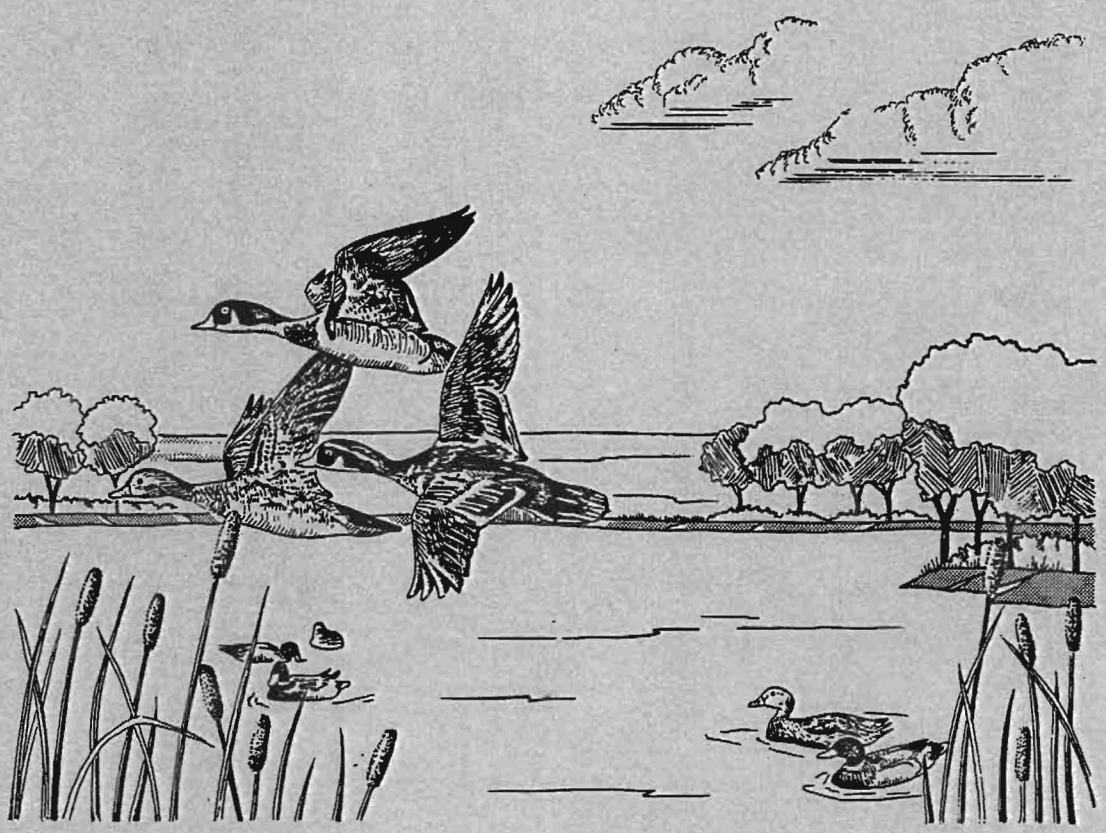
WELUT-85/W06
MARCH 1985

EFFECTS OF FLOOD CONTROL ALTERNATIVES ON FISH AND WILDLIFE RESOURCES OF THE MALHEUR-HARNEY LAKES BASIN



Fish and Wildlife Service

U.S. Department of the Interior

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March 1985

EFFECTS OF FLOOD CONTROL ALTERNATIVES ON FISH AND WILDLIFE RESOURCES OF THE MALHEUR-HARNEY LAKES BASIN

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Results of a Workshop Sponsored by
Portland Ecological Services Field Office
and
Malheur National Wildlife Refuge
Region 1 - U.S. Fish and Wildlife Service

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EXECUTIVE SUMMARY

Malheur Lake is the largest freshwater marsh in the western contiguous United States and is one of the main management units of the Malheur National Wildlife Refuge in southeastern Oregon. The marsh provides excellent waterfowl production habitat as well as vital migration habitats for birds in the Pacific flyway. Water shortages have typically been a problem in this semiarid area; however, record snowfalls and cool summers have recently caused Malheur Lake to rise to its highest level in recorded history. This has resulted in the loss of approximately 57,000 acres of important wildlife habitat as well as extensive flooding of local ranches, roads, and railroad lines. Because of the importance of the Refuge, any water management plan for the Malheur-Harney Lakes Basin needs to consider the impact of management alternatives on the hydrology of Malheur Lake.

The facilitated modeling workshop described in this report was conducted January 14-18, 1985, under the joint sponsorship of the Portland Ecological Services Field Office and the Malheur National Wildlife Refuge, Region 1, U.S. Fish and Wildlife Service (FWS). The Portland Field Office is responsible for FWS reporting requirements on Federal water resource projects while the Refuge staff has management responsibility for much of the land affected by high water levels in the Malheur-Harney Lakes Basin. The primary objective of the workshop was to begin gathering and analyzing information concerning potential fish and wildlife impacts, needs, and opportunities associated with proposed U.S. Army Corps of Engineers (COE) flood control alternatives for Malheur Lake. The workshop was structured around the formulation of a computer model that would simulate the hydrologic effects of the various alternatives and any concommitant changes in vegetation communities and wildlife use patterns.

The simulation model is composed of three connected submodels. The Hydrology submodel calculates changes in lake volume, elevation, and surface area, as well as changes in water quality, that result from the proposed water management projects (upstream storage, upstream diversions, drainage canals) and the no action alternative. The Vegetation submodel determines associated changes in the areal extent of wetland and upland vegetation communities. Finally, the Wildlife submodel calculates indices of abundance or habitat suitability for colonial nesting birds (great egret, double-crested cormorant, white-faced ibis), greater sandhill crane, diving ducks, tundra swan, dabbling ducks, and Canada goose based on hydrologic and vegetation conditions. The model represents the Malheur-Harney Lakes Basin, but provides water quantity and quality indicators associated with additional flows that might occur in the Malheur River Basin. Several management scenarios, representing various flood control alternatives and assumptions concerning future runoff, were run to analyze model behavior. Scenario results are not intended as an analysis of all potential management actions or assumptions concerning future runoff. Rather, they demonstrate the type of analysis that could be conducted if the model was sufficiently refined and tested.

Early in a model development project, the process of building the model is usually of greater benefit than the model itself. The model building process stimulates interaction among agencies, assists in integrating existing information, and helps identify research needs. These benefits usually accrue even in the absence of real predictive power in the resulting model. This workshop initiated interaction among the primary State and Federal resource and development agencies in a nonadversarial forum. The exchange of information and expertise among agencies provided the FWS with the best information currently available for use in the Planning Aid Letter it will develop at the Reconnaissance stage of the COE study. If the COE subsequently initiates a Feasibility Study, this information will be refined further and will aid the FWS in preparing its Coordination Act Report on any flood control alternatives proposed by the COE.

The model building and testing process also helped identify model limitations and more general information needs that should be evaluated for further

study prior to preparation of an FWS Coordination Act Report. Major needs associated with the Hydrology submodel include a more detailed representation of hydrologic units (separately consider Harney Lake, Mud Lake, and Malheur Lake or the three hydrologic units within Malheur Lake, rather than a combined lake system) and explicit representation of groundwater storage and discharge in water budget calculations. A better representation of the hydrologic units will require more detailed topographic data for the basin, capacity-elevation and elevation-surface area curves for each unit, and better water flow data between the units. Additional water quality parameters and constraints on proposed canal operation due to conditions in the Malheur River might also be added. Key Vegetation submodel needs include fine-tuning existing vegetation relationships in the model and adding relationships to address the influence of historical conditions on vegetation development, effects of very rapid changes in lake level, effects of wildlife populations (e.g., carp, muskrat), responses of vegetation to habitat management actions (e.g., haying, grazing, burning), and better representation of sago pondweed dynamics. A complementary geographic information system might also be developed for spatial analyses. Major needs that should be evaluated for the Wildlife submodel include addition of other wildlife species that have important effects on habitat on the Refuge (e.g., carp, muskrat) and consideration of additional life-cycle requisites and controlling variables for species presently in the model. Some of these limitations could perhaps be overcome if historical data on habitat conditions were developed to use with historical data on wildlife populations.

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INTRODUCTION

BACKGROUND

Malheur National Wildlife Refuge (MNWR or the Refuge) is located in the Malheur-Harney Lakes Basin, approximately 32 miles southeast of Burns, Oregon (Fig. 1). The Refuge was established in 1908 to protect colonial nesting birds from extinction by depredations of plume hunters. Its mission has since been expanded to include production and maintenance of migratory birds with special emphasis on threatened, endangered, and sensitive species.

The MNWR consists of over 180,000 acres of diverse habitat. Malheur Lake is the largest freshwater marsh in the western contiguous United States, providing excellent waterfowl production habitat as well as vital migration habitat for birds in the Pacific Flyway. Private land in the Silvies River floodplain is similarly used. Harney Lake, the natural sump for the basin, is often dry or too brackish for most uses, but is heavily used by waterfowl and shorebirds during high water years. Adjacent uplands are typical of semiarid lands in the West. Agricultural crops, grown on and off the Refuge, utilize spring irrigation to promote early maturity during the short growing season. Agricultural production on the Refuge is primarily in the Blitzen Valley.

Water has historically been a problem in the area. Agricultural demand for irrigation water has increased greatly, but direct diversions for flood irrigation provide water for only a relatively short period in the spring. Residential flood damage has increased due to floodplain development near Burns. The MNWR is primarily dependent on the natural inflow from the Silvies and Blitzen Rivers as a source of water. Any water management plans to control flooding and provide more stable irrigation supplies must, therefore, consider potential impacts on the hydrology of the Malheur-Harney-Mud Lake system and the Double-O and Blitzen Valleys.

