

Moses Lake Proposed Phosphorus Criterion and Preliminary Load Allocations Based on Historical Review

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Moses Lake Proposed Phosphorus Criterion and Preliminary Load Allocations Based on Historical Review

by

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Abstract

Over the last 50 years, Moses Lake and its watershed, including groundwater, have been altered permanently by human activities, especially the use of Columbia River water for irrigation farming. During the last 30 years, at least 13 studies of Moses Lake indicate that anthropogenic activities, particularly agricultural practices, have contributed to a hypereutrophic state for the lake. It has been estimated that over 75% of the total phosphorus (TP) load to Moses Lake originates from agricultural fertilizers and farm animal wastes. As of 1989, it was reported that only 20% of the irrigated land had implemented recommended water and nutrient controls, resulting in a nutrient concentration reduction of less than 2% in the Crab Creek inflows to the lake. In addition to these agricultural impacts, climatic variation, internal loading, and adding dilution water to the lake can also have a significant influence on the water quality of Moses Lake.

To better manage water quality, a total maximum daily load (TMDL) assessment for Moses Lake and its major sources was made based on a review of data from previous studies of the lake. An in-lake TP criterion was proposed based on the water quality target established in 1978 to reduce the seasonal, in-lake TP concentration to 50 ug/L. Although this TP value exceeds the lake nutrient criterion established in Washington State water quality standards for surface water, it is recommended that 50 ug/L TP be the new criterion for Moses Lake.

Preliminary load allocations to achieve this TP concentration in the lake were recommended for the following major sources to the lake: Rocky Coulee Wasteway, Rocky Ford Creek, Crab Creek, and groundwater. Phosphorus loading from these sources was considered manageable; however, load allocations for nonpoint and point sources within each of these sources were not established in this study. This study recommends allocations be established in the future, based on the discharge characteristics of point sources and land-use classifications of nonpoint sources.

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Executive Summary

Purpose of this Report

The Washington State Department of Ecology (Ecology) recognizes Moses Lake as an important natural resource of Washington State, providing wildlife habitat, recreation, and water supply. Ecology's Eastern Regional Office (ERO) is concerned about the water quality in Moses Lake, a Class A waterbody, which is listed on the 1996 303(d) list for total nitrogen (TN) and total phosphorus (TP). Several restoration projects have been conducted on Moses Lake and its watershed over the last 20 years, including lake dilution, sewage diversion, agricultural best management practices (BMPs), and construction of a tributary nutrient retention pond. Despite improvement in lake water quality as a result of these projects, TN and TP levels remain elevated resulting in the persistence of blue-green algae blooms.

As a result, ERO requested that Ecology's Environmental Assessment (EA) Program report on the status of Moses Lake water quality and, if possible, develop a total maximum daily load (TMDL) for nutrient loading to the lake based on *historical data*. The federal Clean Water Act requires Washington State to establish a TMDL for each pollutant on the 303(d) list violating water quality criteria. The TMDL is then apportioned between point and nonpoint sources as wasteload and load allocations (WLAs and LAs), respectively. The primary goal of the ERO request was to have the EA Program develop an allocation strategy that could be used to improve lake water quality and ultimately lead to removing Moses Lake from the 303(d) list. While this report presents preliminary allocations, a major conclusion is that additional work should be completed before establishing a final TMDL and allocation strategy for the lake.

Objectives

The objectives of this study were to:

1. Review the body of work comprising the diagnostic and restoration work completed on Moses Lake from 1963-1998.
2. Identify the historical restoration projects implemented on Moses Lake and its watershed, and evaluate the current status of the restoration efforts.
3. Assess which nutrient – TN or TP – is most limiting, based on historical work.
4. Establish and recommend an in-lake nutrient criterion, based on historical data.
5. Model and estimate preliminary TP load allocations for Moses Lake to meet the in-lake nutrient criterion.
6. Recommend additional study of Moses Lake that can be used, with the historical data, to finalize allocations.

Brief History of Moses Lake

Ecology reviewed available historical documents for Moses Lake. These included University of Washington reports and master's theses from 1963 to 1989, describing the problems, causes of the problems, and a restorative work plan for Moses Lake. From this material, Ecology evaluated the current status of Moses Lake and the effectiveness of the almost 20-year-old restoration work plan.

Moses Lake is a natural lake originally created by wind-blown sand dunes, which dammed part of the Crab Creek watershed. As one of the largest lakes in Washington State, Moses Lake is an important natural resource providing recreational and aesthetic opportunities. The primary water quality problem identified in the historical studies of Moses Lake is the hypereutrophic blooms of blue-green algae, which can impair the recreational uses for the lake during the summer months.

Excessive nutrient enrichment has accelerated the growth of algae in Moses Lake, resulting in the predominance of blue-green forms of algae. Blue-green algae blooms form into unsightly floating mats, and are blown onto the beach where they decompose and cause odor problems. Localized fish kills are associated with periods of large algal blooms, and toxicity problems exist for some animals that drink the water. Several beaches have been closed to swimming at times, due to unsafe visibility in the water.

