are related mostly to differential maximum growth rates of phytoplankton and herbivores in seasonally cyclic systems and to environmental feedbacks that slow invertebrate metabolism.

Units 18 to 20. 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 15 to 5 percent range in conversion efficiency. The actual conversion efficiencies are less well defined at this trophic level than at the herbivore level, and the submodel structure is based more on process theory than on empirical evidence. Specifically for New Mexico reservoirs, which tend to be mesotrophic to eutrophic, the efficiencies fall to somewhat less than the 10 percent average conversion (Cole et al. 1985) witnessed at many sites (Brylinski et al. 1980). There is logical explanation for the use of this range of conversion efficiencies (e.g., carnivores are more oxygen demanding and thus more likely to be limited by the oxygen depression often 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 conversion efficiency varies around 10 percent in both oligotrophic and eutrophic lakes. However, data used in Morgan et al. (1980) reflects a combination of herbivorous and carnivorous fish. If herbivorous fish increase proportionally in eutrophied environments, the efficiency of total fish conversion will increase.

In addition to the herbivorous fish already discussed, fish production is split into zooplanktivores, zoobenthivores, and piscivores. Zooplanktivores and zoobenthivores are determined by the relative productivities of their food items and the food conversion efficiencies indicated by the level of net primary production.

Unit 21. The final products of this portion of the model, before the model is linked to fish population submodels, are estimates of production by herbivorous, zooplanktivorous, zoobenthivorous, and piscivorous fishes. In water with few species of fish, these divisions may not accurately predict actual fish production because some habitats are not occupied by fish. For example, in a large reservoir with all habitats present but with only largemouth bass and bluegills, the littoral zone alone would be likely to have substantial fish production, because these species rarely feed in other habitats. 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. The model would in this instance predict potential habitat production once appropriate species were introduced. To assure the actual initial status of each habitat, data on each fish population present must be collected for model input.

Fish Population Submodel

Unit 22 (Figure 14). Data on fish density and mean biomass must be collected for each age group present in the lake to initiate a model that partitions habitat resources into individual populations. In this model, "species populations" are more properly call "guilds" of closely related species. Species are aggregated into 9 guilds: crappie, sunfish, white bass, black bass, catfish, walleye, northern pike, carp and suckers, and trout. The same population dynamics are used for black crappie and white crappie, for example. These data are required for projections and should be obtained periodically to check model performance.

Unit 23. The model predicts the fish production by age group once given (1) the production for a feeding group in each habitat, (2) the coefficients needed to partition food and space resources among guilds, and (3) the appropriate production-biomass ratios needed for each guild.

Unit 24. The partitioning coefficients are calculated based on: (1) the relative contribution each food group (zooplankton, zoobenthos, fish) comprises in stomach contents, (2) the relative abundance of each life stage of the guild in the habitat zone, and (3) an estimate of food consumption rates of each lifestage of each guild (larvae, juvenile, older fish) under optimum conditions. Data used were derived from summaries in Leidy and Jenkins (1977).

Unit 25. The production potential is distributed to fish according to a production-biomass (P/B) ratio to determine the production per guild for each mean individual weight of fish within a guild, including larval and juvenile-fish life stages. An example of the P/B distribution is provided for black bass in figure 22. Data used were derived from

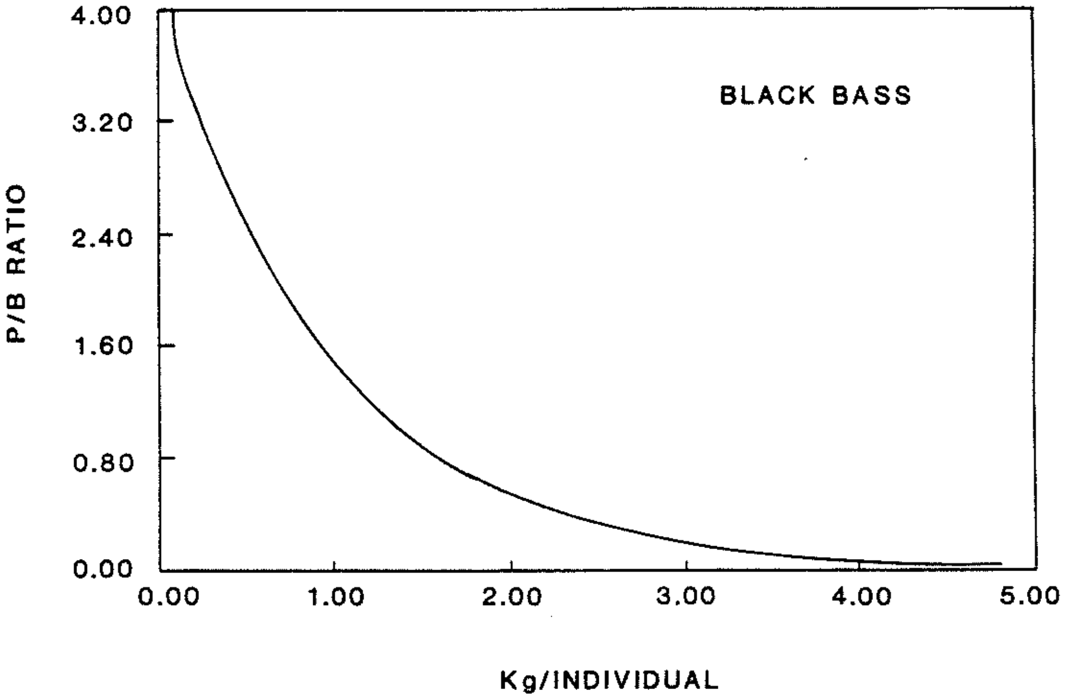

Fig. 22. An example of a submodel which simulates distribution of production among the biomasses (P/B ratio) of different weight classes of fish in guilds inhabiting reservoirs. The P/B ratio is equal to the population growth coefficient.

Cole et al. (1985) and data summarized in Carlander (1969 and 1975). The P/B ratio is equal to the population growth coefficient.

Units 26 and 27. The individual habitat productions for each species are summed to give the total guild production for the entire reservoir.

Unit 28. Biomass and mean size serves as a base for estimating fecundity, recruitment, and growth. Biomass and size data may be derived from initial input data, new data, or model-generated data.

Unit 29. Biomass in each reproductively capable age group of females and the number of mature eggs per unit biomass indicate the fecundity per age-class (a sex ratio of 0.5 is assumed in the model for all guilds).

Unit 30. From fecundity information, the total potential reproduction for the species is calculated by multiplying egg counts per female times total female biomass.

Units 31 and 32. Recruitment into the 1-year-old age-class and the size of recruited stock next year are both functions of first-year survivorship. The first-year survivorship of each guild performs uniquely with respect to water-level fluctuation. Figure 23 shows an example of such a relationship. Only spawned eggs and yolk-sac larvae are considered vulnerable to water drawdown. The vulnerability is based on the estimated distances from shore that spawning occurs, length of time spawning occurs and the development rates of egg and yolk-sac larvae. The process of estimating these interactions is mechanical and indicated in figure 24. The data are based on life history information primarily and secondarily related to estimated effects of water-level fluctuation on fish. The calculated loss due to water-level fluctuation is removed before other mortalities take their toll.

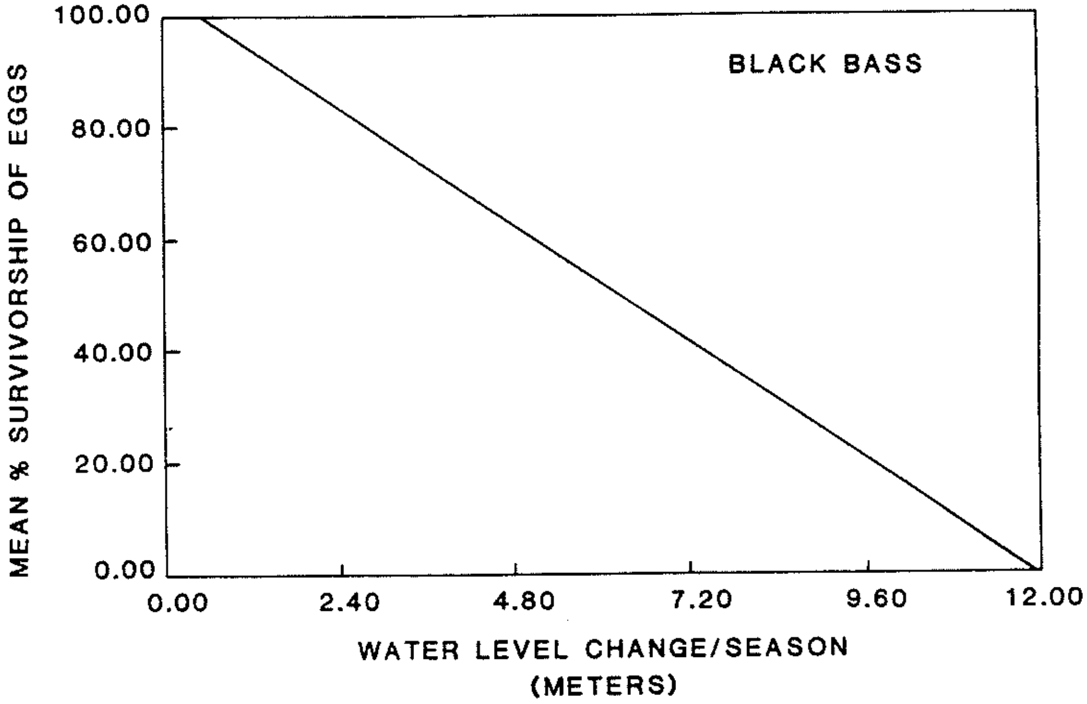

Fig. 23. An example of how a submodel which simulates the effect of water-level change over a spawning season on egg survivorships.

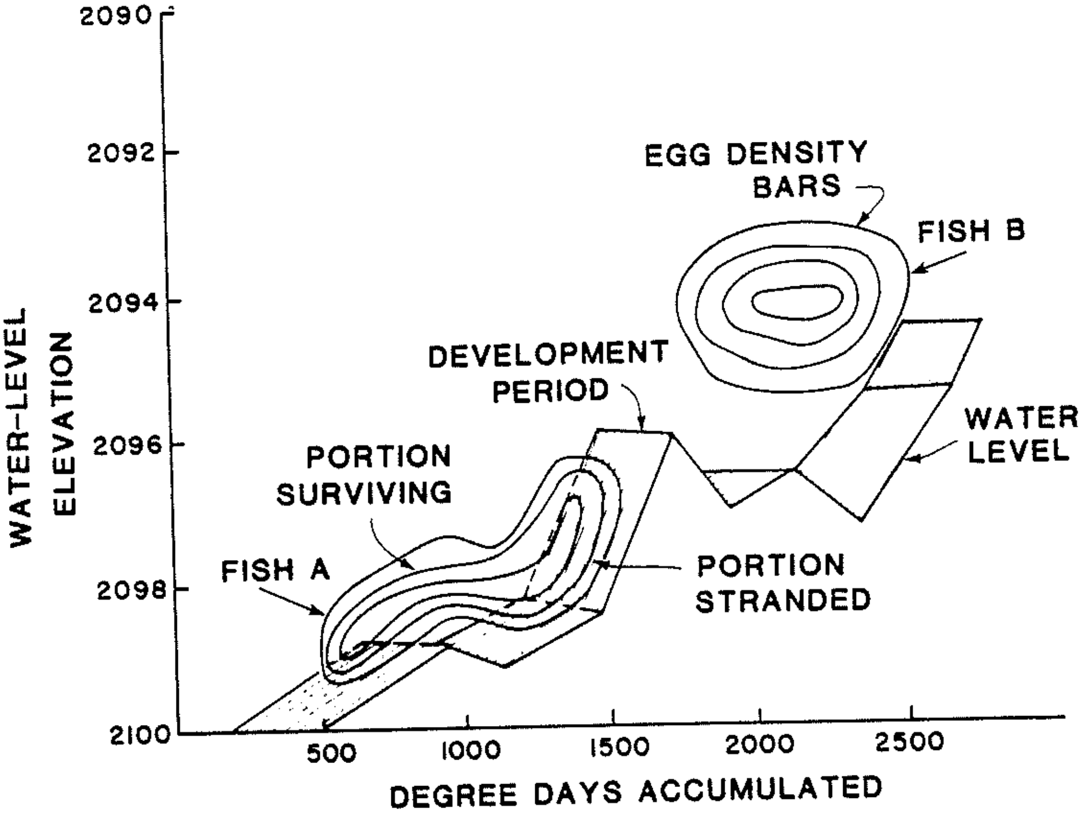

Fig. 24. An example of the mechanical approach to estimating the relationship between water-level fluctuation and egg survivorship indicated in Figure 23. Where development time is long enough and egg laying is close enough to shore, a fraction of the eggs are stranded before they hatch. Fish A is vulnerable because its eggs are close to shore. Fish B is not vulnerable because its eggs are laid at elevations far enough from shore to avoid stranding.

Post-yolk-sac larvae and juvenile fish are assumed to be vulnerable to starvation as well as to predation. The predation mortality is assumed to be the same as for older fish. Once this fraction is removed and the food is partitioned, all young fish not growing less than a minimum rate are eliminated by "starvation". All species within a feeding group are presumed equally capable of converting their food into biomass (no competative advantage is assigned). From the distribution of production to young fish, based on P/B ratios and competition coefficients,, the growth rate of surviving fish is predicted and the biomass and density of next year's 1-year-old age group is calculated (see Mathematical Appendix).

Unit 33. Growth of 1-year-old and older age classes is calculated by distributing production within the species according to estimated mortality rates and P/B ratios defined in the model for each age class (figure 22). Life expectancy is a function of growth rate based on interpretation of data presented by Carlander (1969 and 1975). The fastest growing fish within a guild have a life expectancy half as great as the slowest growing fish. The growth rate during the preceding year determines the death rate for the year in question. Once the death rate is known for the year in question the growth can be calculated and indicate the new death rate for the next year.

Unit 34. After all calculations have been made to predict growth, mortality, and reproduction, the biomass and density for next year's fish in all age groups is estimated. This information is recycled for calculation of subsequent guild dynamics for periods up to 5 years (figure 25).

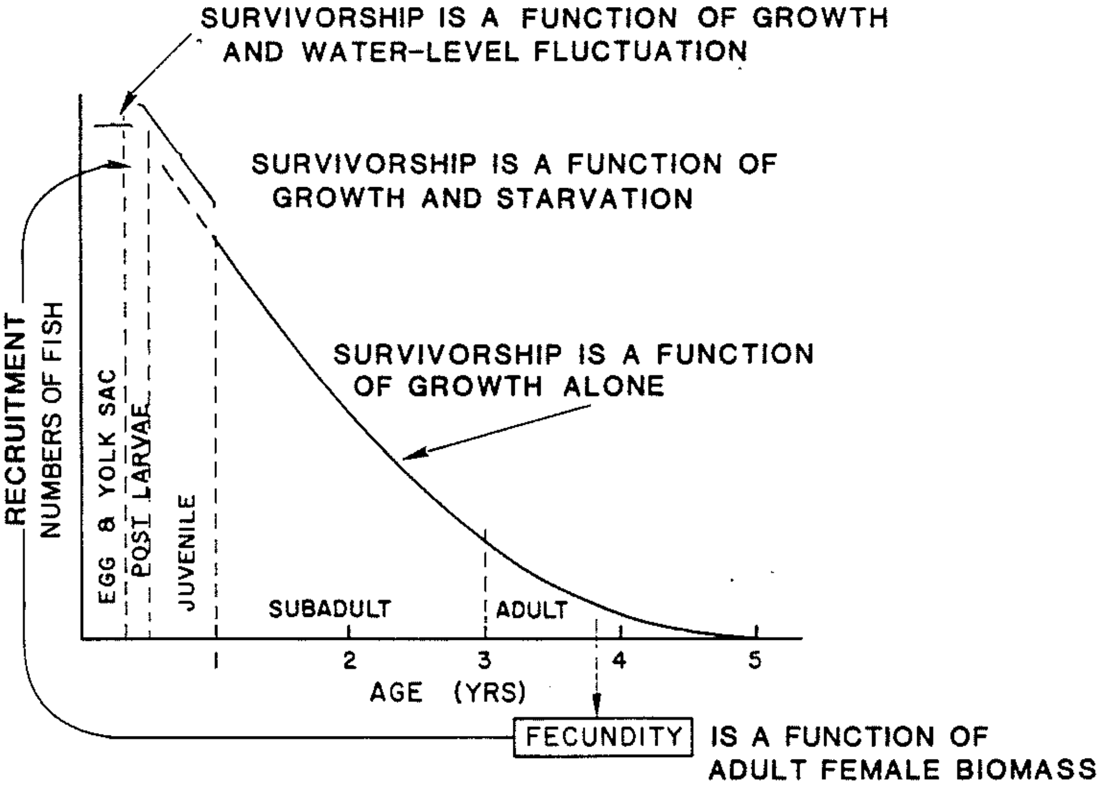

Fig. 25. A schematic overview of the operation of the fish population model.

