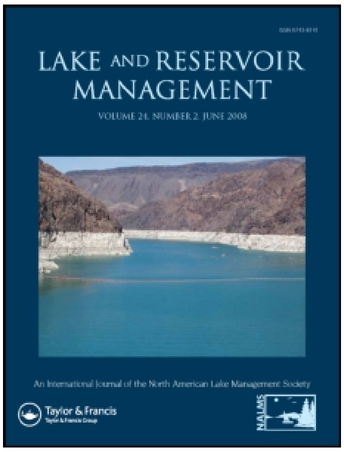

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Phosphorus reduction by dilution and shift in fish species in Moses Lake, WA

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Phosphorus reduction by dilution and shift in fish species in Moses Lake, WA

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Abstract

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Water quality over most of the area of Moses Lake improved greatly over a 25-year period (1977–2001) due largely to the addition of large quantities of low-nutrient Columbia River water as well as changed irrigation practices and diversion of wastewater. The oligotrophication of Moses Lake from hypereutrophy to borderline mesotrophy was accompanied by a marked shift in fish populations, determined by creel census and biological surveys that included electrofishing and gill netting. The catch fraction of panfish (crappie and bluegills) decreased markedly; largemouth bass decreased to a lesser extent, while smallmouth bass, walleye and brown bullhead increased several-fold. These population shifts are consistent with observations elsewhere in response to oligotrophication and piscivory.

Key words: dilution, fish, oligotrophication, species shift

Increased production of fish in lakes and reservoirs resulting from eutrophication is well documented (Oglesby 1977, Jones and Hoyer 1982, Downing et al. 1990) and expected due to increased food supply. However, the change in fish community structure with eutrophication, as well as with oligotrophication, is of more interest to the sport fishing public. Eutrophication fosters habitat changes that adversely affect piscivorous fishes while favoring detritivores (Leach et al. 1977, Haines 1973, Persson et al. 1991, Egerston and Downing 2004). Two important cool-water species, smallmouth bass (SMB) and walleye (WAL), are among the piscivorous species relatively intolerant of eutrophic waters, while carp is a detritivore that thrives with enrichment. Moreover, these two piscivores have increased following oligotrophication due to phosphorus reduction; SMB in Lake Erie (Ludsin et al. 2001) and WAL in the Bay of Quinte, Lake Ontario (Hurley 1986a). Smallmouth bass were also observed to distribute toward the oligotrophic portion of a trophic gradient in a Kentucky reservoir (Buynak et al. 1991).

In contrast, largemouth bass (LMB) tend to thrive in mildly eutrophic waters (Maciena and Bayne 2001), possibly because they do not require the gravelly-to-rocky substrata as do SMB and WAL, and are thus more tolerant of increased sedimentation that usually accompanies eutrophication (Leach et al. 1977, Ludsin et al. 2001). Further, LMB are warm water species and tolerate higher temperatures and thus do not suffer as much from the temperature/dissolved oxygen (DO) “squeeze” characterized for cool-water striped bass (Coutant 1985, 1987, Zale et al. 1990, Young and Isely 2002). Walleye have similar temperature and DO requirements as striped bass, with SMB temperature requirements intermediate between LMB and WAL (Fry 1947, Kitchell and Stewart 1977, MacClean et al. 1981, Hurley 1986b, Buynak et al. 1991).

Moses Lake in eastern Washington has undergone oligotrophication from hypereutrophy until restoration measures were undertaken in the 1970s, to low eutrophy that existed in the 1980s, to borderline mesotrophy by 2001. Major shifts in fish species composition have accompanied the oligotrophication. This paper briefly describes the lake’s improved water quality, largely documented elsewhere (Welch et al. 1992, Welch forthcoming), and the recorded shifts in sport fish populations (Burgess 2000). While the evidence is strong that SMB and WAL (and other percids) are relatively intolerant of eutrophication, there are few published cases of fish species change associated with lake water quality improvement (i.e., oligotrophication). The changes in Moses Lake over a 25-year period have been dramatic, from a fishery dominated by black crappie and bluegill to one dominated by WAL, but with a marked increase in SMB and brown bullhead (BB).