As a large, shallow hypereutrophic lake, Moses Lake has garnered the attention of limnologists and engineers in the last 30 years as a potential model for lake restoration. This attention has resulted in many studies that meet the requirements for site-specific diagnostic/feasibility lake studies Phase I and Phase II Federal Clean Lake Projects.

Moses Lake and its watershed have been permanently altered since the inception of the Columbia Basin Irrigation Project (CBIP) in the early 1950s, when the U.S. Bureau of Reclamation (USBR) began importing Columbia River water into the upper Crab Creek watershed to promote the development of irrigated cropland. The Phase I studies indicate that anthropogenic activities, primarily agricultural practices and operations associated with the CBIP, were creating a hypereutrophic state in Moses Lake through nutrient enrichment.

Although Moses Lake is listed for both TP and TN on the 303(d) list, the historical studies on Moses Lake have shown that TP is the nutrient to control to limit algal biomass. This strategy of managing TP to control the algal growth rate is supported in literature, even for lakes where nitrogen may be limiting growth. On this basis, Ecology recommends that Moses Lake be de-listed for TN from the 303(d) list and that future lake management activities and decisions focus on the control of TP to manage algal biomass in Moses Lake.

Review of Historical Lake Management and Restoration Measures

Several major restoration measures have been applied to Moses Lake to address the hypereutrophic state. These include dilution of Parker Horn and Pelican Horn, diversion of the sewage effluent from Pelican Horn, agricultural BMPs in the Crab Creek watershed, and a nutrient detention pond on Rocky Ford Creek. Nearly \$3.5 million was spent implementing the various controls. The water quality in Moses Lake has improved since applying the various restoration measures. Particularly, dilution and sewage diversion have been shown to be successful at improving water quality.

Dilution waters from the CBIP have been purposely used to improve water quality in Moses Lake since 1977, and diversion of effluent took place in 1984. By 1988 Moses Lake had exhibited over a 70% decrease in TP and chlorophyll *a*, compared to the earlier baseline years of 1969-70. Compared to other baseline years such as 1963-64, the percent overall reduction was less but still represents a successful shift from a hypereutrophic state to a eutrophic state in most years.

While dilution has been established as part of the permanent restoration plan for Moses Lake, operationally it has been difficult to obtain the needed amount of dilution flows at the desired times. The historical studies suggest an optimum dilution input of 80,000 acre feet distributed throughout the summer or about 16,000 acre feet per month, May through September. In 1980 the USBR had agreed to provide a minimum flow of approximately 15,000 acre feet per month, April through August, for about a 15-year period. A review of the dilution flow through Moses Lake in the past 22 years indicated that inadequate dilution took place during most of the summers.

The amount of water released from the East Low Canal to Moses Lake is controlled by the USBR. They release water based on the supply and demand at Potholes Reservoir, which receives irrigation return flows and natural runoff (also running through Moses Lake) and is supplemented, as needed, from the East Low Canal. Dilution water may only be able to be delivered to Moses Lake when there is enough storage space in Potholes Reservoir to accommodate the releases. During years with high, late-winter, early-spring runoff (such as in the 1990s), inadequate dilution may have contributed to years with blue-green algae blooms in the lake.

As expected, sewage diversion afforded dramatic results with sharply declining TP levels in Pelican Horn. While studies in the late 1980s showed reduced TP concentrations in Crab Creek as a result of BMPs, later studies in the 1990s showed increased TP concentrations, though these studies employed a different study design from the earlier studies. As currently designed and maintained, the detention pond on Rocky Ford Creek does not appear to be an effective restorative measure.

Further improvement from all of these restorations have been, and will be, mediated by the highly variable internal TP loading that takes place within Moses Lake. Historical studies reveal that the growing season internal TP loading has nearly a 100% variation around the mean, with the internal TP load sometimes exceeding the external TP load during the growing season of some years. This highly variable load may only be controllable in the long-term, without expensive internal controls such as alum applications, with a long-term reduction in external TP loads.

Developing In-lake Nutrient Criterion

To control blooms of blue-green algae caused by the hypereutrophic conditions in the lake, it is necessary to establish nutrient criteria for Moses Lake and allocate loads to specific sources. The proposed nutrient TMDL assessment presented in this report is designed to address impairments to the characteristic uses of Moses Lake, caused by excessive phosphorus loading and the resulting hypereutrophication and algal blooms. The protection of characteristic uses by the adoption of water quality standards and criteria lies under the authority of Ecology.

In this report both EPA and Washington State guidelines were evaluated to develop a site-specific nutrient criterion which would protect the characteristic uses of Moses Lake. Several earlier studies, particularly those under the direction of Eugene Welch of the University of Washington, have been conducted along the guidelines to develop site-specific nutrient criteria for Moses Lake. These studies have drawn a link between TP concentration and an endpoint indicator, chlorophyll *a* concentration. They found that a maximum concentration of 50 ug/L TP would limit chlorophyll *a* concentrations to an endpoint target of 20 ug/L during the growing season (May- September) in Parker Horn. Accordingly, the endpoint target of 20 ug/L chlorophyll *a* maximum concentration would significantly reduce the likelihood of hypereutrophic conditions (i.e., blue-green algae blooms) in Moses Lake.