Units 35 and 36. A function of guild-specific fishing effort is generated based on a number of economic parameters and an intrinsic value assigned to each guild. The intrinsic value is a function of the biomass of fish regardless of guild. These empirical relationships have been estimated from effort-yield data (collected by researchers at NMDGF) and fish biomass data (collected by researchers at NMSU) gathered at six New Mexico reservoirs (Cole et al. 1985).

For this version of the model, we assumed that natural mortality and fishing mortality are totally compensatory, i.e. the survivorship is a constant as long as the force of fishing mortality does not exceed the estimated force of total mortality in the population. If the force of fishing mortality is calculated to exceed the force of natural mortality, then a new total force of mortality is calculated for next year's entire population over 1-year old (feedback to unit 33 in figure 14). The new survivorship estimate then is used to calculate next year's population structure.

Unit 37. To calculate the fishing mortality, the fishing effort and catch per-unit of fishing effort have to be included. The fishing effort only partly depends on fish biomass in suitable size classes (over 0.075 kg/individual). Other factors estimated in the economic model and described in the economics section also influence the effort and determine the yield or harvest. Only if the harvest rate is calculated to be higher than the natural death rate will it feed back to reduce survivorship for next year. At this point a "surplus yield" can be estimated (that biomass of fish that dies of non-fishing causes including poaching and hooking mortality, in excess of the biomass that dies from fishing harvest) as a measure of the under or overuse of the fishery resource.

Unit 38. The model operator has the capacity to modify stocking and harvest regulations and therefore influence fishing effort, harvest rates, and fish survivorship. The model operator must provide numbers of stocked fish in three size classes (fry, fingerling, catchable) to estimate the effect of stocking. Stocked fish are assumed to behave like native fish in the model. Fish length limits can also be superimposed by model operators. Use of a length limit fully protects from fishing mortality any size category defined by the model operator. Hooking mortality and poaching are considered part of the non-fishing mortality.

Unit 39-40. Economic values are determined as described in the economic section, providing information for management decisions (Unit 40).

Connecting-Water Submodel

Unit 41 (figure 15). Figure 15 shows variations in the primary model used to predict fish biomass in connecting waters. Net plant production (Unit 14) is first calculated as described for reservoirs. Once an estimate of net production is generated it is reduced by variation in two limiting factors. The fraction of sand, which is unstable and provides little base for fish food production, is included as a regulatory agent that reduces the predicted fish production and biomass level.

Unit 42. Seasonal fluctuation in connecting-water width also reduces the potential fish production and biomass as a consequence of primary producers and associated invertebrate zoobenthos being stranded during low water.

Unit 43 and 44. Organic load available for conversion and transfer to fish production is estimated. Allochthonous load must be empirically determined and added (Unit 14). The allochthonous load is assigned to be zero in the model.

Unit 45. A fractional multiplier is used to represent the 1 percent conversion efficiency of fish from the calculated available organic load. This conversion efficiency is an average estimate based on 10 percent conversion at an invertebrate level and assumption that all fish are invertebrate feeders. A P/B ratio of 1.0 is assumed for the whole biomass of fish present based on lower than average estimates of P/B ratios determined for fish populations. Lower than average ratios were believed to reflect relatively low fishing pressure that we assumed to exist in the connecting waters.

Economic Model Description

General Overview

Figure 26 is a flow chart description of the management linkages to angler benefits and county income and employment, as determined by the economics model. Inputs to the economic model come from other parts of the model as well as separate sources.

Units 1-4. A model user (fisheries manager) can influence economic benefits and county income through several pathways. Fish stocking and harvest limits (unit 2) can be altered by the model user to influence economic values after processing occurs in the biology model (unit 3). For each site in the Rio Grande Basin, the biology model computes average fish biomass per hectare (unit 4) and passes the result to the economics model. Fish biomass is calculated from the mean summer fish weight multiplied by fish density. Only catchable-size fish over 0.075

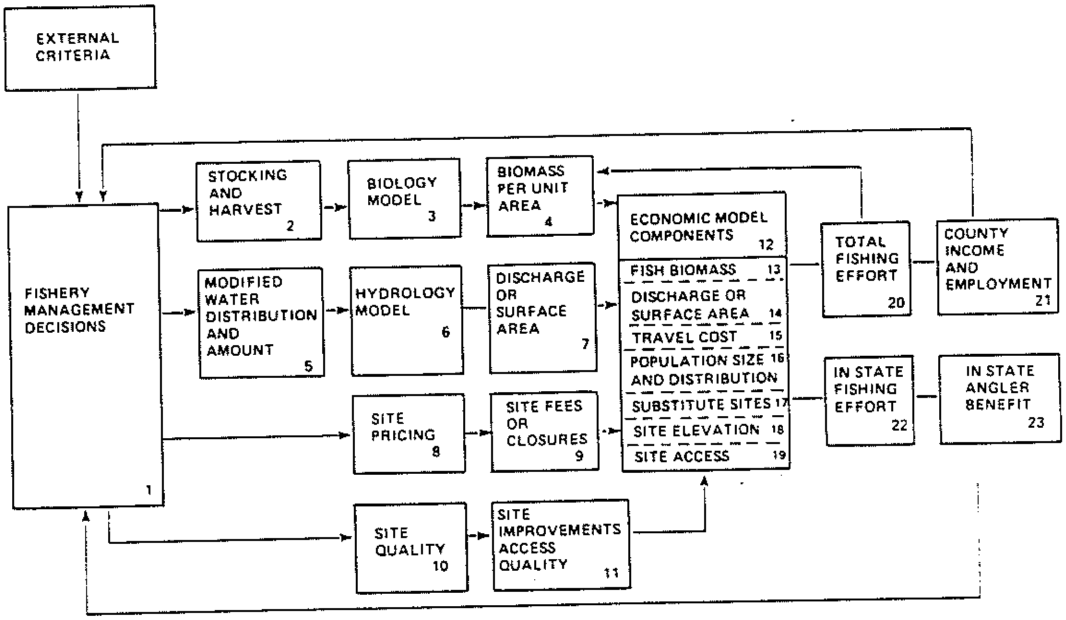

Fig. 26. A flowchart of the economic component of the Rio Grande Basin Model.

kg are included in the biomass estimate. All game fish are included but carp, suckers and forage fish are excluded because they are exploited little in New Mexico. The biology model is constructed to allow an economic evaluation of the policies which directly change stocking and fish harvest limits.

Units 5-7. The model user also can affect water distribution and amounts including water-right purchases (unit 5). These modifications are processed in the hydrology (unit 6) model which predicts the mean summer discharge for connecting waters and surface area for reservoirs (unit 7). These values are then passed to the economics model.

Unit 10-17. Fisheries management decisions, such as site pricing (unit 8) and site-quality improvements (unit 10) can be entered directly into the economics model. Examples of site pricing decisions include charging on site fees or closing sites for repairs or other purposes (unit 9). Site quality changes capable of evaluation include provision of more or less picnic and camping areas, upgrading or downgrading State Park status, increasing or decresing site access or providing more or less vegetation and shade (unit 11).

Unit 12-24. The economics model (unit 12) is a series of equations constructed with multiple regression methods to estimate direct, in-state angler benefits (unit 24) and county income and employment (unit 22). Both county income-employment and direct angler benefits were determined by angler effort at each site. In the economics model, angler effort (Unit 13) is determined by fish biomass, discharge (connecting water) or surface area (reservoirs), angler income, angler travel cost, human population size and distribution, substitute fishing sites, and site elevation.

Calculated angler use and the predictive equations in the economic model are the basis of the computer simulation of regional economic benefits. With this model planners can measure the economic benefits to off-site county residents and to on-site anglers caused by alternative sport-fishery management choices.

Angler effort (demand) and benefits were estimated with data obtained from a field survey during summer 1981. A survey questionnaire was administered in person to a "random" sample of 870 water-based recreationists at 15 intensively used sites in the Rio Grande Basin. The survey questionnaire included 77 questions for non-anglers and 100 questions for anglers, which required about 15 minutes per respondent. Questions were directed at assessing participation rates, travel-related expenses, zone-of-origin, attitudes about sport-fishing and environmental quality and other socioeconomic measures. The sample size at each site was proportional to the extent and distribution of sport-fishing activity at sites in the Rio Grande Basin as indicated by the New Mexico Game and Fish Card Survey (Patterson, 1978). Interview locations were randomly selected at sites where there were many possible fishing locations. More than 40 percent of the interviewed people identified fishing as their primary recreational activity. Most data for the income-employment part of the model were taken from a time series of census and related government publications over the period 1975 to 1982. The following description defines the development of the multiple regression models in more detail.

Unit 12. From the field study, we estimated the interdependent site demand schedules for 21 sites in New Mexico's Rio Grande Basin. For each site, we isolated the separate roles of price (travel cost), availability of substitutes, and various site-quality attributes as separate visitor demand determinants. After estimating multisite demand schedules for the 21 sites, the interdependent demand schedules were included in the Rio Grande Basin simulation model with links to hydrologic and biologic components. In the model, management decisions affect each site's demand schedule through one of three general routes. First, any of a variety of options which modify the fish biomass (biology) can modify angler demand. Second, options designed to redistribute water among the sites (hydrology) modify angler demand schedules. Third, economic options, other than those directed at the hydrology or biology of the system (e.g., pricing or site quality decisions), directly affect angler demand functions at relevant sites. With this model a user can comprehensively evaluate the net sport-fishery benefits from hydrological, biological, and economic management choices in the Rio Grande Basin.

For each site, per capita participation by zone of visitor origin was specified to depend on the price (travel cost per typical individual trip including travel time) of reaching that site, price of substitute sites in the Rio Grande Basin, area or discharge of water at the site, fish biomass per unit area at the site, site access, site improvements, and a proxy for environmental quality, site elevation.

All site demand equations were estimated using pooled multiple linear regression, with all price and most site-quality variables entering each site's demand equation linearly. The demand-equation parameters were estimated by pooling cross-section data on site prices with time series data on site quality. Seemingly-unrelated regressions were used with the side restriction imposed that cross-site price coefficients are equal (Cichetti, Fisher, and Smith 1976). Imposing these restrictions on the demand coefficients ensures that the measured multiple-site benefits are uniquely defined for any series of watershed management decisions applied to the model.

Angler benefits were computed for a management choice of no change from observed site prices and qualities in 1981. For each (ith) zone of origin, angler benefits per capita (of zone-of-origin population) were measured as the maximum (jth) site price minus the actual travel cost per trip multiplied by half of the zone's 1981 observed participation rate (Cicchetti, Fisher, and Smith 1976). For a given zone of origin, maximum site price is the entry fee which would be just enough to reduce that zone's participation rate to zero. Per capita angler benefits were multiplied by the zone's total population to find total angler benefits for the zone of origin. These benefits were then aggregated over 13 zones of origin and 21 sites to compute total statewide angler benefits for the Rio Grande Basin.

Separate regression models were also constructed to examine the effects of recreational fishing on income and employment in the Rio Grande Basin. An ordinary least squares regression model was developed for each, based on measure of income, population distribution, and angler days of effort.

The site-demand equation that was included in the simulation model also was used to predict angler participation associated with changes in site price or site quality. In addition, the estimated site-demand equations were used to predict the effect of angler "pressure" on fish biomass at each site. Specifically, angler use at each site based on the estimated demand equations for a given period used in conjunction with the biology model to compute possible depletions of fish biomass at each site in the following year. This feedback from economic demand to fish biomass has significant management implications, particularly at smaller sites where angler harvest can be the predominant source of fish mortality.

Unit 13. Site qualities and their impact on visitation were measured from data gathered from sources other than the survey. Data from New Mexico Game and Fish Card Survey was used to estimate biomass per unit area (using a relationship between yield and biomass determined by Cole et al. 1985) and total angler participation.

Fish biomass per unit area was estimated as the catchable game fish per unit area for both reservoirs and connecting waters. Without legal limits, the smallest catchable game fish was assumed to be 0.075 kg. Fish biomass was expected to have a positive effect on participation. Harvest limits imposed by regulation can reduce the available biomass and thereby depress participation in the short run. Stocking, by increasing biomass, usually increases participation.

Unit 14. In developing the model, geological survey data were used to measure surface areas for the eight major Rio Grande Basin reservoirs and streamflows for the 11 major connecting waters (USGS 1975, 1978, 1981, 1982). The economics model responds to surface area for all reservoirs and average summer discharge for all connecting waters. Water quantity was expected to have a positive effect on total site participation.

Unit 16. During the field survey, data were obtained on travel costs (prices) to measure direct angler demand (effort) and benefits (figure 1, unit 22). This site "price" was determined by distance from the zone of origin to the site, the number in the party sharing expenses, related expenses, and the cost of travel time. Travel time values were obtained indirectly by estimating how visitors trade off distance for travel time (McConnell and Strand 1981). The other three determinants of price were obtained directly from the survey.

Angler benefits from modified site pricing policies are also measured. An increased site price (or in the extreme case a site closure) reduces per capita participation at that site and increases participation at substitute sites. A higher site price reduces per capita and total participation from each zone of origin. Thus increasing a site's price reduces angler benefits from each zone of origin and thus statewide. (However, part of that lost angler benefit may in some cases be recovered as increased revenue from site fees received by the management agency).

Price per individual trip includes round-trip distance multiplied by $0.27 per mile (Ref: U.S. Federal Highway Administration) plus the value of travel time in transit. Using methods developed by McConnell and Strand (1981) travel time for the sample of site visitors interviewed was estimated to average $10.50 per hour. For a given site, lower prices at substitute sites were expected to have a negative effect on per capita participation. Higher prices elsewhere would have a positive effect on site visitation.

Unit 17. For each site, we estimated total visits and the distribution of visits by zone of visitor origin. Total visits were obtained from the New Mexico Game and Fish Card Surveys (Patterson 1980) while the distribution of visits from different zones of origin were measured directly from the field survey.

Unit 19. Site elevation is one important indicator of environmental quality in New Mexico. Increases in elevation up to a point in New Mexico, generally lead to denser vegetation, more shade, cooler temperatures, and fishing sites more attractive to summer anglers. Because most fishing is done in summer we expected increased elevation to positively influence participation.

Angler benefits from management choices directed at improving site qualities will increase in the model. Site quality changes have to be interpreted in terms of a net change in elevation, making this management input more abstract than most others. But once that interpretation is made, by including the adjusted angler demand equations into the computer simulation model, angler benefits for any site quality modification can be recomputed. Essentially, management choices directed at a series of sites will change estimation of each of those site's per capita angler participation rates and maximum site prices. Per capita and total angler benefits are then recomputed accordingly.

Unit 20. Site access for connecting waters was estimated partly by the number of highway crossings for all connecting water stretches. Road access at sites was expected to have a positive effect on participation. Additionally, for reservoirs and connecting waters, access was also indicated by "site improvements" in the form of state parks (assigned a value of 1 where state parks exist and a 0 where no state parks exist and the number of picnic grounds and campgrounds). Incorporated in the site improvements is boater access via boat ramps. Site improvements, like road access, were expected to positively influence participation.

The Income and Employment Models

Unit 15. The measure of income predicted in this model was real per capita personal income in all Rio Grande Basin counties (U.S. Department of Commerce, Bureau of Economic Analysis). The time period included was 1975 through 1981. Data on per capita income were collected for all New Mexico counties in which income was specified to depend linearly on the following factors:

1. The United States per capita income (U.S. Department of Commerce, Bureau of the Census) — National fluctuations in income and the associated business cycle are assumed to affect regional economic activity in New Mexico.

2. The percentage of persons 25 years and older in the Rio Grande Basin who have completed 4 or more years of college (U.S. Department of Commerce, Bureau of the Census) — Above average educational attainment is assumed to be correlated with high regional income.

3. The percentage of persons in the Rio Grande Basin who are employed (U.S. Department of Commerce, Bureau of the Census) — Employment is measured as the civilian employed persons plus the members of the Armed Forces divided by total county population. Demographics (e.g. percentage of very old persons or very young persons who are not likely to be members of the labor force) are assumed to affect regional per capita income.

4. The percentage of regional income derived from farming and mining (U.S. Department of Commerce, Bureau of Economic Analysis) — Non-industrial income is assumed to affect aggregate regional income in New Mexico. For example, farm income is very important in causing annual fluctuations in income in some counties because farm income varies widely from year to year.

5. The percentage of persons in the Rio Grande Basin who live in a town of 2000 or more inhabitants (U.S. Department of Commerce, Bureau of the Census) — Urban areas are assumed to generate higher per capita income than rural areas.