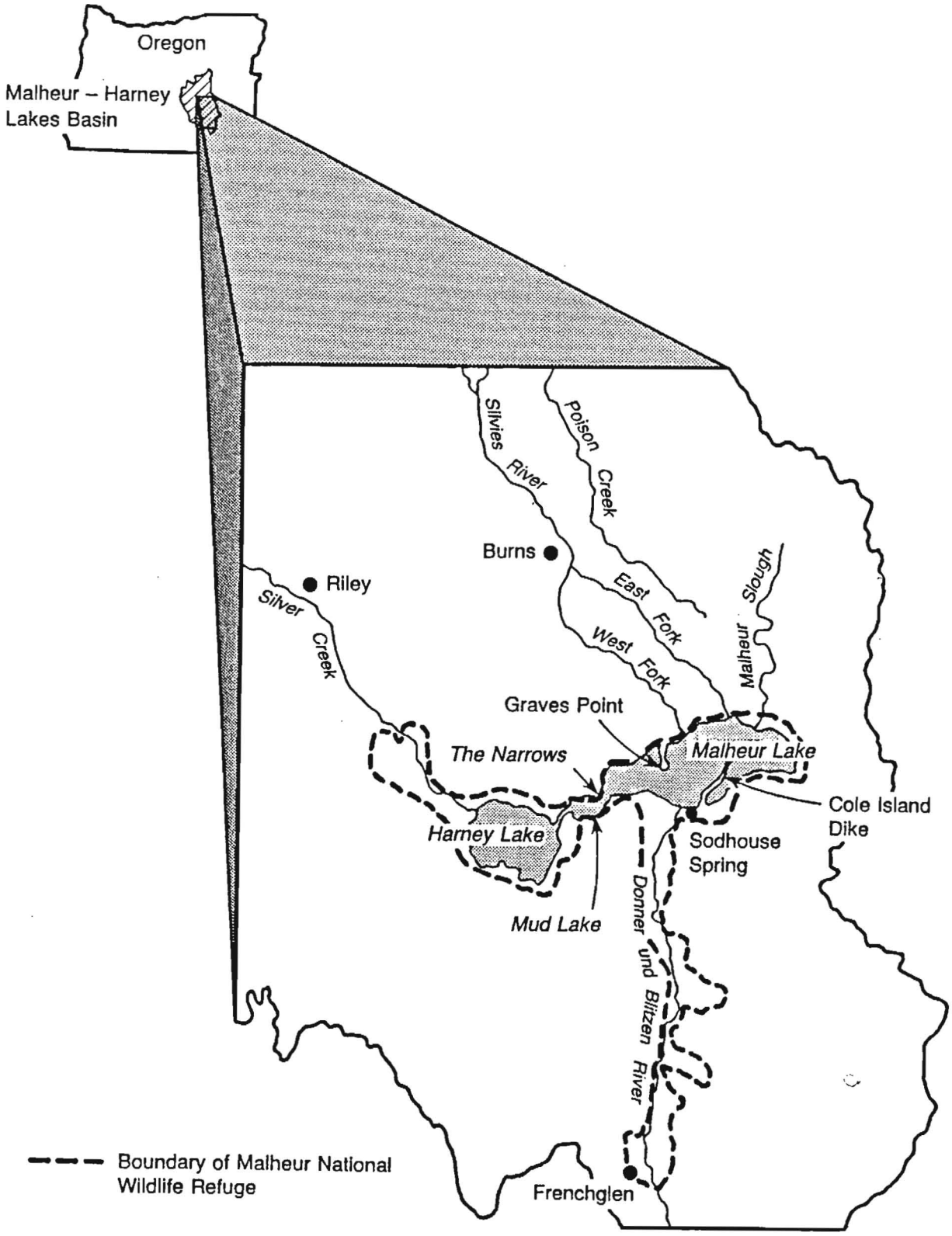

Figure 1. Malheur National Wildlife Refuge.

Several studies have been conducted in the past to evaluate multipurpose storage projects on the Silvies River (U.S. Army Corps of Engineers 1957, 1977; U.S. Fish and Wildlife Service 1957) and ditches to drain flood waters from Malheur Lake to other drainage basins (U.S. Army Corps of Engineers 1982). In each case, no action was taken on the proposed project because of water rights and water use problems, unfavorable cost/benefit ratios, potential impacts on the Refuge, or questions concerning the Corps of Engineers (COE) Emergency Authorization or Small Project Construction Authorities. Recently, however, record snowfalls and cool summers have caused Malheur Lake to rise to its highest level in recorded history. This has caused flooding of 25 ranches, railroad lines and some roads around Burns, and most of the marshes of MNWR. The Refuge has lost approximately 57,000 acres of wildlife habitat, which has impacted a variety of important migratory bird species.

The COE has recalculated flood losses and found that a drainage ditch from Malheur Lake to the Malheur River would have a favorable cost/ benefit ratio. A Reconnaissance Level Study has been initiated for which the U.S. Fish and Wildlife Service (FWS) will submit a Planning Aid Letter. If a Feasibility Study of one or more alternatives is initiated by the COE, the FWS will be requested to prepare a Coordination Act Report. This report would be provided to Congress along with the Feasibility Report sometime in FY 1986. The Coordination Act Report would contain a detailed analysis of fish and wildlife impacts associated with the project.

WORKSHOP OBJECTIVE

The Portland Ecological Services Field Office and the MNWR sponsored a workshop on January 14-18, 1985, to begin gathering and analyzing information concerning potential fish and wildlife impacts, needs, and opportunities associated with proposed Corps of Engineers flood control alternatives for Malheur Lake. This report documents the results of that workshop.

APPROACH

The facilitated modeling approach that was used at the workshop (Holling 1978) was developed by environmental scientists and systems analysts at the University of British Columbia and the International Institute for Applied Systems Analysis in Austria. The approach is organized around a series of 3- to 5-day workshops that define information needs and promote a common understanding of the issues. These workshops are followed by periods of information collection, analysis, and synthesis. The workshops are attended by participants from key agencies and interests, who collectively represent a range of scientific expertise, management responsibility, and decisionmaking authority. These individuals are both involved in the workshops and also undertake some of the key tasks of information collection, analysis, and guidance that occur between workshops.

The focus of these workshops is the construction and refinement of a quantitative, dynamic simulation model of the system under study. Early in a particular application, the process of building the model is usually of greater benefit than the model itself. Benefits of the model building approach include:

(1) The development of a simulation model enables participants to view their expertise in the context of the whole system, thereby promoting interdisciplinary and interagency communication, understanding, and collaboration.

(2) The model building process focuses attention on the interrelationships and indirect connections between components of the resource system. These connections often represent the points at which various agencies and interests must interface in their attempts to deal with the complexities of the resource issue.

(3) Model building forces identification of the assumptions being made, both stated and unstated, in day-to-day management and decisionmaking activities. A clear statement of assumptions and their implications to other workshop participants provides better understanding, and perhaps better support, of management decisions and represents a set of clearly stated questions or hypotheses for analysis.

(4) The simulation model provides a logical framework for synthesizing a variety of existing information.

(5) Finally, the attempt to quantify environmental, economic, and social processes associated with the resource issue quickly and objectively identifies gaps in data or conceptual understanding of the system, which can be translated into research priorities.

With sufficient refinement, models sometimes can provide a reasonable representation of future consequences of various management or decision alternatives. The involvement of managers and decisionmakers in the model building process helps ensure that potential users understand the strengths and weaknesses of the resulting tool.

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These individuals contributed the vast majority of the ideas and information contained in this report. In documenting the results of the workshop, we have attempted to retain both the content and sense of the discussions, but accept full responsibility for errors of fact or interpretation.

WORKSHOP MODEL

SCOPE

Bounding Exercise

Combined operational, development, and resource management issues, such as those in the Malheur-Harney Lakes Basin, typically involve complex interactions among a variety of economic, social, and environmental factors. Although some individual components of such a system may be well understood, the complexity of component interactions generally results in poor understanding of the system as a whole. Simple representations of poorly understood systems often provide valuable insight into system behavior under different management or development alternatives, although they may not provide sufficient detail and credibility for actual decisionmaking. The representation used in a simulation model must, therefore, be sufficiently detailed and flexible to address all concerns adequately, yet must remain simple enough to be understandable. Problem simplification for better understanding is stressed in the early phases of the workshop modeling process; addition of realistic complexity is stressed in later phases to provide a level of detail consistent with management and decision needs.

The workshop process approached the bounding problem through a group discussion of actions (those activities that management can undertake to manipulate the system toward some desired end) and indicators (those performance measures used to evaluate the response of the system). Because indicators are the links between the simulation model and participants' perceptions of the system, it is important to compile a comprehensive list that represents the concerns of all interests. The actions and indicators initially

identified at the workshop are shown in Tables 1 and 2. For the purposes of this report, they are organized into the groups that became major components (submodels) of the simulation model. Management actions are listed only under the submodel that contains the computer code implementing that action; however, the actions may affect indicators in more than one submodel.

The discussion subsequently turned to consideration of the spatial and temporal resolution necessary to represent the components and processes implied by this set of actions and indicators. Spatial resolution concerns the geographic extent of the model, as well as the degree to which that geographic area needs to be subdivided into smaller units in order to represent the dynamics of the processes involved. Temporal resolution refers to the basic time step of model calculations and the number of iterations needed to cover the time horizon of interest.

On the basis of the actions and indicators and associated discussions, it was decided that the workshop model should consider the Malheur-Harney Lakes Basin. The Malheur River Basin was not included in the initial modeling effort because of limited time during the workshop. Participants felt that some of the water quantity and quality indicators produced by the model could be used now to address potential problems in the Malheur River Basin and that submodels addressing impacts in that basin could eventually be added. The Malheur-Harney Lakes Basin was originally divided into six subunits (Malheur Lake, Mud Lake, Harney Lake, Double-O Unit, Silvies River, Blitzen Valley). However, limitations in the spatial resolution of the Hydrology submodel (see WORKSHOP MODEL - Hydrology Submodel) ultimately precluded the use of these subunits. The basin was therefore treated as a single unit during the workshop.

Considering the projected life-time of the proposed flood control projects and the length of long-term wet/dry cycles in this part of the U.S., participants felt that a time horizon of 30-50 years was appropriate for the model. Although most habitat and wildlife indicators are generally presented annually, monthly information on water levels and flooded vegetation is needed to predict

Table 1. Management actions identified at the Malheur workshop.

Submodel	Action
Hydrology	- No action
	- Canal from Malheur Lake to Malheur Gap • capacities - up to 2,000 cfs • lake level - control at 4,093 ft or higher • timing (by month)- based on conditions in the Malheur River
	- Canal and tunnel from Malheur Lake to the Alvord Desert (capacity, lake level, and timing considerations for this alternative not specified at workshop)
	- Storage project on Silvies River for flood control and irrigation deliveries
	- Diversion from Blitzen Valley to Catlow Valley
	- Emergency action to dam Malheur Gap
	- Altered use or rehabilitation of water management structures in Blitzen Valley
	- Future precipitation scenarios
	- Dam between Malheur and Harney Lakes (with one of the canal alternatives)*
	- Rehabilitation of Cole Island dike*
Vegetation	- Habitat management (haying, grazing, burning, re-establishing riparian vegetation, natural regeneration, reseeding)*
	- Land exchange or easement programs*
Wildlife	- Carp control*
	- Predator control (coyotes, ravens, raccoons)*
	- Muskrat management*

*Indicates the action was identified but not incorporated into the model due to lack of time or information.

Table 2. Performance indicators identified at the Malheur workshop.

Submodel	Indicator
Hydrology	- Lake elevation
	- Minimum and maximum annual lake elevation
	- Total surface acres
	- Surface acres by depth
	- Volume of storage
	- Flow in the rivers and canal
	- Precipitation
	- Water quality • TDS • conductivity • sodium adsorption* • turbidity* • alkalinity* • boron* • pH* • suspended solids*
Vegetation	- Acres of • wet meadow • flats* • cattail-burreed • bulrush • open water • brush • grasslands • riparian* • submergents
	- Interspersion of emergents and open water*

Table 2. (concluded)

Submodel	Indicator
Wildlife	- Colonial nesting birds
	- Greater sandhill cranes
	- Diving ducks
	- Tundra swans
	- Dabbling ducks
	- Canada geese
	- Carp*
	- Muskrats*
	- Predators (coyotes, ravens, raccoons)*
	- Antelope and deer*
	- Game fish*
	- Botulism losses*

*Indicates the indicator was identified but not incorporated into the model due to lack of time or information.

wildlife use of the Refuge and Silvies River floodplain (e.g., spring migration, fall migration, spring nesting and brood-rearing). A monthly time-step was therefore used in the model.