Ecology proposes adopting 50 ug/L TP as the in-lake nutrient criterion to develop a nutrient TMDL for Moses Lake. In this report, Ecology provides a preliminary load allocations, though again, a major recommendation is that additional work should be completed before establishing a final nutrient TMDL and allocation strategy for the lake.

To establish preliminary load allocations in this report, Ecology calculated the mean and 90th percentile annual loads to Moses Lake. Using these loads and historical data, Ecology developed the steady-state solution to the mass balance equation to calculate the steady state in-lake TP concentration. Ecology allocated the manageable loads to achieve the proposed nutrient criterion, based on different dilution and loading scenarios.

Based on this preliminary load allocation assessment, Ecology recommended that with no dilution and a 90th percentile annual load, an across-the-board TP load reduction of 50% from all manageable sources would be necessary to meet the in-lake nutrient criterion and protect the characteristic uses of Moses Lake. With adequate dilution, a 30% external load reduction would be necessary to meet the in-lake nutrient criterion.

Inadequacies of the Historical Work

In addition to publishing this report summarizing the historical studies of the lake, Ecology is proposing to conduct a study to assess the current status of nutrient loading to the lake and nutrient concentrations in the lake. Ecology is planning to conduct this study during water year 2001 (October 1, 2000 to September 30, 2001). The major reasons for conducting this study are:

- No comprehensive water quality assessment of the lake has been done since the mid-1980s; multiple sources of data were used to develop the historical work, now 20 years old.
- Water quality data are needed to assign nutrient load allocations to the major nutrient sources. The historical work rarely addressed all the incoming loads at once and did not model the lake in a way to set a maximum incoming load of TP to achieve the 50 ug/L criterion.
- New water quality data, together with findings and recommendations from the historical studies, are needed to set nutrient TMDLs for the lake.
- A TP TMDL for Moses Lake is needed to satisfy the requirements of the federal Clean Water Act and to help meet the water quality goals established for the lake by the previous studies.

Conclusions and Recommendations

1. Although Moses Lake is listed for both TP and TN on the 303(d) list, the historical studies on Moses Lake have shown that TP is the nutrient to control to limit algal biomass. This strategy of managing TP to control the algal growth rate is supported in literature, even for lakes where nitrogen may be limiting growth. On this basis, Ecology recommends that Moses Lake be de-listed for TN from the 303(d) list and that future lake management decisions focus on the control of TP to manage algal biomass in Moses Lake.
2. Ecology proposes adopting the in-lake TP criterion of 50 ug/L to develop a nutrient TMDL for Moses Lake. Based on available knowledge, this nutrient criterion seems to protect the characteristic lake uses, has a basis in the historical lake restoration efforts as an achievable target, and probably best reflects the historical development of Moses Lake.
3. The dendritic nature of Moses Lake has allowed investigators to view the lake in a more complex manner, segmenting the different basins and arms for modeling purposes. Lake responses to loading changes and other restoration measures may vary in different parts of Moses Lake, suggesting the importance of regarding localized effects when evaluating management decisions. A dynamic computer model for Moses Lake should be developed to look at the seasonal and spatial effects of loading changes throughout the entire lake.
4. It is recommended to develop and maintain a sampling survey strategy to allow for a current annual assessment of nutrient loading to Moses Lake, including whole-lake nutrient concentrations. This will permit an evaluation of current restoration measures and their effects, as well as supplement historical work, in establishing TP load allocations for the major nutrient sources.

5. A binding agreement should be made with the USBR to provide regular dilution (water additions) on an annual basis, especially during critical conditions (May-September), so that dilution will be a reliable restoration technique used in the management of Moses Lake. It is also recommended to study the possibility of using dilution, even during high-flow years for Crab Creek and Rocky Ford Creek.
6. Dilution can constitute a restorative management technique and be helpful in achieving water quality goals. However, to achieve these goals, particularly with a margin of safety, external loads will need to be reduced. A total external load reduction of 30% of manageable sources will most likely ensure protection of water quality in Moses Lake. It is predicted that a load reduction of this order will result in a less than a 10% exceedance of the in-lake phosphorus criterion. A 30% load reduction should result in much better water quality during normal years, particularly if dilution water is available as well.
7. It is estimated that over 75% of the TP load to Moses Lake originates from agricultural fertilizers and farm animal wastes. As of 1989, it was reported that only 20% of irrigated areas had implemented water and nutrient controls, amounting to a potential nutrient concentration reduction of less than 2% in the Crab Creek inflows to Moses Lake. It is important to mitigate these agricultural sources to Moses Lake, as this is the key to reducing external phosphorus loads. The Moses Lake Clean Lake Project initiated irrigation and fertilizer controls concentrated in the Crab Creek watershed, but the study project concluded in 1990. Existing BMPs should continue to be monitored, and more extensive BMPs should be applied, within the Moses Lake watershed.
8. Rocky Ford Creek is generally driven by groundwater, either fed by springs or groundwater entering its channel enroute to Moses Lake. The average TP concentration of the spring source of this tributary is significantly elevated above the average TP concentration of groundwater elsewhere around Moses Lake (e.g., 98 ug/L versus 51 ug/L, respectively). An earlier study indicated that perhaps a direct conduit exists between Rocky Ford Creek's source springs and Brook and Round lakes, which serve as nutrient sinks in the Crab Creek drainage (Bain, 1985). Other agricultural blocks lying near Soap Lake were also indicated as a probable source of phosphorus. As the major source of TP during a normal year (37%), and given the unusual and yet consistent elevated TP levels, groundwater sources of TP for Rocky Ford Creek should be studied more fully to mitigate them. If controls can be designed for the groundwater TP sources, then TP limits for the fish hatcheries should also be established.
9. Crab Creek experiences variable flows. Large flow events can occur in late winter from run-off of melted snowfall and rain. These flow events carry large TP loads to Moses Lake, essentially flushing the Crab Creek drainage of nutrients. The necessary BMPs to help curb this late-winter flushing should be studied and implemented.
10. Ecology recommends that daily flow monitoring on Rocky Ford Creek be reinstated by the U.S. Geological Survey. Also, it is recommended to establish a discharge relationship for the mouth of Rocky Ford Creek and the gaging station.