6. The per capita angler days in the Rio Grande Basin (data for total angler days from NMDGF card surveys multiplied by number 5 above, the percentage of persons who live in a town with over 2000 people. We assumed that the greater the urban influence in the county of concern the more a given angler day of fishing will raise the region's income. This assumption is thought to be true because urban areas usually exhibit greater spending interdependence and thus offer more opportunities for angler expenditures to be respent in the local income stream.

In the employment submodel, total employment, defined as total civilian employment (Bureau of Business and Economic Research, University of New Mexico) was specified to depend linearly on income when the time period included is 1975 through 1981. Income is defined as total personal income (U.S. Department of Commerce, Bureau of Economic Analysis).

By using both the income and employment models in sequence, the impact of a sport-fishery management decision at any given site can be gauged with measures of (1) income generated in the county at which the site is located through its effect on angler days as determined by the angler demand model and (2) through the income model, the impact on employment in the same county.

User-friendly Version of the Model

Objectives

The primary objective for the user-friendly version was to make the full power of the model available to users without requiring any special knowledge of programming, thus freeing users to concentrate on developing model predictions for application to management concerns. Users can run the model easily by responding to questions or selecting menu options. The programming and file-management operations that allow for easy use and direct the calculation of predictions are invisible to the user. The APL high-level language used to develop the user-friendly version of the model makes such conversational interaction with the user possible. Users are also protected from the consequences of typographical errors or nonsensical responses to requests for data; erroneous input from the user results in a repeated question, not in a crash of the program.

A second objective of the user-friendly version was to make the model available on a desktop computer, avoiding the costs and logistical problems of access to a mainframe system. The user-friendly version of the model can be run on an IBM PC or compatible system with a minimum of 384-K RAM and 2 disk drives, the PC or MS DOS 2.0 operating system, and STSC AP:*PLUS/PC high-level language. Faster execution of the program can be obtained with additional RAM memory configured for 240-K virtual disk drive and 16-K print spooler. Having the model on a microcomputer makes it available any time, and eliminates the need for obtaining remote access to a mainframe (usually over long-distance telephone lines).

Capabilities

The user of the user-friendly version can designate the reservoirs and connecting waters in the Rio Grande system to be covered by each model run, from any single reservoir and its downstream reach to the full system. The user also selects the calendar years covered by the model run. Model predictions can then be generated for any of the three model components (hydrology, biology, or economics) alone, or for all of the linked model components, depending on objectives for a particular run.

Scenarios

The most powerful use of the model as a management tool will be the comparison of model predictions from several carefully designed scenarios or sets of input conditions. Scenarios encompass a stream flow and reservoir storage regime for water movement through the Rio Grande system, fish stocking patterns and harvest regulations, and the existence of parks and recreational facilities. The user may specify additional details. Then based on such a set of input conditions, the model provides predictions of actual stream flows, changes in reservoir areas and levels, the resulting fish production and availability to anglers, use of basins and streams in terms of angler days, and other details of water conditions, biological responses, and economic impacts. The comparison of the differences in predictions resulting from small or large changes in the input-condition scenarios makes possible the evaluation of management alternatives, costs and benefits, consequences of particular actions or regulations, and so on.

Scenarios can be based on historical stream flow regimes for 1975 through 1983. "What if" scenarios can be based on some modification of historical water flow and storage regimes, or on a complete specification of a hypothetical water regime. Similarly, users can modify the input conditions for the biological and economic models as well.

Whenever model predictions are displayed or printed, the input conditions that define the scenario used for the run are displayed or printed as well, to provide an indication of the basis for differences in predictions when different scenario results are compared.

Examples

The impact of a very wet year on reservoir levels, stream flows, fishing quality and angler use of reservoirs and streams can be examined by comparing two model runs, the first based on unchanged historical flows from a selected year, and the second based on the same year with stream flows doubled for April, May, and June.

The general benefits to anglers from stocking programs could be examined through comparing predicted fish yields and angler days from two runs of the biological and economic conceptual models, one without stocking, and one with a typical stocking regime. The specific benefits for a particular time span or set of water conditions could be examined with the inclusion of the hydrological model.

The impacts of entry fees for parks on angler use of all reservoirs in the system could be evaluated by comparing runs of the economic submodel, or all three conceptual models linked, with and without fees.

The scenarios indicated above are only fairly simple examples of the kinds of questions that can be addressed through the model. Different, more complex, or longer-term scenarios can be developed to examine other management and policy issues. The user-friendly version of the model is structured to allow easy implementation of scenarios designed by the users.

Mechanics

The model has been designed to be easy to use, while still allowing the control over input conditions and the flexibility of operation necessary to get full benefit from the capabilities of the conceptual models. The user has to think, but can concentrate on the nature of the scenarios to be modeled rather than on the mechanics of the modeling process.

Menus

The user-friendly model is menu driven, and needs only single keys to select menu options. Each menu pertains to either setting the input conditions for or actually running the hydrological, biological, and economic models. Each menu is divided into information options, action options, options for moving to other menus, or quitting.

Information Available

The information options call up screens with background information and instructions for the action options of each menu, or for the operation of the menu system itself. Such explanations are available at any time the user must make choices for setting up and running the model.

The model contains historical information on stream flows, reservoir volumes and areas, and rainfall and evaporation rates for 1975 through the most current year's data available from USGS monitoring stations (USGS 1976-1984). The historical information may be used in constructing scenarios for model runs. The user has an option to see the historical information for one or more years, up to four variables at a time, in graphic form.

Running the Model

The action options include selecting the time span and geographic area to be used, setting input conditions for a given model run, running the hydrological, biological, or economic models (or an appropriate combination), and examining results of a completed run in detail. The action options are structured to allow the user to run all or any part of the model that makes sense, and at the same time to force the user to set conditions for each model run in a logical way. Some actions are prerequisites for others. For example, the user must select the reservoirs and calendar years to be covered by a run before actually running the model. In such cases, action options do not appear on the menus until the prerequisite actions have been taken. Any action option can be taken repeatedly to correct mistaken input if necessary.

It is easy for the user to examine the input conditions set for any model run, and to change them if desired. Input data can be changed by simply entering a different number after the current value has been displayed. If no new number is entered, a value remains unchanged. The facility of setting up revised initial conditions easily is very important for using the full power of the model, since comparing model predictions from different scenarios is essential for evaluating management alternatives.

Time Requirements

The convenience and accessibility of running the full model on a microcomputer has a trade off in terms of the time needed for a run. The biological portions of the model takes the longest to run, using about 6 minutes for a four-season run on a single reservoir. A run of the complete hydrological, biological, and economic models for one year on Elephant Butte Reservoir takes about 10 minutes. With a properly configured desk top system, printing of model results can take place concurrently with the model run, allowing a printout to be available a minute or so after the model run has been completed.

Model Limitations

General Overview

The model in its present form is most versatile for predicting fishery dynamics and values specifically for mainstream reservoirs of the Rio Grande. The model can also predict the long-term mean annual fish production, but not the yield for any other river basin in New Mexico, or elsewhere, for which proper input values are made available. The required input values include seasonal solar radiation, mean season allochthonous suspended organic carbon, mean seasonal ratio of total organic carbon to total suspended organic nitrogen, total phosphorus, total nitrogen, allochthonous suspended solids in the reservoir (algae removed), water inputs every two weeks, water outputs every two weeks, and the density and individual biomass by age class for each fish species present, fishing harvest regulations, and fish stocking rates. Examples of model application to 12 reservoirs in the state are given in Cole et al. (1985).

Some of these data are available for larger reservoirs in the state that are monitored by the USGS or other organizations. However, many similar reservoirs off the mainstream flows are not monitored and therefore require watershed models to predict loadings of water, suspended solids, allochthonous organics, and nutrients. Basin morphologies must also be known (at least area-depth-capacity tables), as well as irrigation draw-offs, water leakages, and evaporation rates. There is an indication that the biomass of harvestable fish (but not the age structure) can be estimated from yield data surveyed by the New Mexico Department of Game and Fish. Although these estimates provide no size or age-structure information, a "typical" age structure may be used to initiate the model. Once the model has been operated for five to ten years, the fish populations tend to come into equilibrium with the ecological regulatory factors. Therefore, the model is best for long-term analyses when applied to reservoirs with little information on fish population structures. For shorter-term analyses, an accurate estimate of age structure and biomass per species is required for input.

If the reservoirs off the mainstream in New Mexico are to be modeled effectively, watershed models that predict loadings of water and material from precipitation need to be incorporated. Also, if yield data is to more accurately represent fish biomass distribution among size classes, we need a better idea of the relative catchability of fish of different species and sizes. Therefore we need to link research-grade creel surveys with studies of fish density, biomass and growth in the same reservoirs.

The economics part of the model could be applied to other water bodies in the Rio Grande Basin, which fall within the range of conditions for which the economic multiple-regression model was developed. In that case, the economics model could be linked to the biology model and angler pressure, yield and economic values then estimated. However, the economics model technically cannot be applied to water bodies outside the Rio Grande until it is shown that anglers in other river basins of the State behave similarly.

The hydrology part of the model is limited to th Rio Grande sampling stations monitored mainly by the U.S.G.S. It is also limited to a relatively short period of historical data that applies to the existing conditions in the Rio Grande Basin, since Cochiti reservoir was filled about 1975. The range of hydrologic conditions witnessed over that period, although quite wide, do not represent all potential conditions — particularly extreme drought — that are of interest. Of course, to be extended to other basins in New Mexico the model requires inputs of USGS data from those basins. The Rio Grande is the best monitored basin in New Mexico, and therefore the most accurately modeled by this methodology. Although water data are well monitored in most parts of the State, the suspended solids, nutrient and allochthonous organic matter are not so well monitored. Because these data determine a large fraction of the variation in fish production, the scarcity of those data is a serious limitation.

A modification of the existing model through addition of a watershed model may improve the prediction of material concentrations, at least in certain parts of the State. It can also indicate where certain short-term studies of watershed processes can take the place of long-term hydrologic monitoring in generating the information necessary for model performance.

The model in its present state can predict responses to altered watershed practices as long as the user introduces expected changes in water, nutrient, suspended matter and allochthonous organics that would accompany the watershed management practice. A watershed model addition to the existing model could be designed to predict effects of watershed alteration.

Development of watershed model would use existing model structure and data obtained at monitoring stations to calibrate the watershed models and test model predictions thereafter. Such watershed models could be used to predict water and material dynamics in tributaries and small tributary reservoirs, thereby extending the model's capacity to virtually all waters in the state where suitable watershed data exists or can be obtained. Such models require long-term weather records, information on watershed phsiography and soils, and functions relating runoff and erosion and eposition rates of materials to climate and watershed characteristics. Depending on the watershed, these inputs range from complete to requiring substantial research.

The connecting-water part of the model is based on much less available data for waters in New Mexico than is the reservoir fraction of the model. Refinement of the connecting-water model to predict guild production of fish with some reasonable accuracy will require hydrologic and biologic data from these environments. Particularly important is the distribution of sediment particle sizes and its ability to support food production for fish. Also important is definition of the ability of stream reaches to obtain, hold, and convert allochthonous organic matter into fish biomass. Because connecting-waters and tributaries behave similarly, any improvement of this model would be best if it pertained to all flowing waters.

The sport-fishing management model is not now truly validated. To do so requires taking new runoff data, as it becomes available; predicting changes in fish mass, fish yields and angler day visit rates, and monitoring selected sites to validate model-prediction. The biological portion of the model pertaining to reservoirs alone has been in part tested and in part validated for its applicability to 12 diverse reservoirs in New Mexico (Cole et al. 1985). Mean annual estimates of fish production and dynamics are generally well simulated with exceptions that can be improved through further research. However the hydrologic and economic models have only been calibrated and are therefore in need of validation. Validation procedures would also test the linkages between the submodels which are important determinants of fishing yield and angler effort.

Lastly, although the model is very easy to use and designed for people without computer expertise, it has not been implemented into a management framework. To do that effectively will require more communication between modelers and managers, including workshops using a detailed but clearly written user manual. Such a user manual needs to be written, tested, then used to develop user expertise and management application.

The rest of this discussion of model limitation pertains to specific difficulties in each of the three main components of the model.

Limitations of the Hydrology Submodels

Two types of limitations exist in the hydrology submodels for reservoirs and channels. These are data limitations (spatial and temporal) and limitation involving model composition. The data limitations are important because they affect model composition. Model composition is important because it determines the predictive ability of the model.

Data Limitations

Several components in the submodels require parameters derived from a measured data base. One example is the set of parameters relating water-quality constituent concentrations — phosphorus, nitrogen, and suspended sediments — to streamflow. The information needed to derive these parameters is not available at all flow gauging sites, or for all constituents, or for all measured flows. Therefore, some parameters at some sites had to be deduced from data obtained at other sites.

Therefore, the confidence of predictions based on those assumed values is not as high as it is for other sites.

Another data limitation arises when the water mass balance of a reservoir is computed. For example, Cochiti Reservoir is not adequately monitored because there are large discrepancies between the measured flows, change in volumes, and calculated evaporation rates. Essentially there is a large loss that can only be attributed to leakage through the reservoirs sides and bottom. Also at Cochiti reservoir, the flows in the two large irrigation diversion canals are only reported on a monthly basis. Although the continuous record can be obtained, it is not now reported on a daily basis by the USGS. Therefore, assumptions were made about outflows in periods less than one-month long. Cochiti Reservoir is particularly notable in this regard, but problems arise at other reservoirs where data for all the major inflows are not available. Therefore, when the model is calibrated, errors are expected that are related to a lack of measurements.

A similar error occurs in estimating reservoir volume from the ever changing elevation-area-capacity tables. As the reservoir fills, the capacity decreases and this decrease is not noted until the next survey of the reservoir. Because several years may pass between surveys, the tables show sharp drops instead of the gradual change that actually takes place. When a new table is introduced, this drop translates into change in volume that cannot be explained by the mass balance computations. It would be possible to develop a yearly table based upon physical process interpretation of the intervening years between survey; however, such an adjustment could not be easily proven to be correct.

Therefore, only the most current table is used in the model to compute all base line elevations and areas and is used for all predictions.

Another group of data that is scarce is channel cross sections for all the stream reaches in the channel submodel. Fortunately, this information can be readily obtained during low-flows season. Therefore, at present, approximations of cross-section information was used for the channel model.

Most of the data limitations cannot be solved easily because of the high cost of long term collection and analyses of the information. Some additional data which can be gathered that would improve model accuracy, and can be obtained at reasonable costs. These needs are addressed elsewhere.

Model Composition

Several parts of the hydrology submodel's composition can be improved. In the areas of reservoir mass balance, the model currently requires pan evaporation and precipitation estimates. Although the values are needed twice each month, these values were pro-rated from monthly totals in order to decrease the need for daily measurements. One improvement would be to use (when possible) the actual measured values. In most cases, however, the amount of net evaporation for a two week period tends to be insignificant when compared with other water fluxes or the reservoir contents. But, to be as accurate as possible, a better resolution is needed. In place of such measurements, an evaporation model would be better long-term choice. Such a model would be driven by temperature (solar radiation) and wind (if necessary). Another limitation is the transfer function method of moving water from one reservoir to the next. First, the functions can only be developed where both outflows and inflows are measured (they are not in some reaches). Second, the temporal resolution affects the function. Strong seasonal effects show up in the record, and these effects also appear in monthly relationships. If the system were perfectly measured, every input and output in the system could be accounted for in the transfer. Until that time, however, the regression based transfer functions will need to act as the lumped mass-balance equations.

Another limitation is the ease of model use for the non-trained individual. First, the user must understand the system. Second, the data files must be properly organized, and third, the user must understand which model parameters to modify in order to change delivery schemes. At present, the model only allows monthly parameters for one year. This will be enhanced so that several years can be developed, if needed, for long-term simulation.

Biology

Much of the information provided in this section is derived from the application of the biological model to reservoirs in New Mexico (Cole et al. 1985).

Unit 1-7 in Figure 3. USGS monitoring of nutrient inputs is relatively infrequent (usually bimonthly or less) compared to measurements of water flow, and spatially limited (three relatively complete monitoring stations along the Rio Grande and none along the Rio Chama). Monthly or bimonthly sampling at existing and additional points in the Basin could improve estimates substantially. Also better estimates of how concentrations behave during snowmelt runoff, rain runoff, and at base flow would improve predictions of loadings and concentrations. The nutrient loadings of those few reservoirs just downstream from monitored sites (Elephant Butte and Cochiti) can be relatively accurately estimated but more remote waters in the system are less accurately monitored. Nutrient loading is a major variable controlling the net primary production in mainstream reservoirs and total fish production. Seasonal loadings of nutrients can vary by 10:1 or more between high-and-low loading years. Statistical confidences in seasonal loading estimates for any one seasonal discharge at a well sampled USGS station are roughly ±t0 percent, mostly because of inadequacy of estimation of concentrations during high-runoff conditions. The confidence declines with distance from the actual USGS sampling point because not enough sites are monitored along the river to more representatively provide nutrient input to all geographical areas represented in the model.