Site description

Moses Lake is a natural lake created by windblown sand dunes that historically dammed Crab Creek. The lake level was stabilized with two dams constructed in 1929 and 1963. The lake has an area of 2,790 ha with a maximum depth of 11.5 m and a mean depth of 5.6 m (Fig. 1). Most of the lake (80% of the area) is polymictic, being too shallow to permanently stratify.

Moses Lake has two tributaries; Crab Creek that drains 80% of the watershed (5,265 km^2), which is mostly dry-land agriculture and rangeland, as well as some irrigated land (11,200 ha), and Rocky Ford Creek that is largely spring

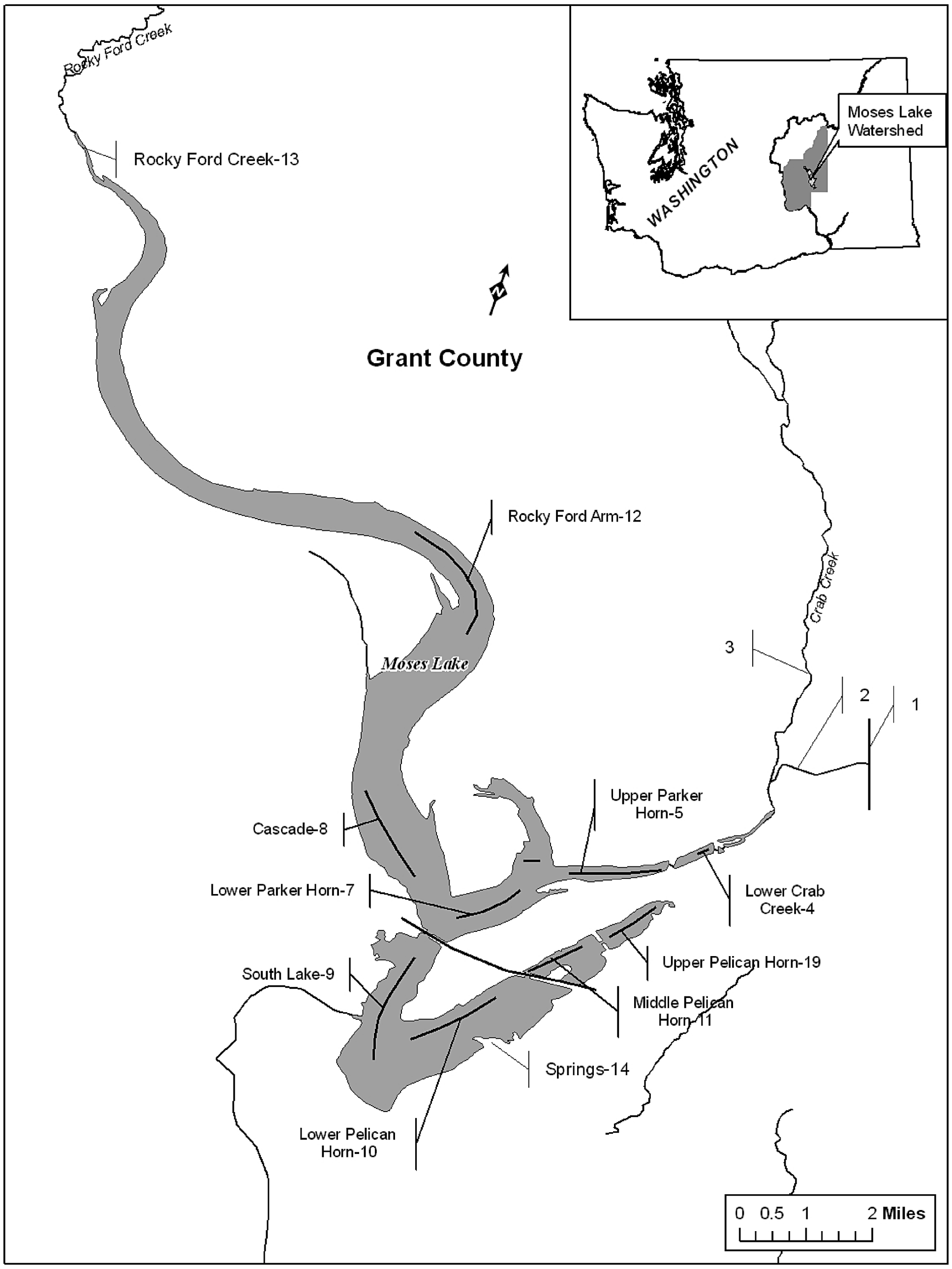

Figure 1.-Moses Lake showing the source of Columbia River dilution water from the East Low Canal (1) entering via Rocky Coulee Wasteway (2) into Crab Creek and then into Parker Horn. Water sampling sites are shown by number and solid lines for transects.

fed. The two streams contribute a similar quantity of inflow to the lake (Jones and Welch 1990). Under normal inflows, with no dilution water added, the lake would have a water residence time of about 1 yr if April–September inflow were considered a year (Welch et al. 1992).

Parker Horn and South Lake represent 26% of the lake's area and are used to depict changes in water quality because most of the dilution water passes through those sections (Fig. 1). Most recreational and fishing activity occurs in South Lake, Parker Horn (which includes a state park and swimming beach) and lower Rocky Ford Arm. The lower part of the Rocky Ford Arm (station 8), representing another 14% of the lake's area, also received dilution water and had water quality similar to Parker Horn.

Methods

Water quality

Composite samples were collected by continuously drawing water from 0.5 m along transects at eight sites in the lake (Fig. 1). The sampling frequency was twice-monthly from April through September during 1969–1970 and 1977–1988. Samples were collected discretely at 0.5 m from the same sites on a monthly basis by the Washington State Department of Ecology in 2001 (Carroll 2006).