Introduction

Problem Statement

The Washington State Department of Ecology (Ecology) Eastern Regional Office (ERO) is concerned about the water quality in Moses Lake, a Class A waterbody, which is listed on the 1996 303(d) list for total nitrogen (TN) and total phosphorus (TP). In the past 30 years, more than 15 studies investigating Moses Lake indicate that several anthropogenic activities – including agricultural practices and operations, on-site and municipal sewage treatment effluent, and fish hatcheries – have contributed to a hypereutrophic state for the lake. Several restoration projects have been conducted on Moses Lake and its watershed over the last 20 years, including lake dilution, sewage diversion, agricultural best management practices (BMPs), and construction of a tributary nutrient retention pond.

Despite some improvement in lake water quality during some years as a result of these projects, TN and TP levels remain elevated and algae blooms persist. As a result, ERO requested that Ecology's Environmental Assessment (EA) Program report on the status of Moses Lake water quality and, based on historical data, develop a total maximum daily load (TMDL) for nutrient loading to the lake. The underlying goal of the ERO request is to have the EA Program develop an allocation strategy that can be used to improve lake water quality and ultimately lead to removing Moses Lake from the 303(d) list. The status of Moses Lake water quality was determined through a review of available data from studies on the lake and its watershed. A 1998 EA Program study of Rocky Ford Creek was also included in the review.

The Total Maximum Daily Load (TMDL) Process

Section 303(d) of the Federal Clean Water Act requires states to implement water quality-based pollution controls on waterbody segments where technology-based controls are insufficient to achieve water quality standards. To meet this requirement, a TMDL must be established for each pollutant violating water quality criteria. The TMDL is then apportioned between point and nonpoint sources as wasteload and load allocations (WLAs and LAs), respectively. A margin of safety is also apportioned into the TMDL to account for uncertainty related to critical conditions, causes of the water quality problem, and loading capacity for the waterbody. Allocations are implemented through National Pollutant Discharge Elimination System (NPDES) permits and nonpoint source controls. The goal of the TMDL is to bring waterbodies into compliance with water quality standards.

Objectives

The objectives of this study were to:

1. Review the body of work comprising the diagnostic and restoration work completed on Moses Lake from 1963-1998.
2. Identify the historical restoration projects implemented on Moses Lake and its watershed, and evaluate the current status of the restoration efforts.
3. Assess which nutrient – TN or TP – is most limiting, based on historical work.
4. Establish and recommend an in-lake nutrient criterion, based on historical data.
5. Model and estimate preliminary TP load allocations for Moses Lake to meet the in-lake nutrient criterion.
6. Recommend additional study of Moses Lake that can be used, with the historical data, to finalize allocations.

Background Information

An important natural resource of Washington State, Moses Lake is located in central Washington within Water Resource Inventory Area (WRIA) #41. Figure 1 is a map of the study area. The climate is semi-arid with four distinct seasons. The hot, dry summer can have air temperatures exceeding 100°F, and the moderately cold winter can have air temperatures reaching below 0°F. The annual rainfall ranges from 6-18 inches, and the average annual evaporation value for the lake is high at nearly 60 inches. The surrounding uplands and scablands of Moses Lake are subject to high wind speeds generally blowing from the south, opposite the flow direction of water within Moses Lake.

Moses Lake was originally created by wind-blown sand dunes, which dammed part of the Crab Creek watershed. The lake had no surface outlet until 1904 when floods created one, lowering the lake over eight feet. Two dams now maintain an original water level elevation of 1,046 feet during the summer recreation season, and a lower winter water level to protect and accommodate maintenance of shoreline docks, bulkheads, and other structures during the winter months. The Moses Lake Irrigation District constructed the first dam in 1929, and the U.S. Bureau of Reclamation (USBR) constructed the second dam in 1963.