Model Structure and Submodel Interactions

The system defined by the actions, indicators, spatial scale, and temporal framework described above was divided into three submodels:

(1) Hydrology - Calculates lake volume, elevation, and surface area based on surface inflows to the lake including effects of upstream storage and irrigation diversions, direct precipitation, evaporation, and flow in the drainage or diversion canals if present.

(2) Vegetation - Calculates changes in acres of various vegetation types based on lake level changes or habitat management practices.

(3) Wildlife - Calculates indices of abundance or habitat suitability for various wildlife species or groups based on lake level and habitat conditions.

Following submodel definition, workshop participants defined the linkages or information transfers between the submodels (Fig. 2). In addition to identifying linkages between the model components, this exercise is useful in promoting interdisciplinary communication and understanding. Workshop participants are forced to look carefully at the kinds of information that they can reasonably expect to obtain from other disciplines (i.e., how their submodel dynamics are influenced by other submodels) and the kinds of information other disciplines expect from them (i.e., how their submodel influences the dynamics of the other submodels). Note that the question asked in this exercise (What information is needed from other disciplines?) is qualitatively different from the more common one that asks what information each discipline can provide.

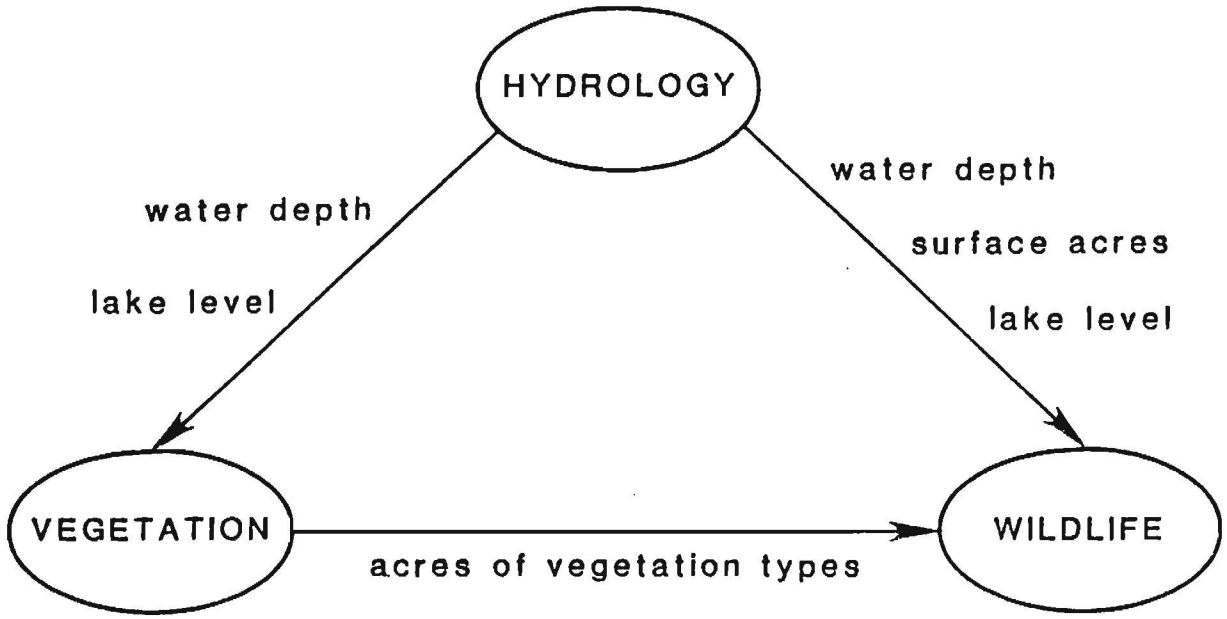


Figure 2. Submodel interactions.

Following this exercise, the workshop participants met in smaller subgroups, one for each major component, to construct a conceptual model representing the internal dynamics of that component. The basic charge of each subgroup was: given a set of actions (identified in the bounding exercise) that you must represent in the model and a set of inputs provided by other subgroups (Fig. 2), describe the mechanisms and processes (rules for change) that occur in your component to produce the set of indicators (from bounding exercise) you must represent and the outputs that other subgroups require from you (Fig. 2). Descriptions of the approach used in each submodel are presented in the following sections of this report. The submodels are written in standard FORTRAN and executed within a general simulation control package called SIMCON (Hilborn 1973).

HYDROLOGY SUBMODEL

The Hydrology subgroup was responsible for developing relationships to represent changes in lake volume, elevation, and surface area and associated changes in water quality. These hydrologic characteristics are used by the Vegetation submodel to calculate changes in various vegetation communities and by the Wildlife submodel, in conjunction with information from the Vegetation submodel, to calculate indices of abundance or habitat suitability for various wildlife species or groups. The Hydrology subgroup was also responsible for incorporating the various flood control projects (Table 1) into the model.

Initial discussions of the subgroup focused on the water budget of the lakes on the Refuge. Much of this information was provided by Larry Hubbard, U.S. Geological Survey, Portland, Oregon, and by Bill Beal, Oregon Water Resources Department, Burns, Oregon. Some of this information is documented in Hubbard (1975). Because of the complex morphology of the Malheur Lake lakebed, three distinct hydrologic units can be defined (Fig. 1). The central unit, bounded by a north-south ridge (Graves point) on the west and Cole Island dike on the east, receives water directly from the Silvies and Blitzen Rivers and from Sodhouse Spring. When water levels in this unit exceed 4,091 ft, water flows through the breaks in Cole Island dike into the eastern unit. There are no surface outlets from this unit, so water remains until the central unit recedes. The unit west of Graves Point is normally a series of ponds 10-500 acres in size separated by a complex network of islands and peninsulas. When water levels exceed 4,092 ft, water begins to move through this complex toward the outlet at the Narrows into Mud Lake. When water levels are changing rapidly, the water elevations in these three units can be different. In addition to this complexity, reliable stage-discharge relationships for the Narrows and for the breaks in Cole Island dike are not available. In wet years, water flows from Malheur Lake to Mud Lake then into Harney Lake. In many years, Harney Lake only receives inflows from Silver Creek and from direct precipitation.

Subgroup participants discussed the possibility of building either a "three-bucket" (Malheur, Mud, and Harney Lakes) or a "five-bucket" (Malheur - east, Malheur - central, Malheur - west, Mud, and Harney Lakes) water budget model. However, time constraints during the workshop, the complexity and information gaps described above, and the lack of separate capacity-elevation and elevation-surface area curves for each lake or unit precluded these approaches. The subgroup therefore decided to treat the lakes as a single lake system, which is a reasonable approximation at lake elevations above 4,092 ft. The general structure of the submodel is diagrammed in Figure 3.

Water Budget

Inflow. River flows corresponding to the Burns gage on the Silvies River, the Frenchglen gage on the Blitzen River, and the Riley gage on Silver Creek are generated in the model based on statistics from long-term gaging data. The model generates an annual runoff for each river by sampling from a normal distribution with the appropriate mean, standard deviation, minimum, and maximum flow for that river (Friday and Miller 1984). The resulting flow can be multiplied by a factor to generate above or below average flows during a specified time period in a scenario. The annual flows are proportioned into monthly flows based on the long-term average pattern of inflow for each river (e.g., 36% of the annual flow in the Silvies River typically occurs in April). It should be noted that this approach does not reproduce historical flow records; rather, the mean, standard deviation, minimum, and maximum of a series of flows generated by the model should closely approximate those of the historical record. Participants chose this approach rather than using historical monthly gaging data for two reasons. First, the gaging data were not immediately available at the workshop and would have taken too long to enter into the computer even if someone retrieved the records. Second, participants wanted to evaluate the consequences of alternative future runoff scenarios not reflected in the historical record.

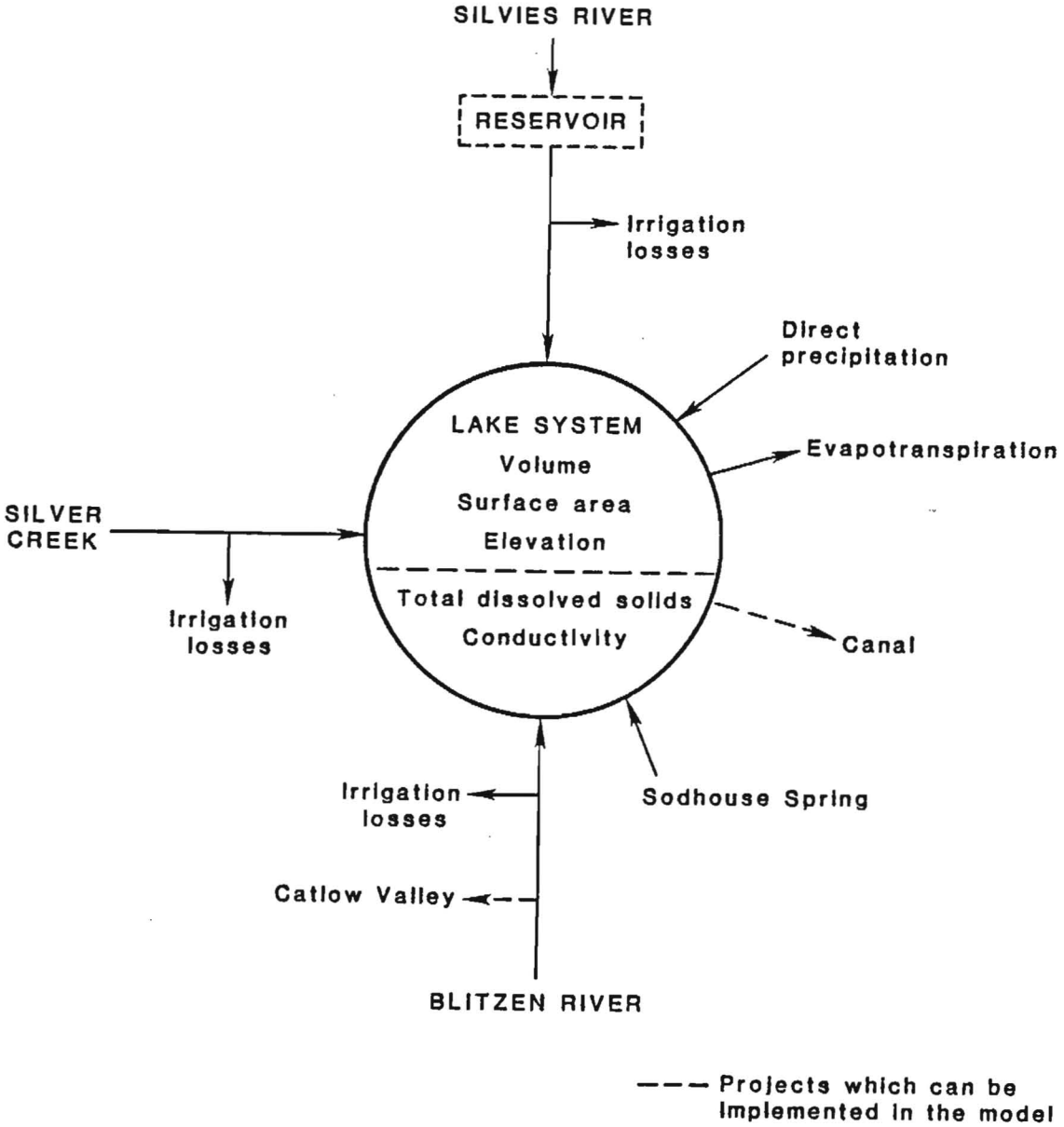


Figure 3. Hydrology submodel.