Filtered samples were analyzed for soluble reactive P (SRP) by the acid molybdate heteropoly blue method and nitrate-nitrogen (N) by cadmium reduction (EPA 1979). Total phosphorus (TP) was determined as SRP after persulfate digestion. Chlorophyll *a* (chl) was determined by the fluorometric method through 1986 and spectrophotometrically thereafter, both corrected for phaeophytin (Strickland and Parsons 1972). For more details on sample collection and analysis see Welch et al. (1992).

Fish population sampling

Angler catch and species composition were sampled by creel census in 1974, 1983, 1991 and 1996. The hours fished in these four years ranged from 120,363 to 375,250 and fisherman trips from 42,180 to 117,970 (Burgess 2000).

Biological sampling was conducted by electrofishing and gill netting in the other years: 1978, 1989, 1999 and 2000. In 1999 and 2000, electrofishing was by boat at sites randomly selected from a total of established sites (~60) along the shoreline. Gill netting was conducted at sites perpendicular to shore and randomly selected from ~30 established sites (Burgess et al. 2007), following guidelines established by Bonar et al. (2000). Biological sampling in 1978 and 1989 was of a reconnaissance manner: sites were not randomly selected and collection sizes were fewer, especially in 1989.

Results

Response to nutrient reduction

In the 1960s and early 1970s, Moses Lake was hypereutrophic with massive summer-long blooms of cyanobacteria, largely Aphanizomenon (along with *Anabaena* and *Microcystis*), that produced extensive scums on the water surface (Bush et al. 1972, Welch et al. 1972). With such masses of algae, near-bottom DO quickly depleted in shallow (1.5 m) areas when wind speed was <3 m/sec and the water column temporarily stratified (DeWalle 1971). Complete mixing occurred at wind speeds >3 m/sec. Such conditions would be tolerated by carp but detrimental to SMB (Haines 1973).

During May–September 1969–1970, TP and chl averaged 157 and 57 μg/L, respectively, throughout Parker Horn and South Lake (Table 1; Fig. 1; Welch and Patmont 1980). Concentrations were well above their respective boundaries for hypereutrophy (Nürnberg 1996). Transparency (Secchi disk) averaged 0.8 m, also indicating hypereutrophy (Table 1).