Moses Lake consists of 6,800 acres (2,750 ha), has a mean depth of 18.5 feet (5.6 m), and a hydraulic retention time of 1-2 years when it is not being diluted (see below). Moses Lake is 20.5 miles (33 km) in length from the north end to the eastern end of Pelican Horn (Sylvester and Oglesby, 1964). Figure 2 shows the bathymetry of Moses Lake. Overall, Moses Lake can be considered to be a shallow, warm, polymictic lake (subject to frequent or continuous circulation),

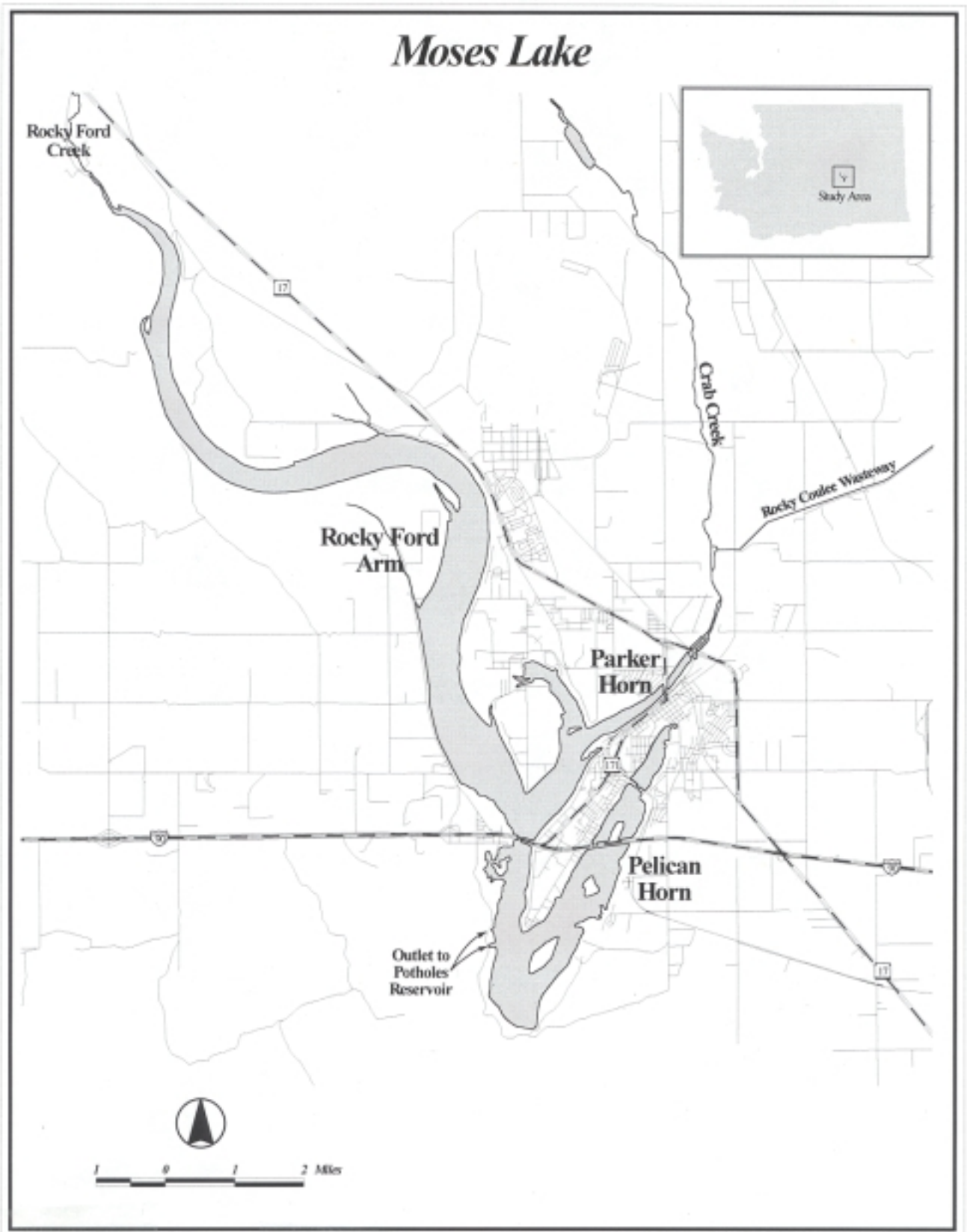


Figure 1. Moses Lake Study Area Map.