The other inflow into the lake system is from Sodhouse Spring, which is represented by a constant monthly flow in the model (Hubbard 1975). Other groundwater inputs were assumed negligible. Evidence since the workshop, however, suggests that these inflows may be significant in the current high water conditions.

Currently, the only management practice that significantly affects flows into the lake system is irrigation. Irrigation losses in each river are calculated by multiplying the irrigated acres in the drainage by a loss rate (acre-ft/acre) for that drainage. The loss rates implicitly account for evapotranspiration and loss to groundwater and are based on the assumption that irrigators will apply 3 acre-ft/acre annually if available.

Proposed projects that would affect inflow to the lake include a reservoir on the Silvies River above Burns and a diversion from the Blitzen Valley to the Catlow Valley. Implementation of the Blitzen diversion in the model causes all flow in excess of irrigation demands in the Blitzen Valley to be diverted. Implementation of the reservoir causes all flow in the Silvies River to be stored for joint use with monthly releases to maintain a specified flood control reservation from January to June, and for downstream irrigation. The irrigation release is calculated as the product of irrigated acres in the drainage and a diversion demand (acre-ft/acre) for the month being simulated. The monthly pattern of irrigation demand changes when the reservoir is implemented in the model; the peak demands come slightly later in the spring and the period of demand is longer than for the wild flood irrigation currently used. This shift in the timing of flows in the Silvies River and the potential change in area flooded are of major concern to the FWS in terms of their impact on migration and nesting habitat for many avian species (Horton et al. 1983).

Direct precipitation. Annual and monthly precipitation are generated using the same statistical sampling and monthly proportioning approach described for river flows. Precipitation statistics for the period of record (1944-1983) were obtained from Local Climatological Data reports produced by the National Oceanic and Atmospheric Administration. A multiplier can also be applied to precipitation to generate above or below average years of precipitation. Volume of water added to the lake system each month is calculated by multiplying the monthly rainfall by the surface area of the lake.

Outflow. There are no natural surface outflows from the Malheur-Mud-Harney Lakes system. The only outflow considered by the model is a canal with a specified capacity and outlet structure elevation. By specifying different values for these parameters, various alternatives for the Malheur Gap or the Alvord Desert canals can be simulated. This includes the potential to specify monthly changes in canal "capacity" to approximate the influence of river conditions in the receiving basin on canal operation. It was assumed that the outlet structure at Malheur Lake would be controlled so that flow in the canal would never exceed the specified capacity. Monthly volume of flow in the canal is therefore calculated as the minimum of either the lake volume above the outlet or the canal capacity. Outflows from the lake to groundwater were assumed negligible because of the low groundwater gradients and low permeability of the deposits underlying the lake bed (Hubbard 1975).

Evapotranspiration. Evapotranspiration is the predominant mechanism by which water leaves the lake system. A statistical sampling and monthly proportioning approach was also used for evapotranspiration. The model assumes that evapotranspiration losses can be adequately approximated by the evaporation from a shallow lake (pan evaporation data adjusted for a regional pan coefficient) (Gay and Holbo 1971; Cruff and Thompson 1967). Statistics and monthly patterns for evaporation were developed from pan evaporation data collected by the Refuge. The regional pan coefficient of 0.74 was initially used in the model but was later adjusted to 0.93 (U.S. Army Corps of Engineers 1975) so that the water budget model produced more reasonable lake elevations under average inflow conditions. The pan coefficient is therefore being used to compensate for the approximations in other parts of the water budget model.

Lake volume, elevation, surface area. The new lake volume each month is calculated by adding inflows and direct precipitation and subtracting outflows and evapotranspiration from the previous month's lake volume. Preliminary capacity-elevation and elevation-surface area curves provided by the U.S. Geological Survey for the combined Malheur-Mud-Harney Lakes system are then used to calculate lake elevation and surface area from the new volume.

Water Quality

Concentrations of water quality constituents vary in Malheur and Harney Lakes. The primary factors accounting for these differences are the volumes of water and associated concentrations flowing into the lakes from rivers, creeks, and springs, the intermittent flows between lakes, and the evaporative concentration of constituents due to high summer temperatures and the lack of any surface outlets. Differences in circulation and mixing in the lakes, and in units within Malheur Lake, further complicate water quality considerations. Because the water budget model treats Malheur, Mud, and Harney Lakes as a single unit, these differences could not be easily considered. A crude "two-bucket" mass balance approach was therefore used to calculate total dissolved solids (TDS) and conductivity. This approach was not expected to produce good estimates of concentrations; rather, it was hoped that the approach might produce a "qualitative" indicator that could be compared in different scenarios.

Total dissolved solids and conductivity. The volumes of water in Malheur-Mud Lakes and in Harney Lake are calculated from the lake system elevation in the previous month (from the water budget model) and crude elevation-capacity curves for Malheur-Mud Lakes and Harney Lake separately. These curves were developed at the workshop from the combined lake curve provided by the U.S. Geological Survey and from very early data for Harney Lake and Malheur-Mud Lakes (Piper et al. 1939). Each month, inflows from the Silvies and Blitzen Rivers, Sodhouse Spring, and direct precipitation are added and losses due to evapotranspiration and canal operation are subtracted from the calculated Malheur-Mud Lakes volume. A new volume for Harney Lake is similarly calculated by considering Silver Creek inflows, precipitation, and evapotranspiration.

The flow of water, if any, between Malheur-Mud and Harney Lakes is approximated by comparing the net surface flow into Malheur-Mud Lakes (Silvies River + Blitzen River + Sodhouse Spring - canal) to the net surface flow into Harney Lake (Silver Creek). When the net surface flow into Malheur-Mud Lakes is greater than the net surface flow into Harney Lake, the difference "flows" into Harney Lake and is added to its volume. This situation generally occurs in the model except when there are very high flows out of Malheur Lake into the canal and the more alkaline, brackish water from Harney Lake is pulled into Malheur-Mud Lakes. In this case, the difference in net flow is added to the calculated Malheur-Mud Lakes volume. This approach assumes that elevations in both lakes are near 4,092 ft and that a physical connection would occur with only a small amount of inflow. This approach does not consider the prevailing south-westerly winds that push water through the Narrows.

The mass of total dissolved solids in each lake is calculated by adding the mass (the product of concentration and volume) in each inflow and subtracting the mass in each outflow from the mass carried over from the previous month. The concentration of TDS in each lake is then calculated by dividing the new total mass by the new volume. TDS concentrations are converted to conductivity estimates for each lake based on a regression provided by Dick Nichols, Oregon Department of Environmental Quality, Bend, Oregon.

VEGETATION SUBMODEL

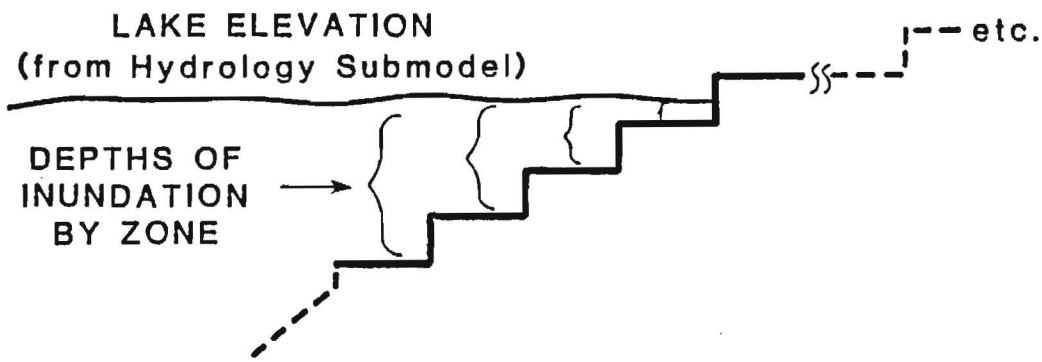
The Vegetation subgroup was responsible for developing relationships to represent changes in vegetation and cover types. Areas of various vegetation and cover types, in combination with hydrologic conditions, are then used by the Wildlife submodel to calculate indices for a number of wildlife species. The Vegetation subgroup decided to focus on relating cover types to lake level (and consequent areas and depths of inundation), rather than trying to incorporate the full set of habitat management actions (e.g., moist soil management, haying, grazing, and burning) that might take place on individual management units.

For the purpose of the Vegetation submodel, the system was considered to be Malheur, Mud, and Harney Lakes and the surrounding area to an elevation of 4,113 ft. Eight exhaustive (all area is in one of the cover types) and mutually exclusive (a given area can be in only one cover type at a time) cover types were defined:

1. Brush
2. Flooded brush, representing brush that has had woody species killed by inundation
3. Dry grassland-forb
4. Wet meadow
5. Cattail (Typha latifolia) - Burreed (Sparganium eurycarpum)
6. Bulrush (Scirpus acutus)
7. Open water, less than 6 ft in depth
8. Deep open water, greater than 6 ft in depth and including all of Harney Lake below an elevation of 4,090 ft

These cover types differ slightly from those identified on the first day of the workshop (Table 2) as a result of discussions within the Vegetation subgroup. The area of submergent sago pondweed (Potamogeton pectinatus) is calculated separately, reflecting the fact that it occurs within a number of the above cover types.

In order to convert the general lake elevation provided each month by the Hydrology submodel to the depths of inundation for various cover types at various relative elevations, the total area was divided into a series of elevational zones (Fig. 4). Generally, each zone represents a 1-ft elevation interval. The exception is the lowest zone (primarily Harney Lake), which consists of all areas below 4,090 ft. Water depth for each zone is calculated each month by subtracting the elevation of the zone from the lake elevation provided by the Hydrology submodel.



Zone #	1	2	3	4	5	6	etc.
Elevation (feet)	<4090	4090	4091	4092	4093	4094	etc.
Area (acres x 10^3)	27	11	12	12	12	11	etc.

Figure 4. Scheme of elevational zones illustrating calculation of water depth in each zone from lake elevation.

Cover Type Changes

Changes among the eight basic cover types are calculated and tracked separately for each elevational zone. Each zone has a total area and estimated ownership proportions (Refuge, private, and other governmental) so that cover types can be summed across zones to produce totals in the system and totals by ownership.

Except for the lowest elevational zone, changes among cover types at each zone are calculated annually based on maximum and minimum depths of inundation at each zone during the preceding year. A change matrix (Table 3) summarizes the conditions under which each cover type is converted to other cover types and the fractional rates of change occurring in a year in which the conditions are met. Conditions at each zone are examined to determine which changes of existing cover types should occur. If the necessary conditions for a change

Table 3. Necessary conditions and rates for annual changes between cover types. Conditions are based on maximum and minimum monthly water depths over preceding year. Rates are the fraction of the original area converted per year.