Beginning in spring 1977, large amounts of low-nutrient water from the Columbia River were diverted from East Low Canal through Rocky Coulee Wasteway and into lower Crab Creek, which enters upper Parker Horn (Fig. 1). From 1977 through 2001, dilution water inputs during April through early (sometimes late) summer averaged 170 × 10^6 m^3, approximately 1.1 lake volumes (Fig. 2). That quantity more

Table 1.-Mean TP, chl and transparency (SD) during May–September in Parker Horn (PH) and South Lake (SL) of Moses Lake. Data are based on transect samples collected at 0.5 m (Welch et al., 1989), and for discrete samples at 0.5 m in 2001 (Carroll 2006). Data omitted were from 1985, due to high internal loading (see text), and 1984, the year of diversion and no dilution water addition. Trophic state boundaries from Nürnberg (1996).

	TP (μg/L)		**CHL (μg/L)**		**SD (m)**	
Lake Section	PH	SL	PH	SL	PH	SL
Pre-dilution, 1969–1970	152	156	71	42	0.6	1.0
Dilution, pre-diversion, 1977–1983	67	85	23	18	1.3	1.5
Dilution, post-diversion, 1986–1988	47	41	21	12	1.5	1.7
2001	18	17	11	10	2.0	2.1
Hypereutrophic/eutrophic boundary	100		25		1.0	
Eutrophic/mesotrophic boundary	25		9		2.0	

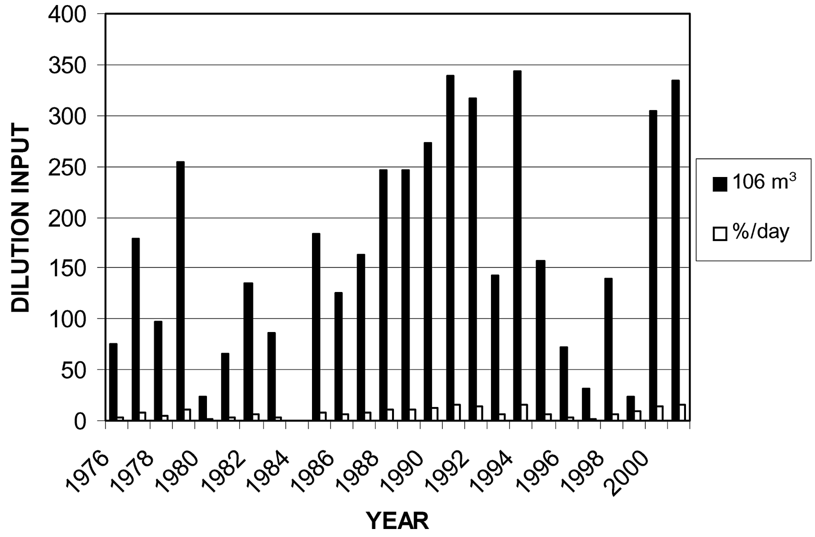

Figure 2.-The quantity of Columbia River dilution water in 10^6 m^3 (solid bars) added during spring-early summer to Parker Horn of Moses Lake from the East Low Canal through Rocky Coulee Wasteway and Crab Creek. Clear bars are water exchange rates for the Parker Horn volume in %/day for the 6-month dilution period, and whole-lake volume is 154×10^6 m^3.

than halved the water residence time to 0.4 years, considering flows during April–September as a year (Welch et al. 1992). The lake continued to receive dilution water each year, excepting 1984. Most of the dilution water passed through Parker Horn and South Lake, but some was pumped into upper Pelican Horn beginning in 1982, and some was transported by wind at least half way up the Rocky Ford Arm (Fig. 1, station 12,). One-third of the water in Rocky Ford Arm was Columbia River water as traced by conductivity, and water quality improved proportionately (Welch and Patmont 1980).