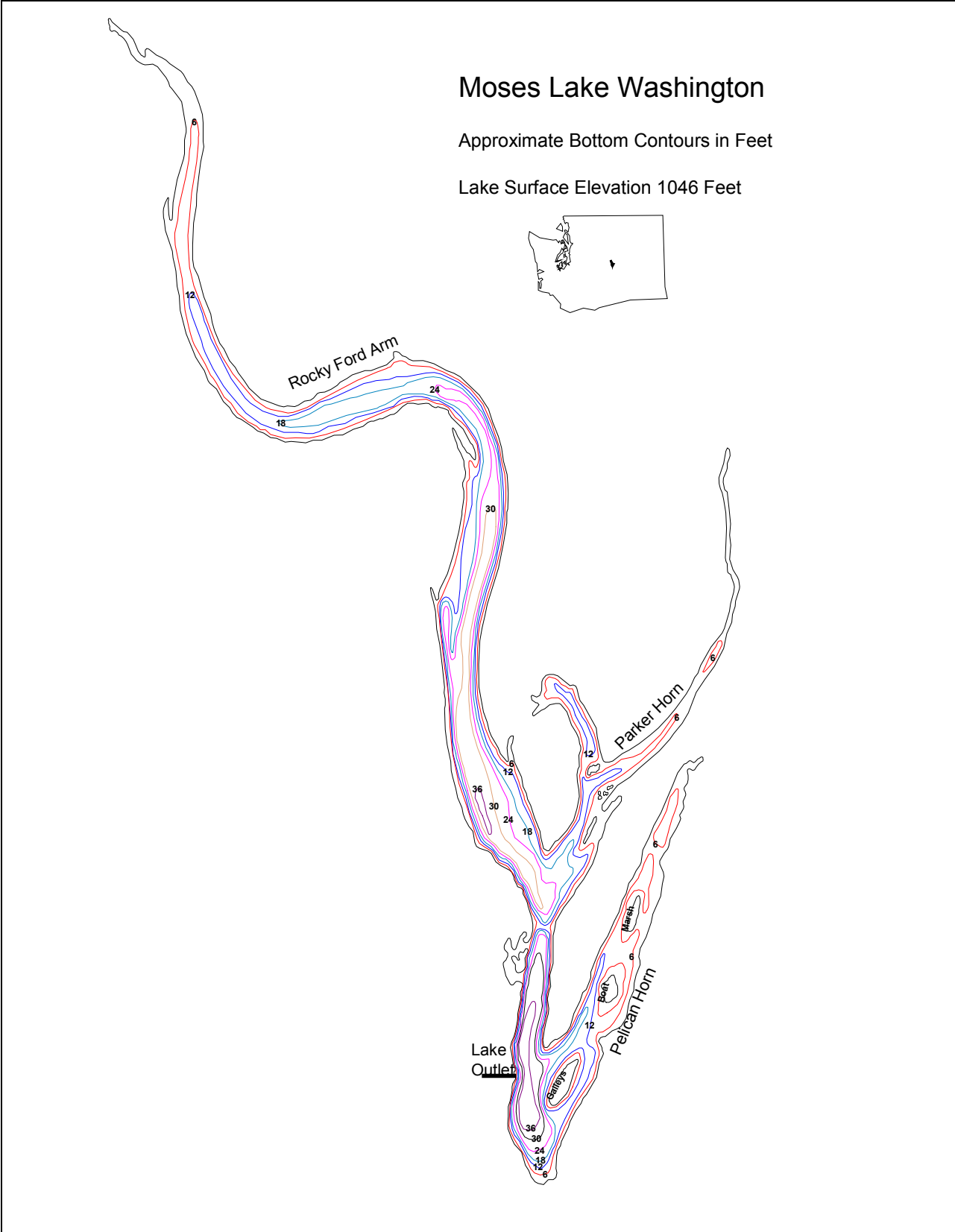


Figure 2. Moses Lake bathymetric map.

because about 80% of the lake is relatively shallow and subject to complete mixing during windy conditions (Welch, et al., 1989).

The Moses Lake watershed contains 2,033 mi² (5,265 km²). The geology of the watershed consists of an unconsolidated glacial sand and gravel mantle over an underlying basalt bedrock of volcanic origin. High hydraulic conductivities of groundwater have been associated with the sand and gravel mantle. The watershed contains both Ephrata and Malaga soils. These soils formed in the gravelly glacial outwash materials transported by catastrophic glacial floods. The surface layer is mixed with fine-grain, wind-deposited loess forming an extremely gravelly-sandy soil with little water holding capability (Bain, 1985).

Since the inception of the Columbia Basin Irrigation Project (CBIP), Moses Lake and its watershed have been altered permanently, influenced by the agricultural practices and cycles within its watershed. In the early 1950s, the USBR began importing Columbia River water into the upper Crab Creek watershed from Franklin D Roosevelt Lake, to promote the development of irrigated cropland under the CBIP. As a result, many additional lakes, ponds, and reservoirs were created in the watershed. Groundwater levels in the watershed were also impacted. In some areas, the groundwater levels rose over 150 feet (USGS, 1995). Further, the total volume of water entering Moses Lake through Crab Creek, Rocky Ford Creek, groundwater, and Rocky Coulee Wasteway (part of the irrigation return flow system) increased significantly.

Dilution waters from the CBIP have been used to improve water quality in Moses Lake since 1977. Moses Lake lies in the center of the CBIP and is an integral part of the system that feeds water from the Columbia River into Potholes Reservoir. Potholes Reservoir acts as a storage and feed system for the lower CBIP. One of the major feed routes to Potholes Reservoir is via the East Low Canal which can discharge to Crab Creek via Rocky Coulee Wasteway, enter Parker Horn, and then exit Moses Lake to Potholes Reservoir.