Loadings of suspended solids are better represented because more sites are sampled more frequently by the U.S.G.S. The relationship between concentrations of suspended solids and light transmission through the water has been developed under limited conditions in three Rio Grande reservoirs (in single surface samples of suspended solids with simultaneous measurements of light transmission). About 89% of the variance in light transmissions was explained by suspended solids in these lakes, each sampled on different days in fall and spring. Little variation occurs in the relationships among the three lakes, indicating the validity of our assumption that dissolved organic concentrations remain relatively constant in the River Basin. This submodel is least reliable when the predicted concentrations of suspended solids are low, partly because accurate estimates of low concentration of suspended solids are difficult and need more specific research attention.

Variations in light transmission is second only to nutrient concentrations in regulating long-term changes in productivity. At this point, our ability to predict the effect of varying loadings of suspended solids on net production sometimes exceeds 50 percent of the mean seasonal value, mostly when the predicted concentrations of suspended solids are relatively low.

Units 8-10. Limits associated with basin morphology are discussed in the hydrology section. To some extent relative errors in simulation of the effects of suspended solids and light on net plant production may be compensatory ven though predictions of both nutrient concentration and light transmission are somewhat uncertain. Concentrations of suspended solids and nutrients in river flows are not independant; high suspended solids are often associated with high nutrient concentrations. However the actions of both are antagonistic in regulating production and therefore the effects anticipated from the changes of one variable alone tend to be dampened by the effects of the other variable. Because of this compensation, estimates of the differential rate at which nutrients and suspended solids settle or precipitat in reservoirs are likely to be major sources of error in simulating primary productivity. Bolin (1985) presents data relative to this point.

Unit 11. Because of variance and methodological differences, the basic coefficient used to estimate maximum photosynthetic efficiency lies roughly between 1 and 3 percent. The 2 percent value used in the model is based on a mean measured in shallow, hypereutrophic tropical lakes (Westlake et al. 1980). As a consequence of this uncertainty, absolute estimates of fish production may be off as much as 50 percent in certain waters, based on that uncertainty alone. However, inputs of allochthonous organics to some extent reduce the influence of that uncertainty (and introduce uncertainties of their own). More research in the most hypereutrophic waters of New Mexico may improve estimates of maximum conversion efficiencies under the temperature fluxes that occur in New Mexico, in contrast with otherwise similar conditions in the tropical reservoirs where this quation was derived.

Prediction of the relative (rather than the absolute) productivity of reservoirs in the Rio Grande system should not be substantially affected by error in the maximum solar energy value used because it is a relatively constant error measured over all reservoirs in the State. If an error exists in this value, all reservoir primary production will be under-or-over-estimated in proportion to the solar radiation received at each lake surface. However, some error is inherent in estimating the incoming radiation needed to run the model. Data are not collected on site and, although the variance from one site to another in seasonal solar radiation is usually less than 10 percent, spatial and temporal variation may be transmitted to fish production estimates in some reservoirs. This source of inaccuracy however is less than for nutrients, light transmission, or allochthonous inputs. The Agricultural Experiment Station at New Mexico State University recently began monitoring solar energy at more sites, increasing the probability of more accurate estimates for all State water bodies in the future.

Unit 12. Temperatures are relatively accurately estimated: the existing models usually predict temperatures within ±10% of the seasonal mean value for all waters except those below large reservoirs. Also, the relative difference in seasonal temperature from one waterbody to another, or year to year in the same waterbody, are relatively small and the predicted relative effect on primary production and other trophic energetics is commensurately minor. Temperature effects therefore seem to be among the least uncertain with respect to their effect on model prediction of fish production and growth. However, the model does not accurately represent temperatures in connecting waters just below reservoirs. These are underestimated in winter and over estimated in summer for certain reservoir tailwaters.

Unit 14. The net effect of error in estimation of net plant production as a consequence of inaccuracies in concentrations of nutrient and suspended solids is also compounded by the inaccuracy in the relationships between photosynthetic efficiency and nutrient concentration. We assume a relationship that has been developed from a world-wide selection of water bodies (Vollenweider 1979) with possible inaccuracies for the more restricted range of the Rio Grande waters. The seasonal P:N ratio of 10 used to determine which nutrient is limiting production is based on estimated ratios of N and P in living cells and are standard assumed values (Westlake et al. 1980). The unexplained variance involved in the relationship between phosphorus and plant production, based on regression studies, is in excess of 20 percent in overview studies (Vollenweider 1979).

The relationship between temperature and photosynthetic efficiency is implied in latitude effects from data collected over the world (Westlake et al. 1980) and from laboratory data reported by Aruga (1964). Laboratory and field data agree closely. Confidence in relationships is greater at higher temperatures where production is often easier to measure but less error is anticipated in this regard than in other plant-environment interactions.

Exchange rate also influences primary production greatly in the Basin because algal biomass is flushed out of reservoirs and connecting waters at high exchange rates. The exchange rate effect is estimated based on the maximum potential for phytoplankton accural of biomass and capacity of production in unlimited circumstance and is an additive effect with nutrient, suspended solids, and light. These data are not well defined. Approximations are used based on theoretical estimates of flushing rates in perfectly mixed reservoirs and growth rates of algae in unlimited environments. For better estimates in the existing reservoirs water masses should be tracked from upper ends to lower ends of reservoirs and their biomass and productivity monitored. One unknown of considerable consequence in this regard is the viability of riverine algae once it is washed into reservoirs. We presently assume it to be negligeable.

Unit 15. Estimates of allochthonous organic loadings and the ratios of C:N are limited by data availability. These data are collected less frequently at USGS stations than are nutrient data. Therefore seasonal organic loadings are assumed to be constant in time based on means at specific sites determined over several years (1980-1983) from USGS data. However, there is considerable variation in organic loads from one part of the basin to another. Summer values tend to be about twice or more than that of winter. Influx of summer-storm runoff can bring in very high values in the river basin where ground-water influx is too low to dilute affects of highly erosive runoff. Allochthonous matter presently is assumed to remain entirely in all reservoirs without passing through, but for some high exchange-rate reservoirs this may not be an appropriate assumption. Allochthonous matter can contribute more than half of the energy base for fish production in the Basin. As data availability now stands, allochthonous sources of energy are more likely to be less certainly predicted than autochthonous sources, especially where the storm flow from temporary runoff channels is frequent. Relationships between the amount of runoff and the total organic matter exported from the watershed needs further definition to improve this part of the model.

Units 16 and 17. The trophic-level conversion efficiencies of herbivores are based on a large number of studies which fairly precisely indicate a range of efficiencies between 5 and 15 percent (in some instances lower and higher values have been obtained, often with uncertainty as to the role of allochthonous detritus in the analysis). Therefore the conversion efficiency has a fairly high probability of being 10 percent ± 5 percent. There is less confidence in the concept that the observed range is at least partly a function of the relative level of organic food base available, mostly because of the limited number of studies at high levels of organic influx and productivity (organic loading). Factors other than the level of organic loading, however, may be important in certain circumstances. One possible factor is the relative amounts of inorganic suspended loading. Inorganic matter could reduce food values of suspended organic matter or sedimented organic matter and the efficiency with which that food is converted to herbivore production.

The effect of temperature differences from season to season and reservoir to reservoir are, as of now, not reflected in the model in any way other than their basic effect on primary productivity. There is some evidence to suggest that the effects of temperature on trophic efficiency of herbivores is a greater effect than that on photosynthetic efficiency. Therefore winter conversion estimates may be highers than they should be. Although no coefficient is included in the model that directly reflects the oxygen concentrations, we assumed that the effect is indirectly accounted for because oxygen concentration is a function of organic loading. But because reservoir morphology is also an important variable which influences oxygen dynamics, oxygen concentrations may in certain instances vary differently than predicted by productivity alone. In the large mainstream reservoirs of New Mexico, however, oxygen concentrations tend not to vary widely among the reservoirs at any one time of the year. So this variable should have little relative effect on estimates of fish production in large reservoirs even though it may have some absolute effect.

Units 18-20. Estimates of the relative fractions of herbivore production which go into zooplankton and zoobenthos are among the least well defined by the literature (Marakowitz and Likens 1984 and Hargrave, 1973 are the main sources). This uncertainty should have relatively little effect on the estimates of total fish production in reservoirs where fish populations are diverse or fish are generalist feeders, but any errors will have large effects on the estimates of the relative production of individual fish guilds that comprise the total. For example, based on our model, in most of the large New Mexico reservoirs we would expect the zoobenthos to comprise about two thirds of the herbivore production (including herbivorous fish) while zooplankton comprise about one third. If, in fact the ratio is the other way around, predicted relative productions of zooplanktivores and zoobenthivores will be in error a proportional amount. Since virtually all larval fish are zooplanktivores and their survivorship depends on the relative density of all zooplanktivores in relation to zooplankton production, this error can have large impacts on the estimated survivorship of young-of-year fish and subsequent growth rates of older fish. In the example described, we would underestimate the survivorship and growth of young-of-year fish and the growth of older zooplanktivores and zoobenthivores. Because piscivores in the model feed indiscriminately on both groups, model estimates of their production would not be affected by this error. However, because 1-year old and older zoobenthivores in reality average a larger size than zooplanktivores, large piscivores may be affected quite differently than small piscivores. This possibility is not included in this version of the model.

The role of filter-feeding, herbivorous fishes like Dorosoma, also is problematic and potentially very important since the relative density of Dorosoma in the mainstream reservoirs where it occurs in New Mexico seem to consistantly comprise a majority of the total fish density (Cole et al. 1985). The fractions of Dorosoma production supported by phytoplankton and by zooplankton is based on gut contents and estimates of relative assimilation oefficienciesin zooplanktivorous and herbivorous fish, but not for Dorosoma itself. Dorosoma is apparently a highly adaptable species capable of surviving in a number of trophic roles. Although there is much evidence of its filter-feeding herbivory, the conditions under which Dorosoma relies on phytoplanktonic foods are not well defined. Depending on the relative fractions it derives from algae, the presence of shad can greatly magnify the production of piscivores because it short circuits energy flows around intermediate invertebrate foods. The relative effectiveness of shad use of algae as indicated in Figure 14 is very much a first approximation based on studies in New Mexico (Cole et al. 1985) and general information about shad life history.

We now assume that all primary production in reservoirs is in the form of phytoplankton and becomes equally distributed throughout large New Mexico reservoirs regardless of the habitat. This assumption is supported by the fact that macrophytic plants are scarce in large mainstream reservoirs of New Mexico. Although periphyton occurs in some littoral zones of large reservoirs, it rarely becomes as well developed as on floating docks, presumably because water-level fluctuation and most available natural substrates are not optimal. However, the combined benthic and planktonic primary production in the littoral zone may exceed primary production offshore.

Studies of benthos and zooplanktonic density gradients in relation to shore in certain New Mexican reservoirs have not shown clear trends with distance from shores in those reservoirs (Cole et al. 1985), and limited studies of depth-related abundance have not indicated any great vertical difference among zooplankton in most reservoirs. Also, shad wherever they are present, appear to be distributed about evenly throughout reservoirs in New Mexico (Cole et al. 1985). Therefore the distribution of fish-food biomass indicates about equal fish production potential in each habitat. But, if in fact there are substantial gradients of production from the littoral and limnetic zones to the profundal zone, the model underestimates relative productivity of littoral and limnetic fishes and overestimates sublittoral and profundal fish production. This could have a small impact on total estimates for the entire reservoir.

Units 21-23. The fish population submodel mathematically partitions energy generated via the production model among all fish within a habitat. To be partitioned appropriately first requires inputs of species and age classes present in the basin segment. The accuracy required for this input depends on its intended use. For predictions of the next year's recruitment and growth, these input data must be as accurate as the desired accuracy of thos predictions. For longer-term predictions, over decades, the required accuracy of the input data is less because the mathematical populations tend to come into an equilibrium (after several years) with a mathematical environment that becomes more or less independent of the initial inputs.

Mathematically representative partitioning into growth of populations depends also on partitioning coefficients and appropriate P/B ratios. The P/B ratios can be viewed as specific growth coefficients (growth per gram of biomass) with food unrestricted. Younger fish have higher specific growths than older fish. If densities of all fish were small enough to allow maximum growth rates in all groups the factor deterimining the partitioning of food energy would be the specific growth rates at the maximum growth rate. This is what the P/B ratio represents and it is based on observed maximum growth rates of those gamefish guilds included in the model. Based on our analysis, there are relatively small differences in the maximum specific growth rates of those guilds; the major difference in size structure at maximum growth is controlled by maximum expectancies. White bass, for example, attain about half the maximum weight of black bass but also live half as long under maximum-growth conditions.

Units 24 and 25. In this model we assume an average partitioning of food and space resources based on average fraction of space used and food resource consumed in fish populations observed in New Mexico and reported in the literature from elsewhere. Of course, the partitioning of resources varies to some extend depends on the combination of species present. That is, the same relative fractions of a guild are not likely to occur in each of the habitats of different lakes if different guilds with different competative abilities and different food resources exist in those lakes. Variations in a limnological variable like water temperature may have a majorimpact on partitioning food resources differentially among cold-water species, cool-water species and warm-water species. This version of the model best reflects an intermediate cool-water condition (indicated by the abundance of Walleye in most New Mexico reservoirs where they have been stocked) and does not vary from one reservoir to another. Based on extreme mean temperatures observed in reservoirs of the Rio Grande Basin (which may average about 5°C), cold water guilds may have a competative advantage at the upper elevations in the basin and warm-water guilds are likely to predominate in the lower end. Therefore, future modifications of the model in search of greater accuracy in estimating resource partitioning may require the addition of temperature as a determinant of resource partitioning effectiveness. Also it may be necessary to determine more specifically for each major reservoir, the fractions of a species found in each habitat and the fractions of food items found in the stomachs.

Although the manifestations of resource partitioning (food percentage in stomachs and relative abundance in habitats) may approximate competitive interactions, there are problems in their interpretation.

For example they assume that biological processes alone determine the relativel abundance of guild in the long term. If, for example, an abiotic event causes massive mortality in young-of-year fish relative abundance would be influenced in a way which misrepresents the partitioning coefficient. Effects of water level fluctuation are already treated separately in the model. Also, fish pass through different feeding stages and the relative abundance of piscivores may be determined by their ability to compete for zooplankton as alrvae as much or more than their ability to transfer to fish foods in juvenile and older stages. We therefore view these partitioning coefficients as a simplified first approximation of an eventually more accurate model in which the coefficients are derived for well-documented stable habitats.

Units 29 and 30. The prediction of total eggs depends on a good estimate of egg-biomass relationships for females which are generally available but are better for some species than others (Carlander 1969 and 1975 for examples). The sex ratio is another coefficient that can vary from site to site. The number of females in the population is the critical knowledge. The sex ratio of adult fish is considered to be 1:1 for want of information that indicates otherwise.

Units 31 and 32. Survivorship and growth assumptions about young-of-year fish can have large impacts in determining the relative importance of different fish-species production and age-class strength. The impacts of water-level fluctuation on young-of-year survival from unlaid eggs is only crudely understood and, because certain game fish are usually stocked, development of empirical relationships between reservoir conditions and young-of-year survivorship is more difficult for these species (it may require experimentally foregoing stocking or somehow identifying stocked fish a year later). Survivorship of 1st-year-fish in other game species, however, may be identified since they are not routinely stocked (*Lepomis*, *Pomoxis*, *Morone*). The only remaining method is to estimate the mortalities caused by water-level fluctuation on young-of-year survival from unlaid eggs is only crudely understood and, because certain game fish are usually stocked, development of empirical relationships between reservoir conditions and young-of-year survivorship is more difficult for these species (it may require experimentally foregoing stocking or somehow identifying stocked fish a year later). Survivorship of 1st-year-fish in other game species, however, may be identified since they are not routinely stocked (*Lepomis*, *Pomoxis*, *Morone*). The only remaining method is to estimate the mortalities caused by water-level fluctuations mechanistically (spawning depths used, rate of change in water level, fraction of eggs spawned at various temperatures, development rates and calculating the relative fraction stranded or exposed to dark waters subject to severe predation). Preliminary estimates of susceptability to water-level fluctuation based on estimation of stranding potential are now being used, but much uncertainty remains. The role of rising water levels, particularly when water is very turbid, is also in question. We presently assume that rising water levels are not likely to change vulnerability of eggs and yolk-sac larvae to predation or disease. However rising water levels can displace spawning adults in certain guilds.

We also assume that all larval fish feed on zooplankton similarly and therefore act more as intraspecific competitors than as interspecific competitors. Some of our reservoir research suggests that this is generally so for larval clupeids and *Lepomis* sunfish with the same mouth sizes (Drullinger, In preparation), and the sequence with which young fish appear may have great impact on survivorship of species. Relatively early spawning species hatched in great abundance, such as gizzard shad, may depress food abundance for later species such as sunfishes or black-bass, and, being larger by then, are able to feed on a larger range of food sizes. This impact is not now included in the model and needs further research for clarification since it may have a large impact on the relative survivorship of these species to first-year recruitment.