New cover type	Necessary conditions of inundation	Conversion rates (fraction per year) by original cover type							
		Brush	Flooded brush	Dry grass-land-forb	Wet meadow	Cattail-burreed	Bulrush	Open water	Deep open water
Brush	not inundated	-	0	0.067	0	0	0	0	0
Flooded brush	inundated for at least 1 month	1.0	-	0	0	0	0	0	0
Dry grass-land-forb	not inundated	0	1.0	-	0.5	0	0.2	0.333	0.333
Wet meadow	maximum inundation of 0-2 ft, dry for at least 1 month	0	0.333	0.5	-	0.1	0.067	0.333	0.333
Cattail-burreed	maximum inundation of 1-2.5 ft, not dry in any month	0	0.25	0.333	0.5	-	0	0.333	0.333
Bulrush	maximum inundation of 2-4 ft, not dry in any month	0	0.25	0.333	0.5	0.1	-	0.25	0.25
Open water	maximum inundation of 4-6 ft, not dry in any month	0	1.0	1.0	1.0	0.5	0.333	-	1.0
Deep open water	maximum inundation greater than 6 ft, not dry in any month	0	1.0	1.0	1.0	1.0	1.0	1.0	-

are not met, the area of that cover type remains unchanged. After the fractional changes between cover types in a zone are calculated, the areas of each cover type in that zone are updated and the process is repeated for the next zone.

The lowest zone is treated somewhat differently for two reasons. First, the Hydrology submodel calculations do not provide realistic lake elevations below 4,090 ft because of the "one-bucket" approach. Second, the vegetation response in Harney Lake is different than in other areas because of salinity limitations. The model thus assumes that all of the area in the elevational zone below 4,090 ft remains in the Deep Open Water cover type.

Sago Pondweed

Considerable discussion was devoted to the complex set of factors directly and indirectly influencing the areal extent of sago pondweed. These included the role of turbidity in limiting the sago pondweed by reduced light penetration, the effect of carp on turbidity, competition between sago pondweed and emergent vegetation, and the role of emergent vegetation in reducing turbidity from wind-generated wave action. The Vegetation submodel was not able to incorporate all of these relationships into a dynamic model of sago pondweed. The calculation of sago pondweed area is based, instead, on a simple proportional relationship to the area of certain cover types. This reflects a distribution of sago pondweed interspersed with other vegetation in several cover types. The area of sago pondweed is thus calculated each year as the sum of the following fractions of the areas in other cover types: cattail-burreed (0.12); bulrush (0.06); wet meadow (0.18); and open water (0.03).

The effect of a reduction in turbidity, such as that resulting from a reduction in carp population, is simulated by introducing a multiplier for sago pondweed at any year. This multiplier then declines by 20 percent per year to a value of 1.0 in order to represent a gradual increase in turbidity (i.e., recovery of carp population).

WILDLIFE SUBMODEL

The task of the Wildlife subgroup was to develop relationships describing wildlife populations or their habitats in the Malheur-Harney Lakes area as functions of vegetation, hydrology, and other important variables. Ideally, it would have been desirable to construct complete representations of the population dynamics of the species of interest. However, most of the important species are migratory and, therefore, many important processes (e.g., winter mortality) occur in areas far removed from the Malheur-Harney Basin. This fact, coupled with the limited time available at the workshop and the large number of species to be considered, prevented construction of complete population dynamics models. The approach adopted instead was to attempt to identify simple relationships describing indices of abundance or habitat availability. Such relationships, which are described in the following sections, were developed for colonial nesting birds [great egret (*Casmerodius albus*), double-crested cormorant (*Phalacrocorax auritus*), white-faced ibis (*Plegadis chihi*)], greater sandhill crane (*Grus canadensis tabida*), diving ducks, tundra swan (*Cygnus columbianus*), dabbling ducks, and Canada goose (*Branta canadensis*). These were judged by participants to be, from the perspective of Refuge objectives, the most important species or groups identified in the bounding exercise (Table 2). Lack of time at the workshop prevented consideration of other species or groups [snow goose (*Chen caerulescens*), carp (*Cyprinus carpio*), muskrat (*Ondatra zibethicus*), predators, antelope (*Antilocapra americana*), deer (*Odocoileus hemionus*), and game fish] and factors affecting botulism losses.

Colonial Nesting Birds

Great egret. The total number of breeding pairs of great egrets is estimated in the model as a function of the surface area of Malheur Lake in May (Table 4) using a regression developed at the workshop. In addition, an estimate of the number of these pairs that would nest successfully is obtained

Table 4. Results of regression analyses relating wildlife species or their habitats to hydrologic and vegetation conditions at Malheur National Wildlife Refuge.

Species or group	Dependent variable	Independent variable	Regression equation	Sample size	r
Great egret	Breeding pairs	Lake surface area in May	Y = .0087X - 356.1	12	0.72
Double-crested cormorant	Breeding pairs	Lake surface area in April	Y = .0064X - 330.9	12	0.72
White-faced ibis	Breeding pairs	Lake surface area in May	Y = .0103X - 515.4	12	0.38
Diving ducks	Breeding pairs	Acres of sago pondweed in previous fall	Y = .0245X + 26.0	12	0.62
Diving ducks	Spring use-days	Acres of sago pondweed in previous fall	Y = 47.1X + 1.72 X 10	3	0.95
Diving ducks	Fall use-days	Acres of sago pondweed in current fall	Y = 78.6X - 24784	3	0.98
Tundra swan	Spring use-days	Acres of sago pondweed in previous fall	Y = 3.5X + 1.05 X 10	3	0.06
Tundra swan	Fall use-days	Acres of sago pondweed in current fall	Y = 11.6X + 3402	3	0.99
Dabbling ducks	Spring use-days	Acres of sago pondweed in previous fall	Y = 34.4X + 5.54 X 10	3	0.36
Dabbling ducks	Fall use-days	Acres of sago pondweed in current fall	Y = 345.5X + 1.15 X 10	3	0.92
Canada goose	Breeding pairs	Acres of bulrush with >1 ft and <6 ft of water	Y = .0170X - 124.4	12	0.71

in the following way. First, the number of breeding pairs is proportioned between emergent vegetation and riparian vegetation. If the lake surface elevation is below 4,100 ft, all are assumed to nest in emergents. If the lake surface elevation is 4,100 ft or above, half of the breeding pairs is assumed to nest in emergent vegetation. Success of the pairs nesting in emergent vegetation is reduced using a multiplier calculated from the rise in lake surface elevation from May 1 to June 1. This multiplier declines linearly from a value of 1.0 with a water level rise of 1 ft or less, to a value of 0.0 with a water level rise of 3 ft or more. Success of pairs nesting in riparian vegetation is assumed to be unaffected by rises in water level.

Double-crested cormorant. The total number of breeding pairs of cormorants is estimated as a function of lake surface area in April (Table 4). The number of successful pairs is determined in a manner similar to that used for great egrets. The proportion of pairs nesting in emergent vegetation is assumed to decline linearly from 1.0 at a lake surface elevation of 4,094 ft, to 0.0 at 4,102 ft. Those not nesting in emergents are assumed to nest in riparian vegetation. The success multiplier for those nesting in emergents depends on lake level rise from April 1 to June 1, declining linearly from 1.0 with a rise of 6 inches or less, to a minimum of 0.0 with a rise of 2 ft or more. Those nesting in riparian vegetation are assumed to be unaffected by rises in lake surface elevation.

White-faced ibis. The number of breeding pairs of white-faced ibis is estimated as a function of lake surface area in May (Table 4). All ibis are assumed to nest in emergent vegetation, regardless of lake elevation. The success multiplier depends on rise in lake surface elevation from June 1 to July 1, declining linearly from a value of 1.0 with a water level rise of 1 ft or less, to a value of 0.0 with a water level rise of 3 ft or more.

Feeding habitat. Estimates of the amount of feeding habitat available are calculated for two groups of colonial nesting birds. For those that wade and feed on invertebrates, feeding habitat is calculated as the number of acres with water less than 6 inches in depth. For those that wade and feed on fish, feeding habitat is computed as the total area with water less than 1 ft in depth.

Greater Sandhill Crane

An approach to estimate the impact of changing lake surface elevations on sandhill cranes was developed at the workshop using maps of known territories. Each of the 72 known territories below elevation 4,112 ft was assigned to a 1-ft elevation band. In the model, when this band is completely inundated, the pair occupying that territory is assumed not to breed in the current simulation year. Total impact is estimated as the sum of the number of territories in the inundated elevation bands. An additional indicator of feeding habitat is computed as the acreage of wet meadow covered by 6 inches of water or less in June.

Diving Ducks

The number of breeding pairs of diving ducks is estimated, using a regression calculated at the workshop, as a function of the number of acres of sago pondweed in the previous fall (Table 4). As with colonial nesting birds, a multiplier is applied to the number of breeding pairs to estimate the number of successful nests. For diving ducks, the multiplier is a function of the rise in lake surface elevation from June 1 to July 1, declining linearly from a value of 1.0 for a water level rise of 6 inches or less, to a value of 0.0 for a water level rise of 2 ft or more.

In addition, spring and fall use-days by diving ducks are estimated as a function of the acres of sago pondweed in the preceeding fall or the current fall, respectively (Table 4). The very small number of data points makes these relationships tenuous at best.

Tundra Swan

Tundra swans do not nest at Malheur, but use the Refuge during their spring and fall migrations. Spring and fall use-days are estimated in the same manner as that used for diving ducks. Once again, the very small sample size should be noted. The poorer relationship (lower r^2) for spring use-days

is probably a result of two factors. First, using sago pondweed acreage from the previous fall as the independent variable does not allow the effects of changes in sago (e.g., consumption by swans and other species) from fall to spring to be taken into account. Second, in spring swans are much less dependent on sago pondweed in Malheur Lake because they have access to flooded agricultural lands in the Silvies River Valley.

Dabbling Ducks

Spring and fall use-days by dabbling ducks are calculated in the same manner as that used for diving ducks and tundra swans (Table 4). For reasons that are probably similar to those given for tundra swans, the relationship in spring is much poorer, but sample sizes are again very small. In addition, an index of nesting habitat for cinnamon teal (*Anas cyanoptera*), one of the most common breeding dabbling ducks at Malheur, is calculated as the number of acres of wet meadow in May with 6 inches or less of water.

Canada Goose

Canada geese at Malheur are largely dependent on emergent vegetation for nesting sites. While there are reasonable data on the number of breeding pairs of geese over the last 12 years, comparable information on the number of acres of emergent vegetation does not exist. An estimate of the number of acres of bulrush present historically was therefore used to approximate emergent vegetation. This estimate was obtained by assuming that bulrush has always comprised about 19% of the surface area of Malheur Lake. This information was then used as the independent variable in a regression to estimate the number of breeding pairs of Canada geese (Table 4). In the model, this regression equation is used, with acres of bulrush covered with water between 1 ft and 6 ft in depth (provided by the Vegetation submodel) as the independent variable, to calculate the number of breeding pairs of Canada geese. Rising water levels are assumed not to affect nesting success because goose nests generally float and many Canada geese nest on top of muskrat houses.

SAMPLE OUTPUT

In the following section, we present sample output generated with the model developed at the workshop. The output includes three scenarios with the same assumptions concerning runoff (an approximation of historical runoff from 1972 to 1984, then 8 more years of above average runoff, followed by 10 years of average runoff), but with different flood management alternatives implemented. In one scenario, a canal from Malheur Lake to Malheur Gap with a capacity of 1,500 cfs and an outlet elevation of 4,093 ft is brought on-line in 1989. In another scenario, a storage project on the Silvies River is completed in 1989 with 1,000,000 acre-ft of joint use storage at full pool and a flood control reservation of 300,000 acre-ft from January to June. The last scenario considers the no action alternative. These scenario results are not intended as an analysis of all potential management actions or assumptions concerning future runoff. Rather, they demonstrate the type of analysis that could be conducted if the model was sufficiently refined and tested.