The amount of water released from the East Low Canal to Moses Lake is controlled by the USBR. They release water based on the supply and demand at Potholes Reservoir, which receives irrigation return flows and natural runoff (also running through Moses Lake) and is supplemented, only as needed, from the East Low Canal. Therefore, dilution water may only be delivered to Moses Lake when there is enough storage space in Potholes Reservoir to accommodate the releases.

The Moses Lake watershed is mostly dedicated to agricultural use divided among dry cropland, rangeland, and irrigated cropland. Wheat and other small grains are the most common crops on the nearly 800,000 acres of dry cropland. The approximately 630,000 acres of native and revegetated rangeland in the watershed are primarily located on channeled scablands. Dry cropland and rangeland are the most common agricultural activities in the upper part of the watershed. The dry cropland yield and the amount of forage on the rangeland are dependent on precipitation, primarily as snow during the winter.

Irrigation water for the over 130,000 acres of irrigated cropland is obtained from either groundwater or surface water sources, which are primarily recharged by the imported CBIP water. A large portion of the surface water irrigated cropland in the watershed is located on over 28,000 acres along Crab Creek near Moses Lake. The irrigation season lasts about seven months each year from April to October. Although there are many types of crops raised on the irrigated cropland, the most common ones are wheat, alfalfa, and corn.

Over 27,000 people live around the lake, with most concentrated in an urban area along the southeast shoreline which includes the city of Moses Lake. The city was incorporated in 1938 and had a population of less than 1,000 until the 1950s when Lawson Air Force Base was established and the CBIP was developing. Population swings followed the closure of the base in 1966, but growth has increased moderately of late. Half of the extended, urban population is served by on-site septic systems or the Lawson WWTP; the other half is served by the city of Moses Lake WWTP (Bain, 1998). The Moses Lake WWTP discharged to Moses Lake (Pelican Horn) until 1984, when it began discharging to a sand infiltration area southeast of Moses Lake.

Moses Lake is used extensively for recreational purposes. Two marinas and several public launch facilities serve resident and visiting boaters. Water skiing is popular and a ski tournament is a usual annual event. Swimming is popular during the summer at four public swimming beaches. Moses Lake has long been recognized and valued as an aesthetic resource. Many homes and local businesses have been designed to take advantage of lake views and waterfront. Many private homes have docks, bulkheads, and other shoreline structures constructed for swimming, fishing, and boat moorage.

Moses Lake is one of the preferred fishing waters in central Washington, attracting anglers year-round from around the region; fishing has contributed considerably to the local economy. At times, a commercial carp fishery has occurred on the lake, but primarily Moses Lake has been famous and important for its warm water fishery (i.e., walleye, large-mouth bass, crappie, yellow perch, and blue gill). Catches have declined in recent years, probably due to over-fishing, but there has been a recent resurgence of favorable catches (particularly walleye and bass) and a club bass tournament was held again this past year, the first in several years. While Moses Lake has historically been a productive lake supporting a strong warm water fishery, the state Department of Fish & Wildlife have regularly planted and maintained a relatively successful rainbow trout fishery. Currently, there are permitted net pens installed in Moses Lake for annual rearing and release of rainbow trout.

The primary water quality problem in Moses Lake is blooms of blue-green algae, which impair the recreational uses for the lake several times each summer. On warm days, the algae floats, forms into unsightly mats, and may end up being blown onto the beach where it decomposes and causes odor problems. Large algal blooms are associated with localized fish kills and toxicity problems for some animals that drink the water. Several beaches have been closed to swimming due to unsafe visibility in the water. In addition to the algal blooms, macrophytes are becoming a problem on some of the lake shoreline areas, perhaps due to increasing water clarity.

Review of 13 Moses Lake Studies

As one of the largest lakes in Washington State, Moses Lake is an important natural resource providing recreational and aesthetic opportunities to many. A number of limnological studies of Moses Lake have been conducted over the last three decades, investigating the algae blooms which impair the use of Moses Lake. As a large, shallow, hypereutrophic lake, Moses Lake has garnered the attention of limnologists and engineers as a potential model for lake restoration. A review of the major studies conducted on Moses Lake was completed to establish the past and current conditions of Moses Lake, and to develop an historical database of nutrient loading to the lake. The following is a chronological listing and brief summary of the studies reviewed.

1. The Moses Lake Water Environment (Sylvester and Oglesby, 1964)

In 1963 the Moses Lake Irrigation and Rehabilitation District (MLIRD) funded an engineering and ecological study of Moses Lake by the University of Washington. This study, which focused on lake restoration, was the first diagnostic survey of the lake. The study found that the lake's eutrophic state was the result of the excessive loads of nitrogen and phosphorus entering the lake from its source waters and from the city of Moses Lake WWTP effluent. An average, annual in-lake TP concentration of 59 ug/L was observed. Phosphorus concentrations were so excessive that the investigators hypothesized Moses Lake was nitrogen limited. Complete annual water and nutrient budgets were calculated and presented, although internal loading of phosphorus from the sediments was not included in the phosphorus budget.