The growth of young-of-year fish depends on the production of zooplankton available to them, which is a function of the zooplankton production, the demand for zooplankton by all zooplanktivores, the availability of any possible alternative foods (small zoobenthos), and differentail competitive advantages of fish in different guilds and size groups. Miscalculations of zooplanktonic productivity will greatly influence estimates of young-of-year survivorship and growths. Misrepresentation of the actual demand for zooplankton, based on required feeding rates for survival and the fraction of food item found in fish stomachs, is also an area with a need for greater quantification. Death due to predation is now assumed, for want of more specific information, to be the same as that calculated for older fish. Death due to starvation results when the density of young fish left after mortality occurs still exceeds the capacity of zooplanktonic production to provide resources for all zooplanktivores. Fish older than one-year old are assumed to be immune to starvation under all but the most extreme conditions. Larval and juvenile fish, however, must grow at certain minimal rates in order to survive to recruitment in one-year-old stock.

Although data exists suggesting these growth rates, the statistical uncertainty in these estimates is not clear.

Units 33-39. In most respects, predictions of angler effort and yield to anglers are central to the purpose of the whole model. The purpose of the model is to manage water bodies for optimal fishing experience within the framework of the natural and economic limitations leading to best overall social benefit from all water use in the state, including agricultural, industrial, municipal and other recreational uses. Measures of angler effort and yield of fish to anglers are the primary means of judging angler satisfaction. Angler effort alone is not enough to characterize satisfaction. If catch rates are high enough, angler effort in total will fall as more anglers go home early with their legally imposed or self-imposed limits. Angling effort is proportional to economic activity and benefits derived, and yield per angler is one major factor influencing effort, although other factors are also critically important. Therefore model assumptions about relationships between fish density and fishing efforts and yields are crucial to model performance. And, extremely important, the relationships between anglers and fish biomass influences profoundly the relative need for accuracy in other parts of the model.

Central to this whole line of thought is the modeled relationships between fish biomass and fishing effort. We assume that the only factor determining the effort is the total biomass of game fish (excluding carp and suckers and small forage species never reported in yields). This assumption is based on observations made between yield and biomass over four years of study in six New Mexico reservoirs (Cole et al. 1985). As a consequence of that study, we concluded that the average angler, a composite of all anglers, establishes a total weight goal for his fishing yield and is satisfied with either many small fish, or a few large ones, or some combination adding to that weight goal. The average angler also is not selective among game fish, giving as much value to a 1-kg crappie as he would to a 1-kg bass or 1-kg walleye (or as much value to a 0.2-kg stocked trout as he would to a 0.2-kg bluegill).

It is important to remember that this relationship between the average "composite" angler and the average "composite" fish, and that there is much variation among individual anglers in their fishing goals. At one extreme are those happy to catch dozens of small pan fish while at the other extreme is the single-minded "flunker" angler. As a consequence of this variation the relationship defined by total fish biomass and angler effort can potentially vary from one site to another, depending on the diversity and biomass of fish present. Small, remote water bodies with limited fish diversity may be less likely to fit this submodel than larger water bodies with greater fish biomass and greater access to anglers. Since the majority of most angling experience in New Mexico depends on the latter category, we feel this submodel relationship is a fairly strong one. However, to the extent it is incorrect, modeled predictions of economic values will be misrepresentative. If for example, there really is some intrinsic, 1-kg black bass value to anglers that is greater than that of a 1-kg walleye value, then lakes with black bass occupying a walleye niche will be more attractive to anglers than lakes with only walleye occupying that niche. Our model does not assume that at present, and it may be one of the more controversial areas that needs further investigation through careful creel census, biomass estimation, and interview.

If this submodel proves correct, then the relative importance of accurate partitioning of lake productivity among guilds within a habitat-feeding group becomes a less critical concern for providing satisfying angler benefits, as long as relatively diverse fisheries of generally desirable stockes are maintained. Maintenance of diversity then depends mostly on maintenance of those guilds that are most likely to die out under the prevailing management conditions. Because specific guilds are unlikely to be identified by anglers for exceptional fishing pressure in this model, other factors are more likely to contribute to the demise of a guild. One obvious factor in New Mexico waters is the vulnerability of a guild to water-level fluctuation. A less obvious factor is the degree to which fishing effort is determined by factors other than fish biomass, such as water-body size, elevation and access; distance to population centers; and availability of suitable alternatives within the same distance to the angler. Small waterbodies with good access, pleasant climate (elevation), near relatively large populations (number of potential angler/ha), and with few other fishing alternatives nearby have very high fishing efforts imposed. The large mainstream reservoirs, in contrast, have low fishing efforts for the biomass present. Where high fishing efforts per biomass occur, relatively rare species are in danger of extinction as they are caught incidentally in a non-selective fishing environment.

Water-level fluctuation that reduces a guild's abundance can interact with the effects of fishing effort. If, for example, black bass are particularly vulnerable to water-level fluctuation, making them relatively rare in an unstocked lake, intense, non-selective fishing pressure, superimposes, on water-level-caused mortality, could severely reduce black bass abundance. This means that stocking of an alternative guild, like catfish, to "take the pressure off" the black bass could do just the opposite, depending on regulations related to fishing methods. In fishing more for the stocked fish with non-selective methods, the black bass population is "fished down" even more. Because small lakes close to population centers are more vulnerable to the negative effects of water-level fluctuation under such circumstances, the degree of impact in such reservoirs may be more important to monitor than in larger reservoirs. However, there may be counteractive impacts because small reservoirs intrinsically have less capacity for water-level fluctuation and therefore less potential impact on fish abundance, and larger reservoirs with greater water-level fluctuations have less fishing pressure. Those lakes that are most likely to be vulnerable are large reservoirs managed for a small recreational pool (e.g. Cochiti Reservoir) with high snowmelt-caused water-level fluctuations.

Centrarchid fish are more vulnerable to water-level fluctuation than other species and therefore should receive the greatest intensity of effort in defining that relative impact. For other guilds, efforts to define that impact are likely to be of lesser consequence. Future studies of water-level impacts should concentrate in littoral areas occupied by centrarchids, using methods that are most likely to determine the relative abundance of spawning adults and surviving young-of-year.

The affect of fishing yield on fish survivorship assumes that fishing mortality and natural mortality of catchable-size fish (usually over 1 year old) are compensatory. Therefore, in theory, all of the mortality calculated to exist in an unfished water body can be directed into fishing-harvest mortality without changing the total death rate in the water body. Basically this assumption requires that all sources of mortality are biological and that fishing mortality completely displaces all other predation and disease. Although there is some evidence for this, there is also evidence for additivity in many waters. The statistical certainty in this assumption is generally unknown.

Units 40-43. The connecting-water model is basically the same as for reservoirs in terms of estimating primary production. The main problems with this use of a model designed for reservoirs relate to the limnological differences between connecting waters and reservoirs. The obvious difference is the relative role of current, which in flowing connecting waters exerts continuing forces on the substrate. In reservoirs the force of currents generated by wind are mainly on a small shore-zone area, and only periodically disturbs the bottom as storms pass through. Although wave currents have some influence in reservoirs they are regarded in this model as a negligeable factor. Also, the exchange rates in connecting waters are so rapid they preclude any development of phytoplankton.

For connecting waters, a term has to be included in the model that considers substrate-velocity interaction. We use the relative fraction of sand and the velocity together to establish this. Velocity is considered an erosive force which acts to resist plant biomass accumulation, and when high enough, velocities can become a limiting force even where substrate is immoveable. In the model, the immovability of the substrate is indicated by the % sand in the substrate. It is assumed that all material finer than sand never settles and is carried through connecting waters to the next reservoir where it is trapped. Therefore the sand fraction represents the easily moved fraction of bottom sediment under prevailing water velocities. Where sand is 100 percent of the substrate, the capacity of the bottom to support algal growth is profoundly dimished by substrate instability (1 percent of the calculated potential otherwise). Where the bottom is entirely immoveable there is no effect on primary productivity. As velocity increases, there is an additional depression of primary production as abrasiveness and erosive force grows. Additionally because water-level fluctuations cause alternate stranding and reflooding the plant production per unit area in fluctuating widths will be less than where the average width are constant.

Most of these relationships are poorly defined in the literature, are highly qualitative or must be deduced rather than empirically determined. For example, the relationships for substrate effects on production are based on the relative amount of organic matter (periphytic growth including settled materials) in sediments of different particle sizes derived from current disturbed areas. The relative abundance of invertebrate organisms associated with the periphytic matter (the food of fishes) has been best measured, and it varies from a biomass in larger substrates that exceeds that in sand by 100 to 1000 times. The effects of fluctuating water are much less documented but generally recognized. Relative affects are estimated from the colonization rates reported for periphyton growth on new substrates — usually about 3 to 5 weeks. Killing exposures that occur an average of once every two weeks then would minimally reduce production by half. Colonization rates and the ability of some algae to withstand drying and recover from dominant elements affect this estimate, but we feel it serves for a suitable first approximation in the model.

Riparian inputs of organic matter are assumed to be relatively unimportant, but the allochthonous import from reservoirs is very important. In this model the allochthonous import is derived from U.S.G.S. data just as for the reservoir model and suffers similar limitations. The linkage between fish and the primary productivity is much reduced in the connecting water part of the model. This derives from several realities. First because zooplankton are not important inhabitants of connecting waters (except as allochthonous export from reservoirs) fish are either zoobenthivores or piscivores. Based on stomach contents, fish in connecting waters which would be classified piscivores in reservoirs are more likely to consume zoobenthos in streams, perhaps because of larger average size of zoobenthos found in connecting waters. As a consequence this first version of the model we assume that all fish are benthivores. Also because the allochthonous matter has relatively high C:N ratio (phytoplankton from reservoirs) we assume average conversion efficiencies from the organic matter to fish of 0.01 percent (equivalent of 10 percent per trophic level exchange.

Habitat differences in connecting waters are relatively small compared to reservoirs. Flow variation in the form of pools and riffles is the biggest difference as well as longitudinal changes in substrate quality, water temperature and oxygen concentration. Pool-riffle ratios and oxygen concentrations tend to be similar within reaches classified as sandy, which differ from other reaches classified as stable substrate. Reaches of stable substrate occur in degrading areas below reservoirs. These are also reaches in which temperatures may be moderated by reservoir effects, water is somewhat clearer, and oxygen concentrations are somewhat depressed. In this version of the model these factors are considered much less important than substrate conditions in determining total fish production.

Partitioning into guilds is not included in the connecting-water model. However, if we assume that partitioning of food resources is indicated by sitribution of biomass of species in each connecting water segment, the estimated production could be translated into biomass by the same method already disucssed for reservoir fishes. In the present model a P/B ratio of 1.0 is assumed as an overall average regardless of species present and the total biomass then serves as an index to economic activity as it does in the reservoir model. At present the fishing intensity in connecting waters is assumed not to be enough to cause decreases in biomass from overfishing. With that assumption survivorship information is not necessary for estimating the continuity of the resource. About most of the stream fishing done in New Mexico is done in waters that cannot be modeled by the approach used here. If stream fisheries are to be accurately represented an advanced model fo the one now available for connecting water is needed because of the need to better simulate inputs and exports of allochthonous matter from each reach in a stream system. Stream reaches often rely much more on allochthonous matter than autochthonous matter for generating organic material that serves as an energy base for fish production.

Economic Model Limitations

Regression methods are only accurate when used to predict within the range of data observed. For extreme decisions, such as drying up a river or lake, the economics model is unreliable. Sampling over a period in which site quality varies more may help (e.g., a year) but the resulting model will be accurate only for the conditions that exist.

The small data base used for the model may have been overextended. The demand equation was estimated from a sample of 780 people with 250 anglers in the Rio Grande Basin in a single season (summer 1981). Subsequent tests of precision indicate that at least 100 observations for each site should be made (a sample of 2100). Also, changes in NMDGF card-survey data related to the zone of origin (zip codes of respondents would help) would help refine the model.

The regional income-employment model was based on regression procedures in which angler days were one of many determinants in the process that generates county income. For some counties, the regression approach cannot identify the relatively small part of county income due to angler participation. Model accuracy may be increased by programming methods in which water and sport-fisheries are viewed as factors included in an aggregate regional production function. Sport-fishery management decisions may be better tracked in the income-generation process using those methods.

We do not clearly understand the process by which fish-management decisions influence anglers' preference. Therefore, we have a limited ability to explain what mechanism operate to effect angler benefits when management decisions are applied. A telephone/mail survey with a larger sample, and more detailed questions should help.

Few data are available for other water-based recreational participation outside of angling. Thus our benefits and regional income measures are based solely on angler participation. For that reason, we have necessarily understated the total recreational benefit from water-management decision because, typically, other recreationists (e.g., boaters) benefit too. Including non-anglers in a telephone/mail survey sample would help us know about non-angler water-based recreation in New Mexico. These should be ascertained simultaneously with angler benefits and income generation because it is difficult to realistically separate other water-based recreation from angling, especially in reservoirs. The preliminary data indicate that some anglers at least prefer a "package" of recreational benefits which can include boating, swimming, waterskiing and wildlife observation. Interactions of those recreational opportunities with angling opportunities cannot be readily identified by separate studies conducted under other auspices. Even though fishing appears to be the primary demand motivating recreational use for most reservoir visitations, the related recreational uses should also be considered to understand more fully how fishing demand is determined.

MANAGEMENT APPLICATIONS

A series of examples indicating specific model uses with case histories are given below.

Example 1: Simulating the historic condition in the Rio Grande Basin. The model can be run using the historic record of runoff from 1975 to 1983 in five-year sequences and assuming prevailing management conditions. With that historic record one can recreate the density, yield and the potential yield of fish in each of the 8 reservoirs by size class for each guild (crappie, sunfish, white bass, black bass, catfish, walleye, northern pike, carp and sucker, and trout) present in each reservoir. The initial fish biomass and age distribution have been estimated for each reservoir but more accurate inputs would increase the accuracy of estimation.

Using density estimates over the next five years, the user can determine how recruitment of new stock will change next year and how that will influence the availability of fish by size class for anglers in subsequent years. These changes will be reflected in the angler effort, which is also available annually for a 5-year sequence. The yield of fish (catch rate per hour) is also available for the same period as well as the theoretical surplus yield not taken by anglers (or the over harvest that could occur if this value turns out to be negative). Lastly, the economic benefits to New Mexico anglers and the changes in income generated by fishing can be requested by the model user for each year. Determining whether or not the existing conditions approach optimum or vary substantially from optimum may be assessed through the: (1) fish densities observed in relation to some desired density, (2) yield observed in relation to some desired yield (e.g. 0.5 fish/hr), (3) under harvest or over harvest reflected in surplus yield per species, (4) economic benefits generated, and (5) local income generated. If these indicators are near optimum for the historical condition the user may wish to exert influence to maintain the optimum. More likely, however, the optimum will not have occurred throughout the historical sequence. The user has alternatives available to asses management effects on developing an optimum. Those capabilities include: (1) population management through stocking or harvest regulations; (2) habitat manipulations of water quanitity and quality, and (3) economic management decisions which influence site access or site quality.

Example 2: Modifying Stocking and Harvest Regulation. The user may modify the historical condition by stocking any of the guilds as fry, fingerlings or catchables. The user has to provide the number of stocked fish and the sizes. Once this is done the model can be rerun to see how the output was altered. Was density maintained? Was yield increased? Was economic benefit increased? Usually the user will record output via the printer and rerun the model using a second stocking alternative. This is usually done repeatedly until some optimum stocking rate is defined. It may take numerous reruns of the model to identify the optimum.

As an alternative to or in addition to stocking, the user can modify the harvest-size limit (including slot limits). Once limits are altered the model is rerun. Then, as for stocking, a range of limit changes can be made with a record of each run kept to estimate the optimum response.

The biological manipulations can be done for any combination of reservoirs. However, because the reservoirs may be interactive in determining the fish densities and yields as well as economic value some large runs including all reservoirs or a group of regional reservoirs (e.g. El Vado, Heron, Cochiti and Abiquiu) should be contemplated first. Thus will reveal the degree to which reservoirs are interactive. If this turns out to be important, all subsequent analyses probably should be done on the reservoir group rather than individually or the results will be misrepresentative of the actual system behavior simulated by the model. If such interactions are not in evidence, reservoirs can be realistically examined singly. The advantage of examining reservoirs singly is the more rapid turn around in computing results. The greater the number of reservoirs, the longer is the waiting-time for results. Another possible disadvantage is that management changes applied to all reservoirs together may require more organization to develop the more comprehensive management alternative.