Columbia River dilution water TP averaged about 22 μg/L, and nitrate-N was also low (34 μg/L; Welch et al. 1989). Phosphorus was most effective in reducing lake trophic state, despite the low nitrate-N in dilution water and persistent N limitation in the lake as indicated by low soluble N:P ratios. That is because high background nitrate concentrations in Crab Creek resulted in greatly increased TN:TP and nitrate-N:SRP ratios in the inflow (Welch forthcoming).

Along with dilution water addition, sewage effluent from the City of Moses Lake was diverted from middle Pelican Horn in 1984, and irrigation practices changed in the 1970s. The switch from largely (two-thirds) rill-type irrigation to largely (three-fourths) spray-type application (Welch and Weiher 1987) may have been a cause for SRP and TP to decrease from 32 to 7 μg/L and 119 to 47 μg/L, respectively, in Crab Creek (without dilution water) during the 1970s and 1980s (Welch et al. 1992). While sewage effluent diversion had a major effect in Pelican Horn where it had been discharged, the effect was much less in other lake sections (Welch et al. 1992). For example, TP, which was much higher in South Lake than Parker Horn during pre-diversion years with dilution, was similar after diversion (Table 1).

Improvement in lake quality in Parker Horn and South Lake was dramatic. By 1986–1988, average TP and chl had declined 70%, while transparency had increased 2-fold to 1.6 m (Table 1; Welch et al. 1992). Although those areas of the lake were no longer hypereutrophic, they were nevertheless still lower eutrophic. The upper half of the Rocky Ford Arm, however, which is directly affected by Rocky Ford Creek with inflow TP > 100 μg/L, remained eutrophic, as did Middle and upper Pelican Horn, even after diversion of wastewater. Mean summer TP at stations 12 (Rocky Ford Arm) and 11 (middle Pelican Horn) were 58 and 77 μg/L, respectively. By 2001, TP at stations 12 and 8 were 24 and 23 μg/L (Carroll 2006).

Net internal P loading contributed substantially to lake TP concentration. Internal loading averaged one-third of the total, internal plus external, during May through September in 10 of the 12 years (1977–1988) when it was positive (average rate 1.9 mg/m^2 per day; Jones and Welch 1990). The highest rate was 4.6 mg/m^2 per day in 1985, due largely to wind mixing in August and September. Data from 1985 were omitted from Table 1 because internal loading dominated lake TP and water quality that year.

Mass balance modeling showed that further increases in dilution water input beyond 180×10^6 m^3/yr would have minimal effect on reducing lake TP due to internal loading (Jones and Welch 1990). Therefore, further improvement in lake quality would come only from a reduction in internal loading (Welch et al. 1992).

By 2001, average surface TP in South Lake and Parker Horn had declined by about 60% from 1986–1988 levels to 17 and 18 μg/L, respectively (Table 1); Chl declined by a lesser amount to 10 and 11 μg/L; and transparency had increased to 2.0 and 2.1 m at the two sites. Total P was well within the mesotrophic range while chl and transparency were borderline (Table 1). Dilution water input that year was sizable but no greater than in 1986–1988 (Fig. 2). What had changed, and apparently accounted for the further improvement in lake quality, was the disappearance of net internal loading, as indicated by mass balance (Carroll 2006). Moreover, while the fraction of algae made up of cyanobacteria (bluegreens) had decreased from nearly 100% in 1969–1970 to 73% in the 1980s, it had relatively vanished in 2001 to <5% (Welch et al. 1992, Carroll 2006). Moses Lake, except for upper and middle Pelican Horn and upper Rocky Ford Arm, had become borderline mesotrophic.

Trophic state indicators still vary from year to year, as expected. Parker Horn TP, sampled on five occasions during summer 2005, averaged 33 μg/L (WQE 2005). South Lake was not sampled, but TP likely would have been slightly less, judging from past years (Table 1); therefore, trophic state was still borderline mesotrophic in 2005.