The scenario results are presented in terms of absolute quantities (e.g., lake elevation, acres of bulrush, breeding pairs of diving ducks). In so doing, we run the risk of imputing greater accuracy to this initial model than is justified. We present the results in this form not because we necessarily believe them to be "correct", but in the hope of promoting constructive discussion. Only by opening the model and its results to criticism can we establish the limits of its credibility. In comparing scenarios, it should, therefore, be remembered that qualitative changes and general trends probably have greater significance than actual numbers. The numbers are included only as points of reference and discussion.

Hydrology

The approximation of monthly lake level fluctuations and the rise in lake level starting around 1980 is shown in Figure 5. The maximum lake elevation in 1984 of the model run is 4,102 ft. Although the model output does not exactly match historical records, the pattern and approximate magnitude of lake level rise are adequate for making relative comparisons among scenarios.

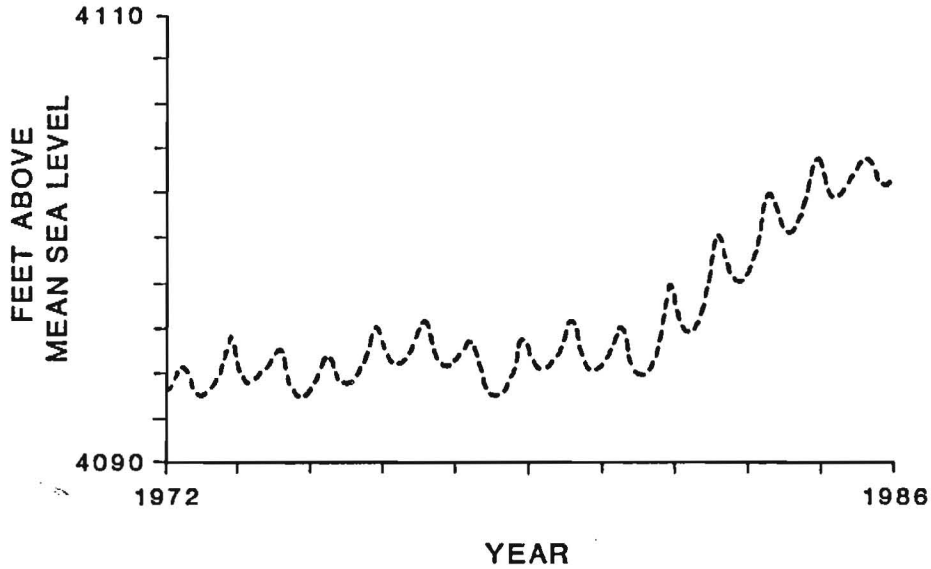


Figure 5. Monthly lake elevations 1972-1986.

The maximum lake elevations predicted each year for a 30-year simulation run are shown in Figure 6. Operation of the canal returns lake levels to the 4,093 ft meander line in about 10 years. Note that a rapid decline in lake level does not occur until runoff returns to average conditions. Also keep in mind that the model allows the canal to be operated at capacity all year if needed; however, actual operation might reduce or eliminate flows in the winter due to ice-up and might reduce flows in the spring when the Malheur River is experiencing flood conditions. The Silvies River storage project has much less effect on lake elevation. Water rights in the Silvies drainage are over-adjudicated, so that except for extremely high runoff years, the model releases all spring inflows to the reservoir over the course of the irrigation season. As a result, there is never much carry-over storage in the reservoir and only small differences in annual inflow to the lake compared to the no action scenario.

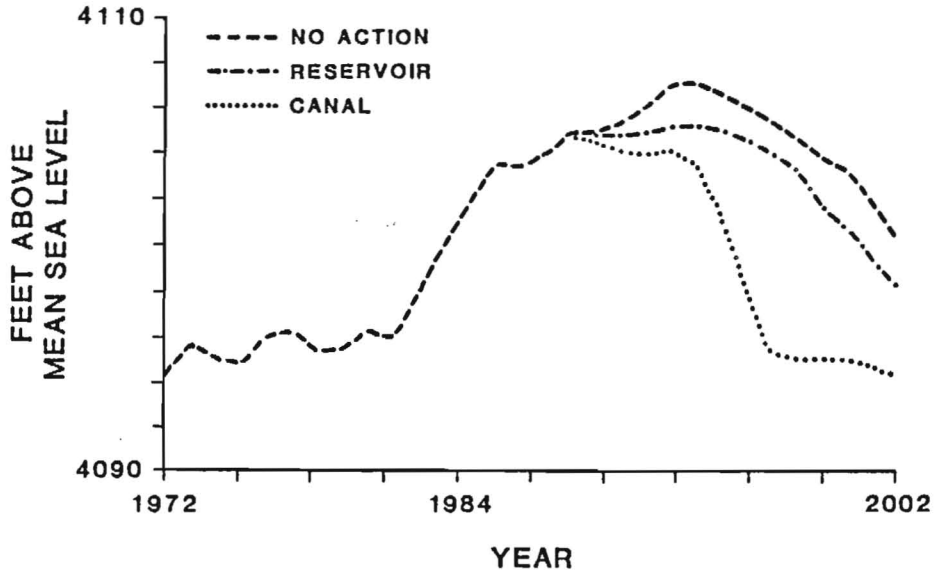


Figure 6. Maximum annual lake level.

Vegetation

All of these scenarios are broadly similar in terms of lake elevation (Fig. 6): roughly stable lake elevations are followed by a period of rapidly increasing lake elevation; lake elevation then roughly stabilizes for a period of approximately 10 years with some additional increase with the no action and reservoir alternatives and some decrease with the canal alternative; and, finally, lake elevation declines with a somewhat sharper rate of decline with a canal.

The total acres of bulrush also follow generally similar trajectories in the three scenarios (Fig. 7). The rapid increase in lake elevation briefly eliminates bulrush. Recovery begins as lake elevation continues to rise and bulrush temporarily stabilizes shortly after lake elevation stabilizes. Near

the end of this period (1989-1992), a second decline in bulrush occurs with the no action and reservoir alternatives because of additional increases in lake elevation. However, lake elevation is slightly falling with the canal at this time and the second decline is absent. In all scenarios, bulrush increases strongly as lake elevation returns to pre-flooding conditions.

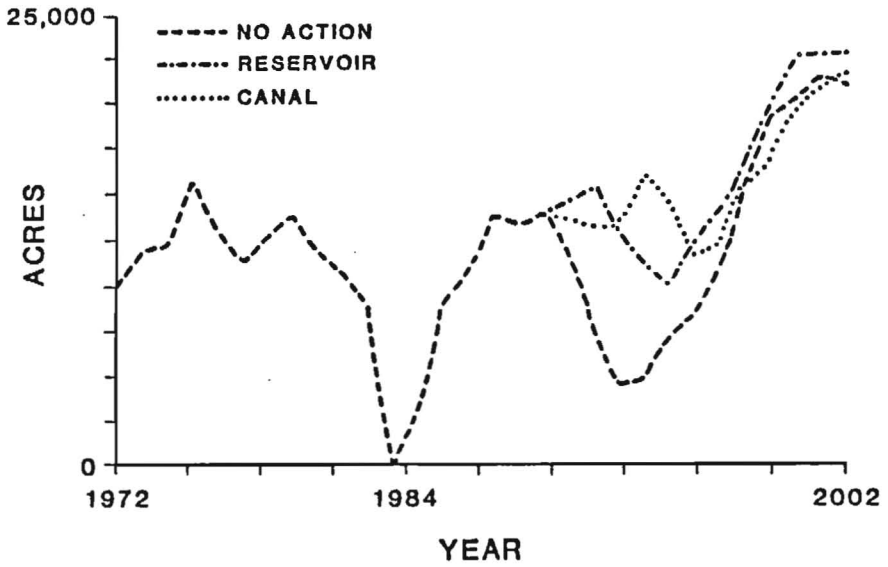


Figure 7. Total acres of bulrush.

The mechanisms causing these changes in bulrush are generally applicable to all vegetation cover types. The total area of any cover type is composed of areas of that cover type in several elevational zones where conditions are suitable. As lake elevation changes, the zones that are suitable for a particular cover type change as vegetation invades new zones and is replaced in other zones. The area of various cover types at any particular time thus reflects a balance between rates of establishment and rates of replacement as determined by lake elevation and the previous history of conditions in various elevational zones.

This balance can be relatively complex. In a period of sustained rise in lake elevation, two counteracting processes take place. Bulrush is eliminated from zones that become too wet and bulrush becomes established in zones that were formerly too dry. The rates at which these processes occur may or may not be balanced, depending on the rate of increase in lake elevation and the previous vegetation of various zones. Early in any period of sustained and substantial increase in lake elevation, the zones being flooded may contain very dry cover types, such as brush, that are not directly converted to bulrush. Thus, a lag is introduced where establishment cannot keep pace with elimination. Later in a period of sustained increase in lake elevation, establishment may equal elimination (or even exceed elimination if the zones becoming too wet never were able to establish bulrush). This is the type of behavior observed in the initial decline and recovery of bulrush in all three scenarios and in the second decline with the no action and reservoir alternatives.

In a period of sustained decrease in lake elevation, the situation is reversed. Bulrush becomes established in zones that were formerly too wet and is eliminated from zones that become too dry. Establishment tends to occur somewhat faster than elimination during the period of declining lake elevation in the last 5 to 8 years of all three scenarios. The tolerance limits and rates of conversion used in the Vegetation submodel result in somewhat higher areas of bulrush after return to "normal" lake elevations than the areas that were used as initial conditions.

Sago pondweed (Fig. 8) is calculated as a proportion of several cover types (bulrush, cattail-burreed, wet meadow, and open water). The general pattern is that of recovery following the sharp decline in the period of rapid rise in lake level. Recovery is somewhat faster in the scenarios with quicker returns to pre-flooding lake elevations (i.e., canal is quicker than reservoir is quicker than no action).

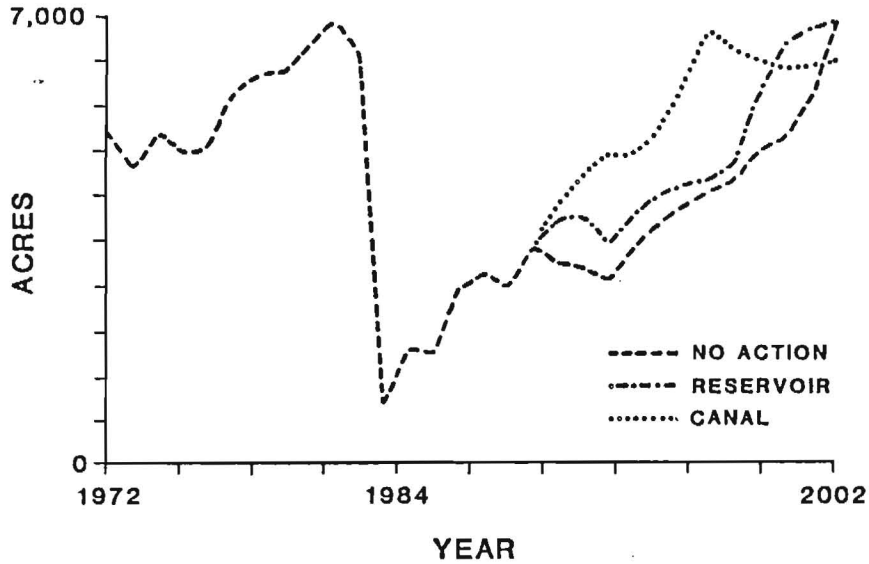


Figure 8. Total acres of sago pondweed.