The model does not do cost-benefit analyses for any management application. The user, for example has to assess the cost of stocking at a level that appears optimum for continuous yield and angler benefit. The user has to determine if that stocking cost is prohibitive and choose an economically feasible stocking rate to produce the nearest to optimum condition allowed by management economics. In this version of the model the user cannot assess effects of stocking and harvest changes in connecting waters. The user can only determine the indirect effects that such regulations may have when applied to nearby reservoirs.

Example 3: Habitat Modifications. Using the same outputs the user can assess the effects of habitat modification. One example of a habitat manipulation would be controlling flow so more water is distributed in one of the reservoirs than was previously stored there. Several examples are obvious. The U.S. Army Corp of Engineers, for example, has been authorized to store several times as much water in Abiquiu Reservoir than previously following certain guidelines. If those guidelines are followed, what effect will they have on fisheries and fishing benefits in Abiquiu Reservoir as well as any other waters which have to be managed differently as a consequence of this change? Cochiti reservoir may also be considered for maintaining a larger storage pool because the reservoir is so close to population centers in New Mexico. What could be the economic benefits added by such redistribution (of course, flood control needs also must be considered)? Galisteo Reservoir, presently designed to catch sediment only, could have water pumped to it from the Rio Grande. The cost of pumping has to be assessed outside the model but once it is assessed, the benefits added by pumping and storing water there can be assessed for a variety of volumes. Of course, to be meaningful, the user has to be familiar with any engineering or legal contraints associated with these modifications. Assessments have to be made of the affect of modification on the total water available to downstream users and in cost analyses done for any management decision (outside the model) the cost incurred by additional evaporation needs to be considered. It is not incorporated in the model.

Other potential modifications can be tested. For example, running the model with Galisteo Reservoir may show a substantial fisheries benefit to people in Bernallio county but, for other reasons beyond control, that approach may not be justified. Instead, however, excavation of groundwater fed ponds along the Rio Grande may provide an economical alternative. Although such construction cannot be evaluated directly in the model as it is, the model can be modified to analyse such choices by the model developers or other modelers.

Example 4: Economic Decisions. The intensity of angler use is influenced in the model by far more than fish yield alone. Factors such as access, presence or absence of state parks, site entrance fees, site closures, or site quality can be altered through the economics portion of the model. For example, the affect of building another state park (with boat ramp access, camping and other amenities) at Abiquiu Reservoir can be analysed. Temporary site closures for repair or other purposes can be examined. The affect of building roads into a river for improved access can be assessed. Again, the benefits are provided by the model and the costs must be provided by the user.

One proxy for site quality is elevation which incorporates a complex of factors such as temperature and vegetation into one term. To the extent that the model user can alter site quality to be like another elevation (e.g. planting shade trees), this variable can also be modified. However, it is up to the user to decide how much elevation change is associated with the site-quality change contemplated.

Example 5: Short-term Predictions. The model user can develop short-term predictions for the next year. However, the user must introduce new runoff data monthly during winter months to make projections for the next year. The data has to be obtained from USGS and other monitoring sources by April of the year in question. A fairly reliable scenario of water-level changes, volumes and surface areas can be predicted after April to assess affects on fish density, by size class, yield, angler effort and angling benefits during the next several months. The model should be run reiteratively to determine the range of possibilities that could occur using only one criterion of change because next years predicted discharge has an element of uncertainty in it. Stocking or harvest regulation changes can then be superimposed on the model predictions to determine the extent to which predicted runoff effects might be ameliorated through altered biological management.

In general, then, the model provides a powerful tool for examining the effects of fishery management decisions (or other related decisions) on the mainstream Rio Grande. However, the user should always keep in mind the models limitations and remember that, as described in the Methods section of this report, that it is at this stage not expected to be a perfect predictor. It is best used in combination with a liberal dose of managerial experience and with continuing research designed to increase the predictive capability.

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APPENDIX I

APPENDICES

MATHEMATICAL DOCUMENTATION, HYDROLOGY

The driving variable of the hydrology submodel is water volume per unit time (reservoirs) or flow rate (streams). 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. 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 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. The forms it is modeled by are explained in the following descriptions. An important model form is the regression equation, which is used in several places of the model.

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, FLOMAD, 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) $Q_m = Am \ Qo + Bm$

where:

Q_m = modified discharge, desired by model user (m = "in" for inflow; "out" for outflow)(c+s)

Q_o = original measured discharge, inflow or outflow

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

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

The parameters A_m and B_m can be modified on a monthly basis by the user. For example, if new irrigation withdrawals are to be considered, the user can set the months of the withdrawals and the amount in each. Up to three inflows and outflows at each reservoir can be specified in this manner.

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 basic 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 is performed in subroutine VOLDIS. The volume determined at this step is

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

where:

V_c = computed volume (acre feet)

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

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

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

The surface area for this volume is

$$(1.3) \quad A_1 = f(Vc)$$

where:

A_1 = initial estimate of surface area (acres)

$f(Vc)$ = an interpolated value as performed by function FCTN which uses a table of elevation, area, and capacity unique to each reservoir.

A first guess at the volume is

$$(1.4) \quad V_1 = Vc - A_1 \ (Kp \ E - P)$$

where:

Kp = pan coefficient for the reservoir

E = pan evaporation, and

P = precipitation.

Equation 1.4 accounts for the net weather effects in the bimonthly period. At this point, V_2 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 estimate is passed to the economics model which is used to predict angler use at reservoirs.

The next operation is computing the water quality constituent concentrations in the reservoir. Water quality constituents are phosphorus, P, nitrogen, N, and suspended sediment, SS. Loadings to the reservoir are found from

$$(1.6) \quad L = (A_i Q_i^{Bi} + C_i Q_i + D_i)\ Lm$$

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)

Lm = a user defined channel, load modifier factor (> = 0), and A_i, B_i, C_i, and D_i = empirically determined (by regression) parameters for that channel and constitutent.

The load modifier factor (Lm) can be used to study increases in supply of any of the three constituents. With these three loads, reservoir volume, reservoir area, and outflow rate, the model calls NUTR to compute the reservoir concentrations for P, N, and SS.

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) Nine years of base data for flows and volumes (can be a synthetic record for years other than observed values)
2) The parameter file containing 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

The challenge is to sort out what upstream sites to include in Qx and to select appropriate values for At and Bt. Table A1 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 A1. Index Flows and Transfer Function Parameters for Each Reservoir.

Reservoir	Qx Index Flow	At	Bt
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
Elephant Butte	Cochiti Outflow[**]	R	R
Caballo	Elephant Butte Outflow	1.0	0.0

[*] Heron is not affected by upstream reservoir operations, just 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.

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

$$(1.8) \qquad C_1 = \frac{L}{(a + bQs + CT^d)}$$

where:

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

L = load to the reservoir

Qs = a "sedimentation" parameter = $\frac{Z}{T}$

Z = hydraulic depth = $\frac{Vc}{A}$ (feet)

Vc = computed volume (acre feet)

A = surface area corresponding to that volume (acres)

T = exchange rate = $\frac{Vc}{Qout}$ (½ months)

Qout = outflow rate (volume (acre feet) in the bimonthly time period), and a, b, c, and d = empirically fit or deduced parameters.

If the value of T equals or exceeds 30, the a, b, c, and d parameters take different values and T in equation 1.8 is replaced by Qs.

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 11 channel reaches from which to choose. The choice is then transferred to CHANL.

Subroutine CHANL. This subroutine reads the flow files created by the reservoir model and/or other files for non-reservoir flows. For example, the Upper Chama is not affected by an upstream reservoir outflow; therefore a non-reservoir flow file, La Puente, is needed. After the appropriate files are read, the model calls FLOMOD which allows the user to modify existing stream flows. It is the same as the flow modification subroutine used in the reservoir submodel. 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:

$$(1.9) \qquad P_1 = \frac{1.486\ S^{1/2}}{N} \ \frac{\ell^{2/3}}{a}$$

and

$$(1.10) \qquad P_2 = \frac{3}{(5 - 2b)}$$

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:

(1.11) $p = aA^b$

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:

(1.12) $T = aA^b$

where:

T = surface top width (feet).

With these parameters, the other relevant computations become:

(1.13) $$A = \frac{Q}{P_1}$$

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

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

(1.16) $$T_s = \frac{\rho f\ V^2}{8}$$

and

$$(1.17) \quad Ds = \frac{Ts}{(S_s - 1)\ \gamma\ \delta}$$

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)

ρ = 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)

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

δ = Shield's parameter (= 0.047)

The next step in the model is to estimate the P, N, and SS concentrations in the streamflow. Two approaches are used. If the channel reach is immediately downstream of a reservoir then the reservoir concentrations are used. If the reach is a remote from the reservoir, concentration-flow relationships are used. The concentration values are computed as they were in the reservoir submodel, except the function name in the channel submodels is RIVCHM.

The parameters in equation 1.6 are indexed by site, chemical, and season. In the reservoir model they are indexed by site, inflow channel, chemical, and season. Finally the model writes the hydraulic characteristics and water quality constituent concentrations to a file for use in the biological and economic submodels.

Subroutine FLOMOD. This subroutine is used to modify stream flows based on upstream reservoir releases. Like the reservoir model, transfer functions are used when measured data allow for such an application. The transfer function takes the same form as equation 1.7. Table A2 lists the channel reaches, index flows and transfer function parameters used. Predicted streamflows are passed to a file for use in the biological and economic 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.

Table A2. Index Flows, Transfer Functions and Method of Determining Water Quality Constituent Concentrations for the Eleven Channel Reaches in the Channel Submodel.

Reach	Index Flow	Transfer Function	Water Quality Concentration
Upper Chama	La Puente	None Used	S[**]
Willow Creek	La Puente + Heron Outflow	None Used	S
Middle Chama	El Vado Outflow	None Used	R
Lower Chama	Chamita	Chamita estimated from Abiquiu Outflow	R
Upper Rio Grande	San Juan	None Used	S
Otowi	Otowi	Otowi estimated from Abiquiu Outflow and San Juan Pueblo	S
Cochiti	Cochiti Outflow	None Used	R
Middle Rio Grande	Albuquerque	Albuquerque estimated from Cochiti outflow	S
Elephant Butte - Caballo	Elephant Butte Outflow	None Used	R
Garfield	Caballo Outflow	None Used	R
Las Cruces	El Paso	El Paso estimated from Caballo outflow	S

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[*] If upstream reservoir releases are changed in the model then the downstream channel flows may need to be estimated. Parameters vary on a monthly basis.

[**] Concentrations found by stream relations (S) or by reservoir concentrations (R).

MATHEMATICAL DOCUMENTATION, BIOLOGY

The biology portion of this model ultimately predicts the numbers and weight of fish harvested. This is done in three stages; the productivity in the basin is computed, the change in composition of fish (numbers and biomass) is altered, and the angler's success and their effect on the fish is predicted. In addition to natural causes affecting fish numbers the fish stock can be altered by stocking of appropriate species.

The production submodel predicts the flow of energy through the basin. The basin is divided into five zones (habitats) based on the degree of light penetration and whether it is offshore/onshore. Energy is transferred from solar radiation into phytoplankton production then six feeding guilds of animals. Three guilds represent the production, or growth, used in the population model.

The population model tracks the numbers and weight of each species occuring in the basin. Each species is divided by age class and lifestage. All animals enter the next age class at the start of the calendar year. Each lifestage represents a different feeding regime and competitive ability. The larval stage is the first six weeks of a fish's existence, the juvenile stage is the time from the individual's seventh week to the start of the new calendar year (this is the first age class), and the adult stage is the amalgamation of all other age classes. To avoid wordiness, a "class" refers to any particular species and age class or species and larval lifestage.

The number of animals at the end of a particular time span is the subtraction of animals dying and the addition of newborn (larval) fish. The weight gain of the entire complex of fish is predicted by the production submodel. Adult fish production is further partitioned into each age class.

The harvest model predicts the numbers of each class caught by anglers. It also computes the affect, by anglers, on fish numbers. The number of fish caught follows a typical catch per unit effort formulation with the total effort being given by the economic model.

The user can alter the fish composition by two methods. Stocking, which results in an addition to the numbers present, and imposing legal limits on the length of the species that can be harvested, which protects certain classes from harvest.

PRODUCTION MODEL

The production model is responsible for determining the total production of the basin. Total production is a seven by five matrix representing seven feeding guilds and five habitats. The model first computes the surface area and volume of each habitat, then determines the rate of primary production and allocthonous loading, then animal productivity. Total production is a function of habitat size and production rate (productivity).

Light Transmission

Water Depth at 1 percent and .01 percent light transmission declines exponentially as suspended solids increase. This is described by the equations:

$$(2.1) \quad d_1 = b_{1,0}\mathrm{EXP}(-b_{1,1}[SS]) \text{ and}$$

$$(2.2) \quad d_{01,0} = b_{01,0}\ \mathrm{EXP}(-b_{01,1}[SS])$$

where [SS] is the concentration (mg./l) of suspended solids.

Surface Area and Volume of each Habitat

Surface area and volume for the surface elevation, and elevation at each light penetration levels is determined in this submode. The vectors SA_d and VOL_d are defined as:

$$(2.3) \quad SA_d = \begin{bmatrix} \text{Surface area at water elevation} \\ \text{Surface area at 1 percent light penetration depth} \\ \text{Surface area at .01 percent light penetration depth} \end{bmatrix}$$

and

$$(2.4) \quad VOL_d = \begin{bmatrix} \text{Volume at water elevation} \\ \text{Volume at 1 percent light penetration} \\ \text{Volume at .01 percent light penetration} \end{bmatrix}$$

These are obtained from the area-capacity curves as explained in the hydrology section.

The basin is divided into five habitats: littoral, limnetic, sublittoral, pelagic, and profundal. Surface area and volume of each zone can be represented by the vectors:

$$(2.5)\quad SA_h = \begin{bmatrix} \text{s.a. of littoral zone} \\ \text{s.a. of limnetic zone} \\ \text{s.a. of sublittoral zone} \\ \text{s.a. of pelagic zone} \\ \text{s.a. of profundal zone} \end{bmatrix}$$

and

$$(2.6)\quad VOL_h = \begin{bmatrix} \text{volume of littoral zone} \\ \text{volume of limnetic zone} \\ \text{volume of sublittoral zone} \\ \text{volume of pelagic zone} \\ \text{volume of profundal zone} \end{bmatrix}$$

Then the matrix equations:

$$(2.7)\quad A_h = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} SA_d$$

and

$$(2.8)\quad VOL_h = \begin{bmatrix} 0 & -d_1 & 0 \\ 0 & d_1 & 0 \\ 0 & 0 & -(d_{o1}-d_1) \\ 0 & 0 & (d_{o1}-d_1) \\ 0 & 0 & 0 \end{bmatrix} SA_d + \begin{bmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} VOL_h$$

determine the surface area and volume of each of the habitats.

Carbon Loading

The amount of allocthonous carbon entering the basin is expressed in the same units as primary productivity.

$$(2.9a) \quad P_c = [C]\ VOL_{in} / (SA\ DAYS)$$

where [C] is the average concentration of incoming allocthonous carbon (gr./m^3), Vol_{in} is the volume(m^3) of incoming water during the period, SA is the average surface area (m^2), DAYS is the number of days in the period, and P_c is carbon loading (grC/m^2/day).

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_l) is affected by temperature in centigrade (E_t), nutrient availability (E_n), suspended solids (E_s), and exchange rate (E_e). These effects operate jointly, and independently, to reduce the maximum efficiency by a given fraction. The equations are:

$$(2.10) \quad E_t = b_{t,o} + b_{t,1}\ T$$

where T is temperature in centigrade,

$$(2.11) \quad E_s = \begin{cases} b_{s,o}[SS]^{b_{s,1}} & , [SS] > 0.1 \\ 1.0 & , [SS] < 0.1 \end{cases}$$

[SS] is average suspended solid concentration, and

$$(2.12) \quad E_n = 1.0 - \mathrm{EXP}(-b_{n,1}[N_1])$$

where N_1 is the limiting nutrient value -- the minimum of ([P], [N]/10.0), [P] and [N] are average phosphorus and nitrogen concentrations (mg./l).

$$(2.13) \quad E_e = \mathrm{EXP}(b_{e,1}\mathrm{EXP}(-b_{e,2}e))$$

where e is the exchange rate of the basin expressed in days.

Photosynthetic efficiency is the product of maximum efficiency and equations

(2.10)-(2.13) or:

$$(2.14) \quad E_1 = E_m E_t E_s E_n E_e$$

Primary productivity is expressed as:

$$(2.15) \quad P_1 = L_o E_1 P_{conv}$$

where P_1 is primary productivity is gr.C./m^2/day, L_o is average light intensity (KCALS/m^2/day) at the water surface and P_{conv} is a conversion coefficient from KCALS to gr. C.