Shift in fish populations

The principal fishery in Moses Lake in the early 1970s was panfish (Fig. 3). Bank fishing for crappie was very popular from the 1950s to early 1970s; however, the catch of panfish declined markedly in the 1970s and early 1980s, from averaging 57% of the catch during 1974–1983 to only about 9% during l989–2000 (Burgess 2000; Table 2). Meanwhile, the catch of SMB increased from an average of <1% during 1974–1983 to >6% during 1989–2000, and the catch of WAL went from essentially zero to an average of 18% during the same periods (Fig. 3; Table 2). In addition, BB catch increased from an average of about 1.5% to >10% (Fig. 3, Table 2). In contrast, the catch of LMB had decreased from an average of about 7% to 2.5% during those two periods. Electrofishing in 2005 caught more than 4000 fish of which 8% were SMB and 5% WAL (averaging over 17 in), so these piscivores remain important components of the fishery (Burgess et al. 2007).

The emphasis by fishermen slowly shifted from panfish to WAL in the creel censuses between 1974 and 1996,

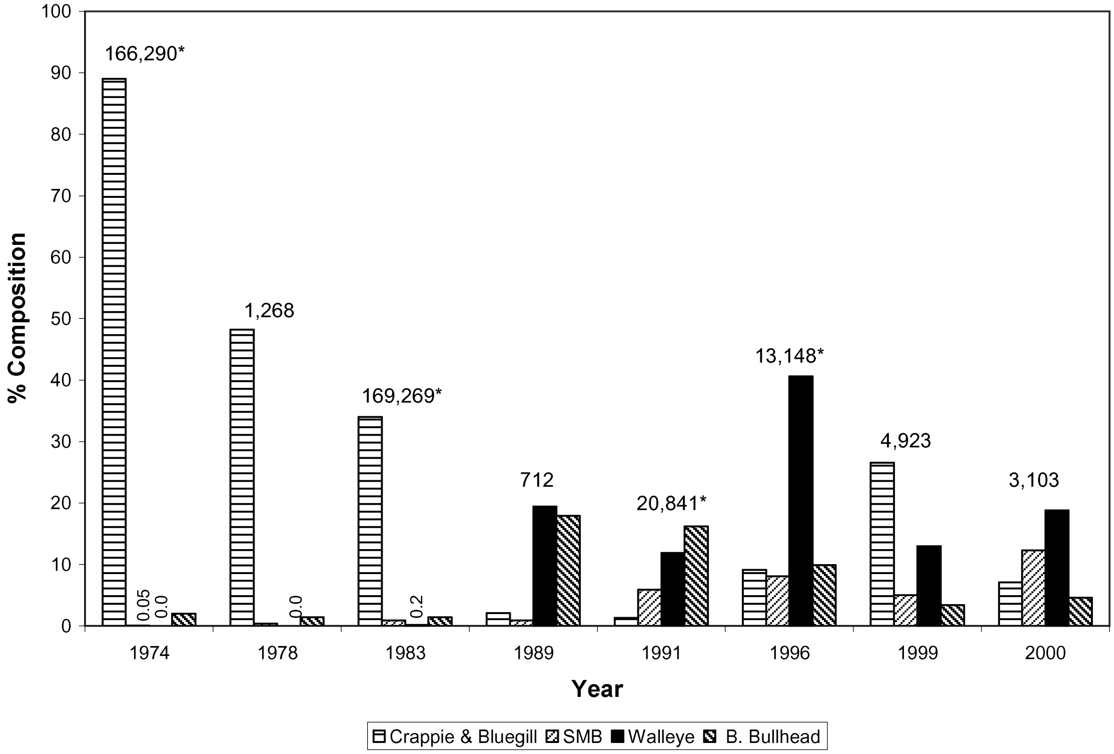

Figure 3.-Angler catch* in 1974, 1983, 1991 and 1996, and biological sampling (electrofishing and gill netting) in the other years, expressed as % of total catch, shown at the top of bars for each year (Burgess 2000, Burgess et al. 2007).

Table 2.-Switch in fish populations associated with change from hypereutrophy and lower eutrophy (3-yr mean, 1974–1983) and to borderline mesotrophy (5-year mean, 1989–2000). Data from Burgess (2000).