The movement of a cover type across zones (as lake level changes) creates a dynamic pattern of ownership of each cover type when combined with the different ownership of various zones. Figure 9 depicts the area of the bulrush cover type in two of the three ownership categories. Refuge land predominates at lower elevations, whereas private ownership predominates at higher elevations. As lake elevation rises and then falls, bulrush moves to higher elevations (out of Refuge ownership and into private ownership) and then returns to lower elevations (out of private ownership and back into Refuge ownership).

Wildlife

In the model, the total number of breeding pairs of great egrets is dependent upon the surface area of Malheur Lake in May. The changes in egret pairs after 1989 (Fig. 10) therefore exhibit patterns similar to those for maximum lake elevation (Fig. 6), which generally occurs in late spring. The prolonged high water under the no action and the reservoir alternatives result in much greater nesting use.

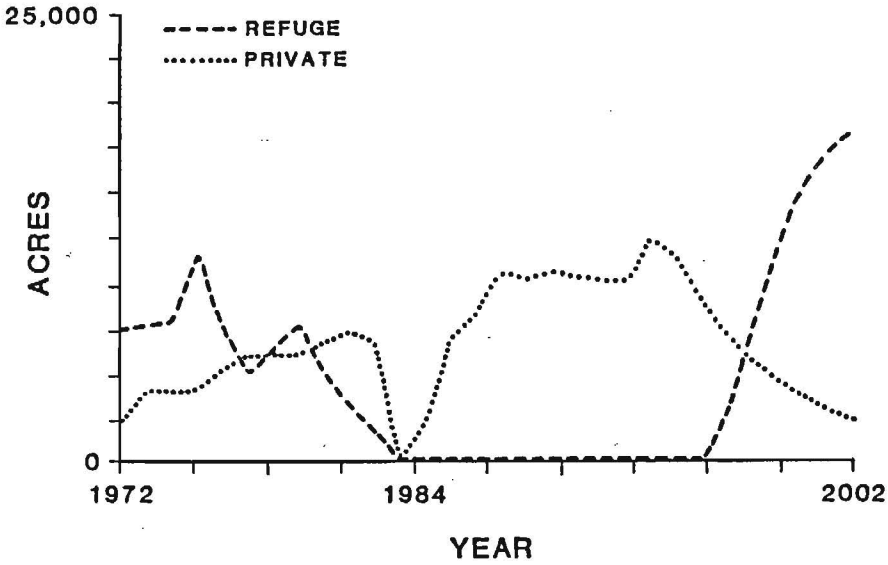


Figure 9. Acres of bulrush on private and Refuge lands.

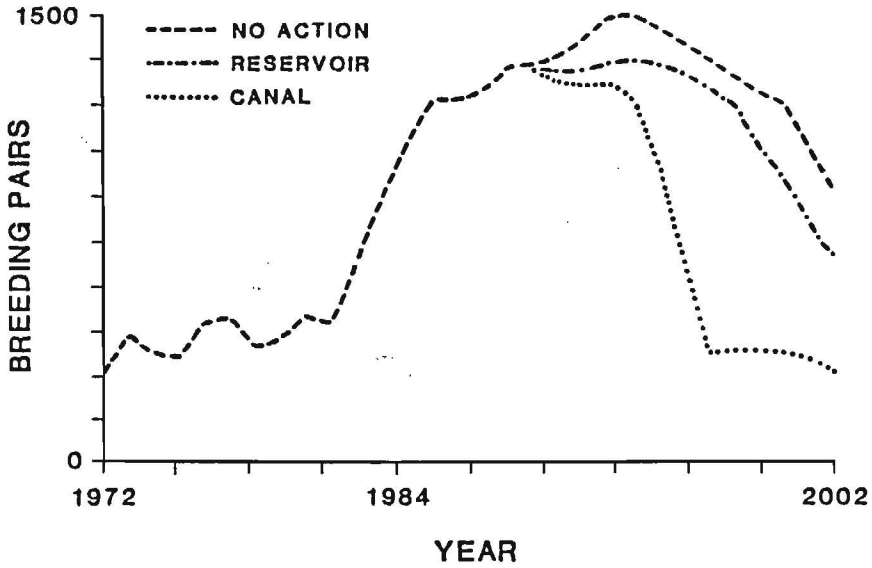


Figure 10. Breeding pairs of great egrets.

The number of greater sandhill crane territories above the lake's surface is shown in Figure 11. The canal and reservoir alternatives result in fewer territories inundated, but the canal allows complete use of all 72 known territories 10 to 15 years earlier than the reservoir or no action alternative.

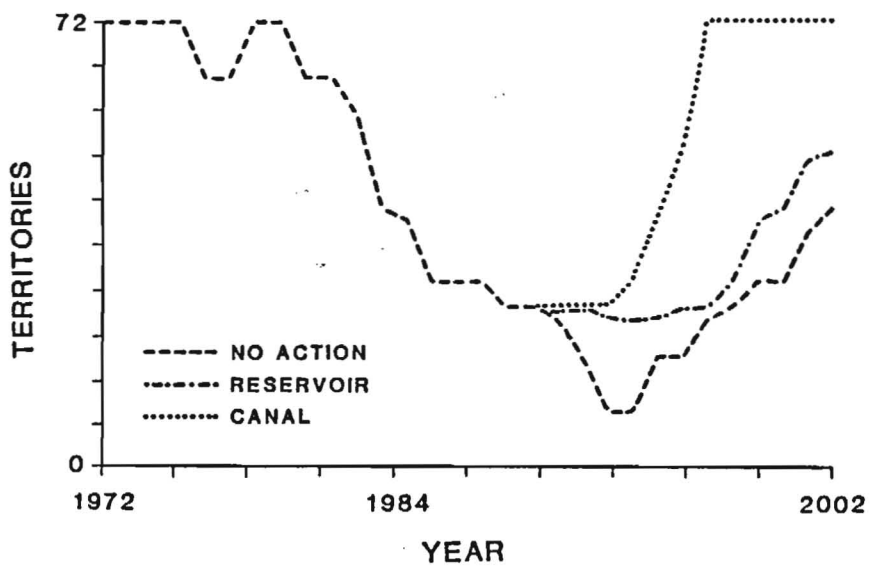


Figure 11. Greater sandhill crane territories.

The number of breeding pairs of diving ducks is estimated as a function of the acres of sago pondweed in the previous fall. Because the rate of pondweed recovery after 1989 in the three scenarios is similar (Fig. 8), there is only a 5- to 7-year difference in the recovery time for breeding pairs of diving ducks (Fig. 12). The rate of recovery of diving ducks is probably over estimated because nesting habitat, which recovers more slowly than pondweed, is not considered in the regression equation.

Canada geese at Malheur are largely dependent on bulrush covered with water between 1 ft and 6 ft in depth for nesting sites. Changes in the number of breeding pairs of geese (Fig. 13) therefore exhibit patterns similar to those for bulrush (Fig. 7). The patterns are not identical because Figure 7 also includes some bulrush not utilized by geese; that is, bulrush covered with less than 1 ft or more than 6 ft of water. Note that only the canal alternative results in any substantial re-establishment of nesting in the 13 years after 1989.

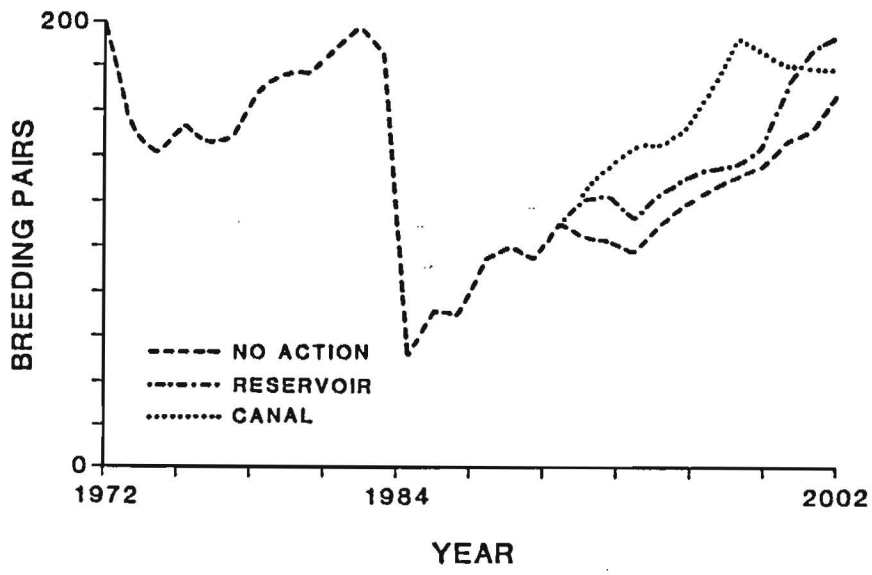


Figure 12. Breeding pairs of diving ducks.

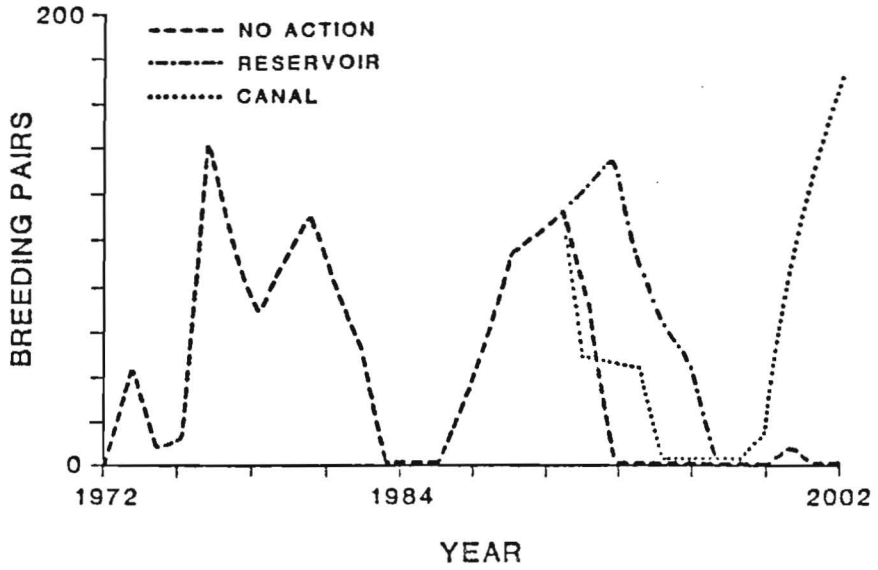


Figure 13. Breeding pairs of Canada geese.