Consumer Productivity

The productivity of the six remaining guilds are functions of total organic loading which is the sum of P_1 and P_c. Consumer production efficiency varies as a linear function of total organic loading:

$$(2.16) \quad EFF. = b_{ef,o} + b_{ef,1}(P_1 + P_c).$$

Herbivore efficiency is altered by the average c:n ratio(CN) of the total organic loading. Herbivore efficiency (EFF_h) is:

$$(2.17)\quad EFF_h = b_{h,o} + b_{bh,1}(P_1 + P_c) + b_{h,2}CN + b_{h,3}(P_1 + P_c)CN.$$

Herbivores are initially divided into zoobenthos and zooplankton. The fraction of primary consumption that is zoobenthos is:

$$(2.18)\quad FRBEN = b_{ben,o} - b_{ben,1}\,(P_1 + P_c) \text{ with the restriction of}$$

$$0 \leq FRBEN \leq 1$$

and

$$(2.19)\quad FRZOO = 1.0 - FRBEN.$$

FRBEN & FRZOO is the fraction of herbivorc productivity that is benthic and planktonic respectively.

Zooplankton may be further split into planktivorous fish and zooplankton. The fraction of zooplankton productivity that is fish is a quadratic function of organic loading: or:

$$(2.20)\quad FRSHAD = b_{sh,1}(P_1 + P_c) + b_{sh,2}(P_1 + P_c)^2$$

again the equation is restricted such that $0 \leq FRSHAD \leq 1$

The fraction of planktivorous fish is defined as 0 if they are not present in the reservoir.

Productivity of each guild is:

$$(2.21)\quad \begin{aligned} P_b &= (EFF_h)(FRBEN)(P_l + P_c) \\ P_z &= (EFF_h)(FRZOO)(1.0 - FRSHAD)(P_l + P_c) \\ P_{fp} &= (EFF_h)(FRZOO)(FRSHAD)(P_l + P_c) \\ P_{fb} &= (EFF).P_b \\ P_{fz} &= (EFF).P_z \\ P_{ff} &= (EFF).(P_{fb} + P_{fz} + P_{fp}) \end{aligned}$$

where:

P_b is zoobenthic productivity (gr.C/m^{2}day),

P_z is zooplanktonic productivity (gr.C/m^2/day),

P_{fp} is planktovorous fish productivity (gr.C/m^2/day),

P_{fb} is benthic fish productivity (gr.C/m^2/day),

P_{fz} is zooplanktivore productivity (gr.C/m^2/day), and

P_{ff} is piscivore productivity (gr.C/m^2/day).

Total production, PTOT, is a 7(guilds) by 5(habitats) matrix which partitions total production for the period. Bottom feeding organisms do not occur in offshore zones and are distributed in relation to the surface area of the habitat. All other guilds are related to the volume of the habitat.

If $P' = (P_o, P_b, P_z, P_{fb}, P_{fz}, P_{ff}, P_{fp})$, and $P_o = P_l + P_c$ then:

$$\text{PTOT} = \text{DAY}\hat{\text{S}} \cdot \text{DIAG(P)} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \text{DIAG}(\text{SA}_h) + \text{DBAR}^{-1} \begin{bmatrix} \underline{1}^T \\ \underline{0}^T \\ \underline{1}^T \\ \underline{0}^T \\ \underline{1}^T \\ \underline{1}^T \\ \underline{1}^T \end{bmatrix} \text{DIAG}(\text{VOL}_h) \tag{2.22}$$

where DBAR is the mean depth of the reservoir, $\underline{1}^T$ and $\underline{0}^T$ are row rectors of 7 ones and 7 zeros respectively, and DIAG (·) is the diagonal operator (i.e. DIAG(x) is a square matrix with the elements of x on the main diagonal).

POPULATION SUBMODEL

The population submodel tracks total numbers and biomass of the fish population occuring in the basin. Inputs to the model are: computed fish production (by habitat and feeding guild), the average surface area of each habitat, the difference between maximum and minimum elevation (water level fluctuation), time period length, and the initial number and biomass of each population. Outputs are end-of-period number and biomass of each population. The model runs on a quarterly basis with two periods in each quarter, thus the smallest time frame is 1/8 year which is the length of the larval lifestage.

Populations are divided into yearly age classes. An age n fish is defined as hatched during the calendar year t-n+1 years before the current calendar year t. Fish are also divided into three lifestages representing different feeding regimes and growth rate potentials and competitive ability. The larval stage is the first life stage of an individual and lasts one half a season. Surviving larval fish are passed (recruited) into the juvenile life stage which lasts until the beginning of the following calendar year. Adult fish are defined as all age classes greater than one year. Larval fish are expressed in a separate array YOS and juveniles and adults are expressed in a matrix N which rows represent species and columns represent age class.

Growth of all fish is computed twice during the season. It is based on the amount of food (production) available and the weight of each class at the start of the half season. Survivorship is computed each half season along with growth. Recruitment of juveniles into adults, which occurs at the end of a calendar year, requires juveniles to have attained a specific size in order to survive the winter.

Total Production

The production submodel computes productivity values in grams carbon dry weight, which is converted to kilograms wet weight of fish. Only three of the seven production guilds represent fish production.

These guilds are indexed by the numbers four (benthic consumers), five (zooplanktivores) and six (piscivores).

(2.23) PFISH(H,G) = PTOT(H,G + 3) * .0083

(2.24) DELT = DAYS/730.00

where:

H = habitat index

G = guild index of population model G = 1, 2, or 3

G + 3 = corresponding guild index of production model

PTOT = primary photosynthetic productivity-the production model's output (gr. c/lake)

.0083 = conversion factor from gr.C to kg wet weight

DAYS = number of days in season

PFISH = production of all fish (kg wet wt./lake)

DELT = timespan of 1/2 season

Incrementing of Biomass and Numbers over Time

At the beginning of winter all fish that survived the previous period immediately enter the next age class. Animals in the last age class vanish.

This recruitment process is described as:

$$(2.25)\qquad N^{1}(S,X) = N(S,X-1) \text{ for } X = 2,3\ldots NAGE(S)$$

$$(2.26)\qquad B^{1}(S,X) = B(S,X-1) \text{ for } X = 2,3\ldots NAGE(S)$$

where:

S = species index

X = age class index

N^{1} = number of animals at the beginning of winter

N = number of individuals

B^{1} = total weight (kg) of the N individuals at the beginning of winter

B = total weight (kg) of the N individuals at the end of fall

$NAGE(S)$ = the maximum number of age classes of species S

To compute the weight gain of the populations (B) requires partitioning the previously modeled production (feeding guild by habitat) into the population cells (species by lifestage).

Partitioning of Production

This unit allocates primary production among the larval fish of each species GRYOS(S), juveniles, GRTH(S,1), and each adult age class GRTH(S,X). Growth is constrained to an allowable maximum specified for each group. If the production allocation allows a fish class to reach its upper growth limit, the excess growth potential is redistributed among the remaining groups. The distribution algorithm is as follows:

A. Initialize arrays used.

B. Compute maximum possible growth attainable for each species and age class.

C. Compute the fraction of each production cell that will go into each population cell.

D. For each species and age class not violating maximum production constraint and if there is remaining allocable production

  1. Partition remaining production
  2. Adjust for excess production
  3. Repeat D

E. Compute partitioning among adults

In A, two arrays are initialized. One array contains the production that is remaining in to be allocated. This is, initially, total production for the half of the season. In remaining loops, it is excess production that will be re-allocated. The second array is the actual partitioning of production into the population cells, and is initially 0. Section D. is the main part of the algorithm. It partitions the production values into the population cells. It then checks to see if any population cell exceeded its maximum and makes adjustments for maximum production. The last step distributes the adult production into each of the adult age classes present.

For the first step A, we define:

(2.27a) PLEFT(H,G) = PFISH(G,H)/2

(2.27b) PPART(S,L) = 0

(2.27c) where

PLEFT (G,H), is Production in the Gth guild and Hth habitat remaining to be partitioned into each species and life stage. In the first iteration, this is the total fish production in the system for that time period.

(2.27d) and

PPART(S,L), is Actual partitioning of PFISH(G,H) defined in (2.23) into species S and life stage L. This starts as zero and is a summation in step D.

Step B defines the maximum weight gain per half season for the Sth species (S = 1...9) and Lth Lifestage (L = 1,2,3) by

$$(2.28a)\quad \mathrm{GADMAX(S,X)} = \mathrm{DELT} \cdot \mathrm{B(S,X)} \cdot \mathrm{BPTOB0(S)} \cdot \mathrm{EXP}\left[\mathrm{BPTOB1}\ \frac{\mathrm{B(S,X)}}{\mathrm{N(S,X)}}\right]$$

$$\text{For } x = 2,3,4,\ldots\mathrm{AGES(S)}$$

$$(2.28b)\quad \mathrm{GMAX(S,3)} = \sum_{x=2}^{\mathrm{NAGE}} \mathrm{GADMAX\ (S,X)}$$

$$(2.28c)\quad \mathrm{GMAX(S,2)} = \mathrm{JUVPB(S)} \cdot \mathrm{DELT} \cdot \mathrm{B(S,1)}$$

$$(2.28d)\quad \mathrm{GMAX(S,1)} = \mathrm{YOSPB(S)} \cdot \mathrm{DELT} \cdot \mathrm{BYOS(S)}$$

where

GADMAX(S,X) is Maximum possible production of the adult age classes.

BPTOBX(S) is Slope and intercept of the function relating individual weight with maximum P/B ratio for species S, for adults.

JUVPB(S) is Maximum P/B ratio for juveniles of species S,

YOSPB(S) is Maximum P/B ratio for larval species S and,

GMAX(S,L) is Maximum production for species S and lifestage L. For adults this is the sum of all adult classes.

Third, step C computes the partitioning coefficients Q:

(2.29) $$Q(S,L,H,G) = \frac{BFR(S,L,H)SA(H)}{\sum_{h} BFR(S,L,H)SA(H)} \; BTOT(S,L) \; C\,(S,L,H,G)$$

where Q(S,L,H,G) is the partitioning coefficient for a particular species lifestage; habitat and guild "effective biomass of the N(S,L) operating on the PFISH (G,H),"

BFR(S,L,H) is the fraction of the BTOT(S,L) that would occupy habitat H if all habitats were equal area,

SA(H) is surface area of habitat H,

C(S,L,H,G) are partitioning coefficients for species and lifestage L on habitat H and guild G,

BTOT(S,L) is total biomass of the Lth lifestage of species S,

Fourth, several iterations are required to allocate all available production among fish classes. The iterations can be viewed as a loop, from (2,30a) to (2.30h) as follows:

START LOOP:

Two normalizing coefficients are computed which (by division) allows the sum of the Q's be 1.

(2.30a) $$QPTOT(H,G) = \sum_{SL} Q(S,L,H,G)$$

(2.30b) $$QFTOT(S,L) = \sum_{hg}\sum Q(S,L,H,G)$$

QPTOT(H,G) is normalizing coefficient for the Q(S,L,H,G) across all S and L, and

QFTOT(S,L) is the normalizing coefficient for the Q(S,L,H,G) across all G and H.

Next, the partitioning into the population cell takes place. It is based on Q normalized by QPTOT, and is summed across all iterations of the algorithm.

(2.30d) $$PPART(S,L) = PPART(S,L) + \sum_{HG}\sum \frac{Q(S,L,H,G)}{QPTOT(H,G)} PLEFT(H,G)$$

The excess production is computed as:

(2.30e) $$PEXC(S,L) = MAXIMUM[(PPART(S,L) - GMAX(S,L),0)],$$

PEXC(S,L) is excess production of the Sth species and Lth lifestage, and identifies a production that is not at maximum. The excess is subtracted, i.e.

(2.30f) $$PPART(S,L) = PPART(S,L) - PEXC(S,L)$$

and the excess is re-partitioned into the cells based on the normalizing coefficient QFTOT, or

(2.30g) $$PLEFT(H,G) = \sum_{SL} \frac{Q(S,L,H,G)}{QFTOT(S,L)} PEXC(S,L).$$

If that population cell is at maximum, the relevant Q's are set to 0. This prevents further production from entering that class.

(2.30h) If (PEXC(S,L) > 0 then Q(S,L,H,G) = 0 for all H,G

> This process is repeated if there is remaining production available and remaining Q's greater than 0.
>
> Go to 'START LOOP' if ($\Sigma\Sigma\Sigma$ Q(S,L,H,G) > 0 and $\Sigma\Sigma$ PLEFT(H,G) > 0)

The adult production is placed into each age class based on their relative growth potential.

$$\text{GRTH(S,X)} = \text{PPART(S,3)}\,\frac{\text{GADMAX(S,X)}}{\text{GMAX(S,3)}} \tag{2.31a}$$

$$\text{GRTH(S,1)} = \text{PPART (S,2)} \tag{2.31b}$$

$$\text{GRYOS(S)} = \text{PPART (S,1)} \tag{2.31c}$$

where GRTH(S,X) is realized production of the N(S,X),

GRYOS(S) is production of the larval S,

Survival and Growth

The proportion of adult and juvenile fish that survive a given time period is higher for slower growing fish. Growth is assumed to occur continuously and uniformly throughout the time period. The biomass gain of the Sth species in the Xth age class is defined by the solution to the differential equation $dB = (-ZB + \grave{G})dt$ where Z is the instantaneous mortality, B is biomass weight, and $\grave{G}$ is the rate of production which is growth (GRTH) divided by the time span.

Larval survival and growth operate differently from juvenile and adult fish. Each larval fish is assumed to require a specified growth rate per half season to survive. Percentage survivorship is defined as the value that results in the specified individual growth given food constraints (GRYOS). Surviving larval fish are added to the next period's juvenile age class.

The computations required are:

$$(2.32) \qquad ZADULT(S) = [BZ0(S) + BZ1(S)\,\frac{PPART(S,3)}{GMAX(S,3)}]\ DELT$$

where:

BZ0,BZ1 are Parameters for the relationship between growth and survivorship

ZADULT(S) is Instaneous mortality rate for adults

The number surviving is given by

$$(2.33)\ N(S,X) = e^{ZADULT(S)} \cdot N(S,X)$$

$$(2.34)\ B(S,X) = e^{ZADULT(S)}B(S,X) + \frac{GRTH(S,X)}{ZADULT(S)}\,[e^{ZADULT(S)}-1]$$

for larval fish, instantaneous mortality (Z) is the root of the equation:

$$(2.35)\ f(Z) = 1 - BRECO(S) + \frac{GRYOS(S)}{BYOS(S)}\,(1 - e^{-Z})$$

where BRECO(S) = Growth of an individual larval fish

and as above,

$$(2.36)\ YOS(S) = e^{-Z}\ YOS(S)$$

$$(2.37)\ BYOS(S) + e^{Z} + \frac{GRYOS(S,X)}{Z}[e^{Z} - 1]$$

where Z is the root of equation 2.35, larval fish immediately enter the juvenile stage (age class 1)

$$(2.38)\ N(S,1) = N(S,1) + YOS(S)$$

$$(2.39) B(S,1) = B(S,1) + BYOS(S)$$

Birth of Larval Fish

Birth and subsequent larval numbers and biomass occurs in the middle of the season. The number and weight of newborn larval fish is based on the number of eggs laid and the survivorship of the eggs. The number of eggs laid depends on the fraction of females in the population, the fraction of females breeding during the season, and the average weight of the mature females. The weight of an individual is considered constant.

Computations required are:

$$\text{YOS(S)} = \sum_{x=2}^{\text{NAGE}} \text{SR(S)Im(S,X)} \cdot \text{ISSAS(S,SEAS) N(S,X)} \cdot \text{BFECO(S)} \cdot \left[\frac{\text{B(S,X)}}{\text{N(S,X)}} \right] \cdot \text{BFEC1(S)} \qquad (2.40)$$

Where Im is an Indicator Function which is 1 if the particular age class s mature or: 0, otherwise and

$$I_m\text{(S,X)} = 1, \text{ if B(S,X)/N(S,X)} > \text{IWT(S)} \qquad (2.42)$$

SR(S) is sex ratio of species S

BFEC0, BFEC1 are slope and intercept for fecundity function for S species,

IWT(S) is weight at maturity, for species S

The survivorship of the larval eggs is related to the degree of water level fluctuation during the season.