Species		3 yrs: 1974–1983		5 yrs: 1989–2000
Bluegill/ crappie	Decreased	34–89% (57%)	TO	1–27% (9.2%)
Smallmouth bass	Increased	< 1% (< 1%)	TO	1–12% (6.4%)
Walleye	Increased	0- < 1% (< 1%)	TO	12–41% (18.1%)
Brown bullhead	Increased	1–2% (1.5%)	TO	3–18% (10.4%)
Largemouth bass	Decreased	1–16% (7%)	TO	0.1–5.2% (2.5%)

while catch rate in general decreased from 1.02/hr to 0.1/hr (Burgess 2000), largely due to the large decrease in panfish (Fig. 3). Despite the decrease in catch rate, fishermen pressure (trips and hours fished) remained rather constant. The shift from an LMB–panfish to a WAL-dominated fishery occurred sometime between 1978 and 1989, and by 1990 the catch of WAL exceeding 15 lbs was common (Burgess 2000). By 2005, the WAL population was considered static (Burgess et al. 2007). Efforts to restore panfish have included stocking 2,700 bluegill in 1989 and more than 5000 adult black crappie from 1995 to 1998.

Total sport-fish biomass (excluding carp) was dominated by WAL in 1999 (29.4%) and 2000 (12.7%); LMB and SMB were about equally represented at a combined 6.2 and 3.9% in 1999 and 2000, respectively. The domination by WAL led to a prey:predator biomass ratio of <1 (Burgess et al. 2007).

Although two sampling methods were used for the 8 years of data, average percent of total catch was not greatly different for the two methods and five species during the latter 5 years of data (Table 2). For creel census and biological survey, the average percent catches were, respectively, 5.2 and 11.9 for pan fish; 2.8 and 2.3 for LMB; 7.0 and 6.0 for SMB; 26.3 and 17 for WAL; and 13 and 8.6 for BB. The differences in these averages were less than that for the ranges in percent of catch (Table 2). Further, the total number in the catches was large, with the possible exception of 1989 (Fig. 3); therefore, use of results from the two methods together to show trends in the populations is considered valid.

Discussion

The cause for the appearance of WAL in the catch in the 1980s is uncertain but they probably entered initially from the Columbia River via irrigation canals. Walleye were probably in the lake but may not have been caught by anglers until they became relatively abundant (Burgess 2000). Stocking of WAL began in 1996 and included 675,000 fry and fingerlings through 1999, well after their marked occurrence in the catch; SMB have not been stocked.

Access from the Columbia River was available previously when the lake was hypereutrophic; therefore, the dramatic change from hypereutrophy to lower eutrophy in most of the lake by the mid- to late 1980s is considered important to the appearance and success of WAL. Adverse effects of eutrophication on WAL and SMB and their positive response to oligotrophication has been observed elsewhere (Leach et al. 1977, Hurley 1986a, Persson et al. 1991). Abundance of WAL and other piscivores was observed to decrease with eutrophy, indicated by transparency (Schupp and Wilson 1992, Heiskary and Wilson 2008). Abundance declined beyond a trophic state index (TSI) of about 50, which is the mesotrophic boundary for transparency of 2 m. Mean summer transparency in Moses Lake was 0.8 m prior to dilution and improved to 2 m by 2001, which seems to be optimal for WAL.

Walleye were probably unaffected by a metalimnetic DO/temperature squeeze in Moses Lake. Surface water temperature during 1986–1988 rarely reached 25°C; 24°C is the maximum tolerable for growth of WAL (Kitchell and Stewart 1977, Hurley,1986b). Trout have been stocked annually by the tens of thousands since the 1960s and have been prevalent in the catch; thus, temperature was obviously not an issue for WAL or SMB.