DISCUSSION

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HYDROLOGY

One of the major limitations of the Hydrology submodel is that it does not consider Harney Lake, Mud Lake, and the three hydrologic units in Malheur Lake separately. These water bodies can differ substantially in water elevation, circulation, and water quality, resulting in different vegetation communities and habitat conditions. These differences can greatly influence waterfowl use patterns. In addition, the proposed flood control alternatives would affect these water bodies in different ways. These differences cannot

be addressed with the present water budget model. The primary factors that precluded development of a more detailed hydrology model at the workshop were: (1) the lack of separate capacity-elevation and elevation-surface area curves for the lakes and units individually; and (2) sufficient data on water flows between Harney Lake, Mud Lake, and the three units in Malheur Lake to develop the stage-discharge relationships the model would need. The U.S. Geological Survey is currently developing capacity-elevation and elevation-surface area curves for Malheur Lake and for Harney-Mud Lakes combined. The raw data would eventually allow such curves to be developed for the three units in Malheur Lake. More detailed topographic data for the basin (e.g., 1 ft contours) might improve these curves and could be used for other analyses. The lack of data on flows between hydrologic units is a more difficult problem to solve. The locations at which gaging stations would have to be installed are presently underwater and, once installed after lake levels drop, these stations would have to be operated for a relatively long period of time in order to establish reliable stage-discharge curves. It is possible that an analysis of past lake levels, gaged inflows, and estimated outflows might provide a first approximation of the flows that must have occurred between units. This information would then be used in conjunction with the discharge-elevation curve for Malheur-Harney Lakes from an earlier study (U.S. Army Corps of Engineers 1975) as a basis for a more detailed water budget model. Gaging data could eventually be used to test and refine the model, but the cost of installing and operating the gaging stations would have to be weighed against the potential improvements in the model.

The other major limitation of the water budget model is that it does not explicitly account for groundwater discharge or storage. Recent evidence suggests that groundwater exchanges may be an important component of the basin's hydrologic budget, at least under some circumstances. The first few years of record snowpack resulted in only slightly higher than average runoff in the Silvies and Blitzen Rivers and in Silver Creek. In the last few years, however, similar snowpacks have caused much higher runoffs. It has been hypothesized that seepage to groundwater and bank storage accounted for the lower than expected runoffs initially but that these aquifers have been at or

near capacity the past few years. Also, the rise in lake levels the past few years has been much greater than can be accounted for by surface inflows. This suggests that substantial groundwater discharge into the lakes may be occurring. Groundwater modeling, in general, is much harder and less developed than surface water modeling. However, an analysis of recent gaging station and lake level data in conjunction with standard groundwater models might be used to develop surface-groundwater relationships suitable for this analysis. Again, the cost of such analyses should be evaluated with respect to potential benefits.

Limitations in the present water quality calculations are primarily due to the inability of the water budget model to consider the lakes (or portions of the lakes) as separate hydrologic units. The underlying problems with a more detailed approach and potential solutions are described above. The most important water quality parameter not presently included in the model is turbidity. It is potentially important because of its effects on sago pondweed production. Modeling such a nonconservative parameter (that is, one that cannot be estimated simply from inputs and outputs of material) is difficult and would require additions to the Vegetation submodel (e.g., stabilization of bottom sediments by various plant communities) and the Wildlife submodel (e.g., number of carp and their influence on turbidity), as well as changes in the Hydrology submodel (e.g., effects of circulation within hydrologic units, effects of wind in shallow areas).

Participants suggested that the influence of Malheur River conditions (flow, water quality) on operation of the canal should be better implemented in the model. The model presently allows constraints to be placed on the amount of water that can flow through the canal each month. This feature could be used, for example, to limit flows in months when the Malheur River would likely experience flood conditions normally. The model does not now allow water quality constraints to be placed on canal flow nor does it allow limitations on canal flow based on simulated flows in the Malheur River. If a Malheur River submodel (hydrology, water quality) was judged to be worth the cost of development, then those constraints as well as downstream impacts

could be simulated. Even without such a submodel, the constraints and impacts can be evaluated on the basis of indicators presently in the model (e.g., canal flow each month) and historic gaging and flood damage data for the Malheur River.

Participants also discussed the possibility of analyzing past wet-dry cycles in this area of the United States as a basis for predicting the most likely precipitation trends for the next 5 to 10 years. This information could be used in the simulation model and in more general analyses. The consensus of the group was that the uncertainty of such predictions probably did not justify the cost. In addition, the analysis of project alternatives can probably be done just as well with best case and worst case precipitation assumptions.

VEGETATION

Limitations of the Vegetation submodel can be roughly sorted into two classes: limitations that could be addressed by fine-tuning the current model (i.e., adjusting and refining estimates of parameter and state variables) and limitations involving the development of additional relationships that may be important in determining vegetation dynamics.

Fine-tuning

Almost all of the areal data used in the Vegetation submodel could be determined more precisely, including the areas in each elevational zone, the distribution of cover types across zones, and land ownership by zone. Resolution could also be improved by using more elevational zones (e.g., at 6-inch intervals) and by using an area-elevation relationship for the area below 4,090 ft in conjunction with a Hydrology submodel that calculated lake elevations below 4,090 ft. The Vegetation submodel currently does not distinguish where a particular cover type is within a given elevational zone (e.g., at the edge of Harney Lake versus the edge of Malheur Lake). This kind of spatial

distinction (e.g., spatial locations within each elevational zone) greatly increases the computational complexity and data requirements, but is generally necessary to develop meaningful analyses and projections of the interspersion of cover types.

The rules for vegetation change could also be fine-tuned by adjusting the rates and necessary conditions for various transitions between cover types. Adjustments might be made to correct problems such as a too-rapid recovery or establishment of bulrush. Some improvement in the behavior of sago pondweed might also be achieved from such adjustments. Some of this type of fine-tuning can be done based on careful synthesis of published literature. What is really required, however, is a clear and relatively detailed understanding of the way the model should behave. Good historical records of actual vegetation changes associated with a variety of hydrological conditions are thus needed to do a very good job of fine-tuning.

Additional Relationships

A number of important relationships are not explicitly represented in the Vegetation submodel. The Vegetation subgroup discussed several of these relationships, but was not able to incorporate them in the submodel because of lack of time at the workshop; lack of a clear, quantitative understanding; or some combination of these reasons. Before outlining some of the additions that might be made to the Vegetational submodel, it is important to note that additional relationships and complexity do not always result in a "better" model. A reasonable approach is to introduce complexity only as it is necessary to achieve improved model behavior. Again, historical records (or records from similar sites) reflecting a variety of responses are invaluable sources for judging how well the model is performing.

Possible additions, or revisions, to the Vegetation submodel include:

1. Change in cover type could be made a function of more aspects of the "history" of a particular area. In the current model, change in cover type depends only on the current cover type and the previous year's hydrologic conditions. Several other aspects of the "history" or condition of an area were suggested as being important. These include soil characteristics, the density or age of the existing community, the length of time the site has been either wet or dry, the nature of the seed bank, the presence and condition of root stocks, and the distance to other communities as it influences supply of seeds or vegetative material.

2. There was some indication at the workshop that the rules for changes in cover type did not well represent changes under conditions of very rapid change (decline) in lake elevation and that the beneficial effects (e.g., stand vigor and enhancement of mineral cycling) of moderately fluctuating lake elevations were not reflected in model behavior. Behavior under these conditions might be improved by incorporating some of the additional site characteristics described above and, further, by relating these characteristics to lake level changes.

3. Relationships could be developed to incorporate the feedback effects of wildlife populations on vegetation (e.g., carp and muskrat).

4. Relationships could be developed for the vegetation responses to a number of "smaller-scale" management actions (e.g., haying, grazing, burning, irrigation, and moist soil management).

5. The basic relationship calculating the area of sago pondweed as a proportion of the area of various cover types could be considerably modified or replaced with a relationship that was directly dependent on the previous area of sago pondweed.

Utility of GIS

A number of participants suggested that a computerized Geographic Information System (GIS) would be useful in addressing many of the issues raised during the workshop. A GIS is basically a system that commits spatial data (e.g., maps) to a computer format and performs various overlays and areal calculations. Developing a GIS for an area can be a tremendously efficient method for conducting many types of spatial analysis. Questions such as the areal extent of various cover types in various elevational zones and land ownership by zone could be efficiently answered by overlaying the appropriate maps or themes. Changes could be quantified by overlaying various historical themes (e.g., cover types at a number of different times).

The cautionary note should be added, however, that any GIS does not necessarily answer all the important questions. For example, a GIS containing the current "condition" of the system will not address questions of historical change without the appropriate, historical themes and may be limited in projecting future change by the level of understanding of the rules for change.

WILDLIFE

Perhaps the most obvious limitation of the Wildlife submodel is that it does not consider all of the species that are important to the Refuge. Certain additional species (e.g., snow goose) are important in their own right from the perspective of Refuge objectives. Others are important because of their interactions with vegetation and other wildlife species. For example, carp, through their impacts on water turbidity, are thought to be an important factor in the growth of sago pondweed, which in turn influences use of the Refuge by a variety of migratory bird species. Similarly, muskrats have important interactions with emergent vegetation communities, which in turn provide important nesting habitat for many birds (e.g., diving ducks). In addition, muskrat houses provide important nesting sites for Canada geese. Incorporation of such species would probably result in a more credible and

useful model, although the cost of obtaining (through field research, literature review, or data synthesis) the necessary information would have to be weighed carefully against the potential benefits.

A second general limitation is that, even for the species that are considered, the model is an incomplete representation of the various aspects of species' life cycles that are carried out on the Refuge. For example, the number of breeding pairs is considered for several species, but the productivity of those pairs is not. Information on factors such as clutch size, hatching success, and mortality of the young would be necessary in order to incorporate recruitment of individuals into the population in the model.

Finally, even those factors or processes that are incorporated in the model do not generally contain representations of all of the important variables. For example, the number of breeding pairs of several species of colonial nesting birds is computed directly (from a regression equation) from the simulated surface area of the lake. Implicit in this calculation is the assumption that adequate nesting habitat is available, either in the form of emergent or riparian vegetation. This may be a reasonable assumption for colonial species that nest in relatively small areas; for other species it may not be as reasonable. Another example involves calculation of the number of breeding pairs of diving ducks as a function of the acreage of sago pondweed. This approach implicitly assumes that sufficient emergent vegetation is available in close enough proximity to the sago pondweed to provide adequate nesting habitat. Similarly, factors other than water rise can influence nest success. Predation may be particularly important in situations where predators and their prey are concentrated in smaller and smaller blocks of habitat by rising water levels. Declining water levels may also be important if the declines occur rapidly during the nesting season. And last, indices of feeding habitat (e.g., acreage with water 1 ft or less in depth for wading birds that feed on fish) may be deficient in that they do not consider the productivity of those areas.

Some of these difficulties could perhaps be overcome if historical data on habitat conditions were available to use with historical data on wildlife populations. Given historical information on changes in vegetation, for example, multivariate techniques might be used to develop better predictive relationships that take into account more of the important habitat factors. Once again however, the costs of obtaining such information must be weighed carefully against the expected benefits. Such an assessment should include not only the probability that additional data would produce better estimates of the impacts of various project alternatives on wldlife, but also the probability that better estimates of impacts would influence decisions concerning those alternatives.

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