(2.43) $$YOS(S) = YOS(S) \cdot [BWLFL0(S) + BWLFL1(S) \cdot WLFL]$$

where:

WLFL is water level fluctuation, and

BWLF0, BWLF1 are slope and intercept for fluctuation function

Truncation of First Year Class

During fall, all juveniles below a specified weight will die. To determine numbers and biomass lost due to this source of mortality it is assumed that individual weight is distributed normally about their mean weight (B(S,1)/N(S,1)) and with a coefficient of variation of 25%. The fraction of the population lost and the average weight of an individual lost is computed. The algorithm used to compute the proportion of survivors consists of five steps:

First, compute average individual weight

(2.44) $$BBAR(S) = B(S,1)/N(S,1)$$

where BBAR(S) is the average weight of a juvenile S

Second, compute the standard normal deviate to find minimum weight, as

(2.45) $$Z(S) = 4 \cdot \frac{WTJUV(S)}{BBAR(S)} - 1$$

where Z(S) is the standardized variable for BBAR(S) and WTJUV(S),

WTJUV(S) is minimum weight of surviving juveniles

Third, compute fraction of numbers lost, as

(2.46) $\mathrm{NLOST(S)} = \Phi\ (\mathrm{Z(S)})$

$\phi(\cdot)$ = the standard cumulative normal probability function

Fourth, compute mean weight of lost individuals

where NLOST(S) is the fraction of N(S,1) lost

(2.47) $\mathrm{BLOST(S)} = \mathrm{BBAR(S)}\ [\mathrm{NLOST(S)} - \frac{1}{4\ 2\Pi}\ e^{-\frac{1}{2}Z^{2(S)}}]$

where BLOST is the average weight of NLOST(S)

Fifth, compute surviving numbers and biomass as

(2.48) $\mathrm{B(S,1)} = \mathrm{B(S,1)} - \mathrm{N(S,1)} \cdot \mathrm{NLOST(S)} \cdot \mathrm{BLOST(S)}$
$\mathrm{N(S,1)} = \mathrm{N(S,1)}\ [1.0 - \mathrm{NLOST(S)}]$

Average Fish Length

The average length of a fish is computed from a typical log-log relationship between weight and length.

Computation required:

(2.48a) $$\mathrm{L(S,X)} = \frac{\mathrm{B(S,X)} \cdot 1000.00}{\mathrm{N(S,X)\ LNWT0(S)}}^{\frac{1}{\mathrm{LNWT1(S)}}}$$

for x = 2,3,4...NAGE(S)

where:

L(S,X) is average (mm) length of the N(S,X).

LNWT0, LNWT1 are slope and intercept of the standard length/weight regressions

Fish Stocking Policies

The model user (fisheries manager) may stock fish of any of three categories; fry, fingerlings, and catchables. [These correspond to the three lifestages of fish modeled; larval, juvenile, and adult.] The result of new stocking is an addition to the existing fish biomass. Numbers stocked of all three groups are given by the user. The user also gives the average length of catchables and fingerlings. Let NSTOCK(S,L) be the number of fish of species S and lifestage L to be stocked by the fisheries' manager and LSTOCK (S,L) be the average length of the NSTOCK(S,L). LSTOCK is not given for fry but their weight is computed by:

$$\text{BSTOCK}(S,1) = \text{WTYOS}(S) \cdot \text{BRECO}(S) \cdot \text{NSTOCK}(S,L) \tag{2.49}$$

where WTYOS(S) · BRECO(S) · is the average size of larval fish. The weight of fingerlings and catchables is based on their average length and is computed by:

$$\text{BSTOCK}(S,L) = \frac{\text{NSTOCK}(S,L)\ \text{LNWTO}(S)\ \text{LSTOCK}(S,L)^{\text{LNWT1}(S)}}{1000.0} \tag{2.50}$$

where LNWTO(S) and LNWT1 are the parameters of the standard length to weight regression and 1000 is a conversion from grams to kilograms.

Next, fry are added to the larval fish by:

(2.51) $YOS(S) = YOS(S) + NSTOCK(S,1)$

(2.52) $BYOS(S) = BYOS(S) + BSTOCK(S,1)$

Fingerlings are placed in the juvenile category *vis*

(2.53) $N(S,1) = N(S,1) + NSTOCK(S,2)$ and

(2.54) $B(S,1) = B(S,1) + BSTOCK(S,2)$

And catchables are placed in the first adult life stage category

$$N(S,2) = N(S,2) + NSTOCK(S,2)$$

$$B(S,2) = B(S,2) + BSTOCK(S,2).$$

Harvest Model

This model computes the total number harvested from angler effort by each species and age class. Numbers harvested is a function of the catchability of the fish, the effort expended (angler days), and the legal restrictions imposed on the harvest. Angler effort is computed by the economics model.

The user (fisheries manager) has the option of considering various length limits. This, in effect, eliminates certain size classes from the legally fishable stock. Three types of limits can be imposed: a minimum length, a slot limit (e.g. no fish between 14 and 16 inches may be caught), and a maximum length. These restrictions can occur in any combination. In addition to these restrictions, an absolute minimum is used representing a minimum legally catchable length. A (0,1) function LGLFSH(S,X) is used to identify whether the fish of species S and age class X is part of the legally fishable stock. The function is:

$$\text{(2.55)} \qquad \mathrm{LGLFSH(S,X)} = \begin{cases} 0 \text{ if } \mathrm{L(S,X)} < \mathrm{MNCTCH(S)} \\ 0 \text{ if } \mathrm{L(S,X)} < \mathrm{LLIM1(S)} \\ 0 \text{ if } \mathrm{LLIM2(S)} < \mathrm{L(S,X)} < \mathrm{LLIM3(S)} \\ 0 \text{ if } \mathrm{LLIM4(S)} < \mathrm{L(S,X)} \\ 1 \text{ otherwise} \end{cases}$$

where L(S,X) is the average length of species S and age class X, MNCTCH(S) is the minimum length of species S that is catchable, LLIM1(S) is the minimum length limit imposed, LLIM2(S) and LLIM3(S) are the lower and upper lengths of the slot limit, and LLIM4(S) is the maximum length limit. If a limit does not exist, its corresponding value is set to 0, unless there is no maximum. With no maximum limit LLIM4(S) is set to an arbitrary high number. If a certain species is never fished (e.g. carp), MNCTCH(S) is set arbitrarily high.

The number of fish harvested by anglers assumed to follow a typical catch-effort formulation. The proportion (p) of fish caught is:

$$\text{(2.56)} \qquad p = 1 - e^{-qf}$$

where q is catchability and f is effort. Catchability is inversely related to the mean weight of the particular class or

$$\text{(2.57)} \qquad q = \frac{\mathrm{CTBLTY(S)}}{\mathrm{w(S,X)}} = \frac{\mathrm{CTBLTY(S)\ N(S,X)}}{\mathrm{B(S,X)}}$$

where N(S,X) is the number of fish of the Sth species and xth age class, B(S,X) is the total weight of N(S,X), and CTBLTY(S) is a "catchability coefficient." Total angler effort for the reservoir is given by the economic model and partitioned among the N(S,X) based upon their proportion of the total weight of the fishable population. The equation is:

$$(2.58) \qquad f = \frac{LGLFSH(S,X)\ B(S,X)}{\sum_{s}\sum_{x} LGLFSH(S,X)}\ ANGDAYS$$

where ANGDAYS is the total angler days for that site and time period (economics model equation 3.1c) based on total angler trips to that site. When all the terms are combined, the proportion of legally catchable fish actually harvested is computed as

$$(2.59) \qquad p = 1.0 - EXP\ \frac{-CTBLTY(S)\ N(S,X)\ LGLFSH(S,X)\ ANGDAYS}{\sum_{s}\sum_{x} LGLFSH(S,X)\ B(S,X)}$$

Next yield of fish harvested is based on the proportion in (2.59), and is defined as:

$$YIELD(S,X) = p\ N(S,X)$$

where YIELD(S,X) is the number of species S and age class X harvested and N(S,X) is the number of species S and age class X that existed at the beginning of the period.

Yield (total numbers of fish harvested) is considered to be compensatory with natural mortality. That is, if YIELD(S,X) does not exceed the natural mortality yield is assumed to have no effect on the number of fish present. If yield does exceed natural mortality then the excess yield is subtracted from the population. Let NDEAD(S,X) be the number removed by natural mortality (i.e.: $NDEAD(S,X) = N^o(S,X) - N(S,X)$) then

$$N^o(S,X) = N(S,X) - MAXIMUM\ (YIELD(S,X) - NDEAD(S,X);\ 0). \tag{2.60}$$

Yield, is determined largely by economic factors affecting the decision of anglers to participate at a given site. This economic model documentation is discussed next.

MATHEMATICAL DOCUMENTATION, ECONOMICS

3.1 Demand and Benefits

Angler visits to twenty-four different Rio Grande Basin water based recreation study sites are observed. The state of New Mexico is divided into thirteen zones for the purpose of classifying angler zones-of-origin. Thus, a 24 x 13 matrix with 312 elements describes the (zone average of) by zone of trip origin.

The following equations are used to compute angler participation (demand) and angler benefits associated with a wide array of fish management policies. Based on observed 1981 New Mexico resident per capita participation rates at the 24 sites from each of 13 zones of origin, we estimated how those participation rates would change due to any policy which modified site pricing or site qualities (equations 3.1). Based on these angler participation predictions we then computed angler benefits (equations 3.2) and agency revenues (equations 3.3) associated with each policy.

Predicted angler participation is computed as:

$$
\begin{aligned}
(3.1a)\quad TRIPCAP = {} & TRIPCAP_0 + B_1\ (P - P_0) + B_2\ (F - F_0) + B_3\ (SA - SA_0) \\
& + B_4\ (PA - PA_0) + B_5\ (E - E_0) + B_6\ (FL - FL_0) \\
& + B_7\ (CR - CR_0) + B_8\ (RE - RE_0)
\end{aligned}
$$

where:

0 subscripts = baseline (1981) observed values

TRIPCAP = predicted annual average trips per capita (of zone population) to the ith Rio Grande Basin site (i = 1...24) from the jth zone of origin (j = 1...13),

P = price per trip, measured as the round trip travel cost (per representative trip) of travelling to the ith site from the jth zone of origin, including a $10 per hour imputed value of travel time, and site fees if any.

F = Average biomass density of fish at the ith site equal for each jth zone of origin (in kg/ha), based on biology model.

SA = (square root of) surface acres at the ith site, equal for each jth zone of origin (lakes only).

PA = (0 1) dummy, indicating whether or not a site is part of the New Mexico State Park System, equal for each jth zone of origin.

E = elevation of ith site in thousands of feet above sea level, a proxy for vegetation density, equal for each jth zone of origin.

FL = mean summer discharge at ith site (streams only) in cubic feet per second, equal for each jth zone of origin.

CR = number of road crossings at ith site (streams only) a proxy for site access, equal for each jth zone of origin.

RE = number of recreational picnic and campgrounds at ith site (streams only) a proxy for site improvements, equal for each jth zone of origin.

B's = parameters estimated from regression analysis, equal for each jth zone of origin.

In (3.1a), each variable is a matrix containing 24 rows (sites) and 13 columns (zones of origin). Each of the B parameter estimates is a matrix containing 24 rows and 24 columns, one element for each site-by-site interaction. Each parameter estimate is assumed to apply equally to visitors from all zones of origin (j = 1...13). B_1 has some non-zero off-diagonal elements, indicating that visits to each ith site is determined by prices at both the ith and some $j \neq i$ other sites. All other B matrices have all zero off-diagonal elements, indicating that all non-price (i.e. "quality") visit determinants at the ith site depends only on ith site qualities. Because of the large size of the matrices, their numerical values are not included in this discussion. Data are available from the authors.

Based on predicted average trips per capita at the ith site from the jth zone of origin due to pricing and quality changes in (3.1a), total trips by site are computed as follows:

(3.1b) TRIPS = (TRIPCAP) (POPULATION)

where TRIPS, a 24 x 1 column vector of total predicted angler trips to the ith site equals the matrix product of ith site jth zone TRIPCAP in (3.1a) and the ith zone's POPULATION.

Similarly, total angler days by site are computed as:

(3.1c) ANGDAYS = Trips (DPT) where DPT is the sampled number of days per average trip.

To compute total New Mexico resident angler benefits from all 24 sites for the jth zone-of-origin each ith site's "maximum site price" for the jth zone must be first determined as:

$$(3.2a)\quad \text{MAXPRICE} = P_0 + (-B_1)^{-1}\ (\text{TRIPCAP})$$

where MAXPRICE = a 24 x 13 matrix of site prices inclusive of average observed 1981 travel costs, P_0 which would reduce jth zone-of-origin visits to the ith site from measured 1981 levels to zero. The -1 indicates a matrix inverse. For each site MAXPRICE is constrained to not exceed maximum observed travel cost to that site from a sampled visitor.

Based on MAXPRICE, direct benefits per capita from the jth zone of origin due to the presence of all 24 sites are determined as:

$$(3.2b)\quad \text{BENCAP} = .5 \times (\text{MAXPRICE} - P)^T\ (B_1)\ (\text{MAXPRICE} - P) + (\text{MAXPRICE} - P)^T\ (\text{TRIPCAP})$$

where the 13 x 13 matrix BENCAP has 13 diagonal elements one for each jth zone of origin. The jth diagonal element indicates the direct angling benefits per capita for the jth zone of origin due to the existence of the 24 Rio Grande Basin sites. "T" indicates a matrix transpose.

Next, aggregate angling benefits from the jth zone of origin are measured as

(3.2c) BENEFITS (J) = (BENCAP (J)) (POPULATION (J))

where the scalar, BENEFITS (J) is total New Mexico resident angling benefits due to the presence of all 24 sites accruing to jth zone of origin anglers.

Statewide resident angler benefits are obtained by summing (2c) over all zones of origin, computed as:

(3.2d) BENEFITS = $(\text{BENCAP})^T$ (POPULATION)

where BENEFITS = a scalar, sums benefits per capita in (3.2a) times population over all zones of origin.

Direct agency revenues associated with site pricing and/or quality policies are an important policy issue. Our model computes these revenues in the following three steps. First we define ith site total revenue as:

(3.3a) REVENUE(I) = (FEE(I)) (TRIPS(I))

where REVENUE(I), is the total revenues received from all zones of angler origin resulting from an entry fee imposed at the ith site. TRIPS(I) is the ith site trip element in (3.1b). It is assumed that an entry fee has the same effect on participation as increase in travel cost.

Second, a fee at the ith site is assumed to increase travel costs from all zones of origin by the amount of the fee. If an agency-imposed fee increases a zone's travel cost to an amount greater than MAXPRICE in (3.2a), that zone's visits are assumed to fall to zero. This "equivalent" increase in ith site price from the jth zone of origin is measured as:

$$(3.3b) \Delta P(IJ) = FEE(I) - P_0(IJ), \text{ for all j zones of origin}$$

Thus the fee is assumed to increase price, P_0 from the observed travel cost level P_0 in (3.1a) by ΔP, with participation rates being reduced accordingly. Note from (3.1a) that both entry fees and site quality improvements affect TRIPCAP. Specifically higher site prices and lower site qualities both reduce TRIPCAP. Therefore, a policy which increases site fees will only result in increased total revenues to New Mexico Game and Fish if the percentage increase in price is greater than the resulting percentage reduction in angler participation.

Third, (3a) is summed over all sites to measure total agency revenues from pricing/quality policies at all 24 sites, i.e.

$$(3.3c) \quad REVENUE = (FEE)^T (TRIPS)$$

where REVENUE is a scalar measuring aggregate revenues over all 24 Rio Grande Basin sites.

3.2 Income and Employment

3.2.1 Income

In much the same way as in-state angler participation can be used to measure total in-state angler benefit, total (in-plus-out-of-state) angler participation at a site can affect county income, particularly in rural counties where recreational exports constitute a major source of revenue. Regression methods were used to isolate the effect of total angler days in generating county incomes, based on time series New Mexico Card Survey data for the years 1975, 1978, 1981, and 1982.

The best fit income generation equation was found to be:

$$(3.4)\quad \text{NMPERCAP} = -4058.77 + .93(\text{USPERCAP}) + 41.78(\text{DIPLOMA}) + 48.84\,(\text{LBRFORCE}) + 21.33(\text{FRMINE}) + .599\,(\text{ANGDAYS}) + 10.63(\text{TOWN})$$

where all variables are defined in the body of the report. Essentially, equation (4) shows that for the kth Rio Grande Basin county, ($k = 1...7$), per capita county income depends on national income, county education levels, percentage employed in the county, percentage of income generated in agriculture, angler days, and degree of "urbanness". Equation (4) demonstrates that angler days exported have a major role in generating county income.

Regarding the income generating role of angler exports, it is useful to consider that ANGDAYS is defined in (4) as number of angler days exported multiplied by the percentage of county population living in towns greater than 2000. Thus, for a county such as Bernalillo, where the urbanness percentage is about 90, one extra angler day generates about $54 in county income (.599 x 90).

3.2.2 Employment

Economic research continues to show a strong causal linkage between regional income and resultant man-years of regional employment needed to generate the income. Using this well-established principle, time series data on annual income and employment were analyzed using OLS regression.

The best fit regression was estimated to be:

$$3.5\quad \text{EMPLOYMENT} = 669.03 + .0001169\,(\text{INCOME})$$

where the interpretation of (5) is: each extra $1000 of regional income. Income requires about .1 extra man year of employment to produce the income.