The pronounced increase in catch of SMB can be largely ascribed to oligotrophication, accompanied by reduced turbidity and sedimentation and probably improved bottom DO, factors that explained their recovery in Lake Erie (Ludsin et al. 2001) and their preference for oligotrophic conditions in a Kentucky reservoir (Buynak 1991). Smallmouth bass are known to thrive in oligotrophic lakes (e.g., SMB are common in oligotrophic lakes in northern Michigan), while LMB are more common in southern Michigan where lakes tend to be eutrophic (N Kevern, Michigan State University, Prof. Emeritus, 2009, pers. comm.). Similar to WAL, SMB would not have been affected by DO/temperature squeeze, because it's preferred and optimum temperature for growth is 25–29°C (Fry 1947, Horning and Pearson 1973, MacClean et al. 1981). Further, SMB were not stocked but were present in the lake in low numbers prior to oligotrophication.

Both WAL and SMB prefer rocky, gravelly substrata with minimal sedimentation and available bottom DO. While Moses Lake has many areas with rocky substrata, sedimentation of the large masses of algae during the period of hypereutrophy may have rendered much of that habitat unsuitable. Moreover, low water column and off-bottom DO in shallow hypereutrophic lakes, during calm periods and following algal bloom declines, are detrimental to sensitive species such as SMB and WAL. Extensive kills of endangered suckers occurred following such events in Upper Klamath Lake, Oregon (Kann and Welch 2005). Diurnal minimum DO is critical to growth and survival of sensitive species (Shumway et al. 1964). Growth of SMB was 2–6 times greater in low fertility ponds where DO was near saturation (± 3.5 mg/L) than in fertilized ponds where DO ranged diurnally from 18 to 2 mg/L (Haines 1973). Growth of carp, however, a highly tolerant species to low DO, had the reverse response. The marked reduction in algal abundance and increased transparency resulting from oligotrophication are indicative of improved habitat for these fish species (Table 1).

Largemouth bass have become less abundant in the lake as water quality improved (Table 2). Smallmouth bass are probably better adapted to the temperature regime in Moses Lake than LMB, which have a slightly higher thermal preference. Being more adapted to the lake's thermal range may have benefited SMB as trophic state decreased to a more favorable level. LMB were stocked in 1989.

Reduction of panfish is more related to predation by the increased WAL population than to reduced primary and secondary production. Increased transparency would have favored such predation. Black crappie represented the largest fraction of food items in WAL stomachs in 2005, although yellow perch were also important (Burgess et al. 2007). Panfish were not included in the diet of WAL in Lake Erie, but reduction of crappie was observed in a Minnesota lake following the introduction of WAL (Bylander 2004).

The improvement in the quality of Moses Lake in the 1980s and 1990s may have been partly due to the changes in fish population structure. The marked reduction in crappie and bluegill, due largely to predation by the greatly increased WAL population, probably reduced zooplanktivory. That reduction should have increased the grazing loss of phytoplankton leading to a reduced chl:TP ratio in the lake. That was not the case, however, because mean summer chl was strongly dependent on summer TP, with the slope of the relation (chl/TP) being similar to that expected from other lakes (Nürnberg 1996, Welch forthcoming). In addition, crustacean zooplankton did not change from 1978 through 1988 during the period of planktivore decline. During that period, Daphnia species were abundant in Parker Horn and South Lake, averaging 27 animals/L (n = 7 yr) and 29% of total crustacean zooplankton. There were no data following 1988, so a subsequent change in zooplankton cannot be evaluated.

These results show that substantial changes in fish species composition have occurred over a period of 25 years, accompanying a change in trophic state from hypereutrophic to borderline mesotrophic. The fish population changes in WAL, SMB and LMB are consistent with the known tolerance of these species to eutrophication, while the dramatic decline in panfish was probably due to predation by the increasing abundance of WAL.

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The cooperation of David Burgess, Washington Department of Fish and Wildlife, in furnishing past fisheries reports and discussing the fishery, is greatly appreciated. Several University of Washington graduate students spent long hours traveling and in the field, collecting countless samples from 12 lake and 5 inflow stations, usually twice per month, and analyzing those samples in the laboratory. Without graduate students and funding from the EPA and the Washington Department of Ecology this work would not have been possible. The fisheries research and report preparation performed by David Burgess was funded by the Bonneville Power Administration.

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