Recommendations included conducting a feasibility study on rehabilitation measures such as filling or deepening shallow areas, controlling carp, and flushing of Parker Horn and Pelican Horn with Columbia River water. Flushing was the only nutrient and algal control recommended at the time. The removal of discharge from the WWTP was not recommended as an alternative, because it was expensive and did not seem effective for algal control because of the apparent nitrogen limitation in the lake (i.e., the wastewater discharge did not contribute much N). Continued sampling and monitoring was recommended.

2. Alternatives for Eutrophication Control In Moses Lake, Washington (Welch et al., 1973)

This study on eutrophication control alternatives for Moses Lake focused on identifying and quantifying the external load sources of phosphorus and nitrogen to the lake. The investigators concluded that half of the load of nitrogen and phosphorus entering the lake was from agricultural fertilizers. The study also concluded that domestic animal waste contributed about one quarter of the nitrogen and phosphorus, and the Moses Lake WWTP effluent contributed about 20% of the phosphorus and 7% of the nitrogen to the lake. It was determined that the Rocky Ford Creek fish hatchery, the Crab Creek fish hatchery, and the Crab Creek livestock auction yard were minor nutrient sources to the lake. Comparing loading estimates to the earlier Sylvester and Oglesby (1964) loading estimates, this study found that phosphorus loading to the lake had more than doubled during the 1960s.

Though nitrate levels were nearly exhausted during the growing season, reduction of phosphorus was considered the best long-term growth limiter. Average annual, in-lake, TP concentrations of 128 ug/L and 167 ug/L were observed for 1968-69 and 1969-70 water years, respectively. Sediment cores indicated low and consistent nutrient content throughout the sediments, eliminating the potential for in-lake sediment release controls (e.g., dredging, alum application).

In this study, the investigators viewed Moses Lake as a multi-basin, segmented lake and noted that lake restoration improvements could be evaluated and implemented on a sub-basin basis. For example, unlike that of Sylvester and Oglesby (1964), this report found there would be value to removing the WWTP effluent from Pelican Horn because of the significant water quality improvements to Pelican Horn, though there might be little improvement to the rest of the lake. The sub-basin approach to managing lake water quality was viewed as a more innovative and effective method.

The report indicated that it was an impossible task to bring Moses Lake into a mesotrophic state because of the morphology of the lake and the extent of existing nutrient loads. The investigators noted that an order of magnitude reduction in nutrient loading would be required to reduce nutrient levels below eutrophic levels. However, they also noted that the hypereutrophic conditions of the lake might be managed to reduce the algae blooms. One proposed method was to use Columbia River water to dilute the inflows to the lake, but it was understood that the use of dilution water would not reduce the amount of nutrients entering Moses Lake from its watershed. A long-range management goal recommendation was to reduce the inflow of nutrients from the Moses Lake watershed through improved erosion control, fertilizer application management, and overall phosphorus reduction in Crab Creek.

3. Moses Lake 1977 Pilot Project (Brown and Caldwell, 1978)

In 1976 the MLIRD initiated the Moses Lake Rehabilitation Project to restore and maintain a desirable water quality level in Moses Lake. In 1977 the MLIRD received initial funding from state and federal sources to begin a full-scale pilot project to dilute Parker Horn with Columbia River irrigation water. The pilot project design was based on the 15 years of investigation by the University of Washington, which identified dilution as an optimum method to improve water quality in Moses Lake. Particularly, the results from bag experiments conducted in situ in 1970 to determine the effect of adding dilution water were influential in developing the dilution project (Welch et al., 1972).

The ultimate goal of the rehabilitation project was to provide high-quality Columbia River dilution waters to all of Moses Lake (via Rocky Ford Arm, Pelican Horn, and Parker Horn). The pilot project examined the effects of three experimental dilution releases to only Parker Horn during the summer of 1977. A monitoring effort was conducted to observe previous lake conditions as well as in situ and post-dilution lake responses. In-lake water quality goals were established for the study: TP 50 ug/L, chlorophyll *a* 20 ug/L, and a Secchi disc (SD) transparency depth of 1.2 meters. Results showed dramatic decreases in chlorophyll *a* and

moderate increases in SD transparency with each dilution release (more or less achieving water quality goals), without a proportional and predicted decrease in TP. Internal sources via resuspension of sediments by wind and carp feeding were cited as suspected contributors of additional phosphorus.

Overall, the model-dilution study was considered successful in showing that dilution was a good restoration technique to improve and maintain the water quality of Moses Lake. A recommendation to dilute Moses Lake throughout the March-September irrigation season was made.

As part of the Moses Lake 1977 Pilot Project, a feasibility study of alternatives to provide dilution water to each of the three arms of Moses Lake was conducted. The study recommended the following:

- Continue to dilute Parker Horn via Rocky Coulee Wasteway.
- Pump water from Parker Horn to Pelican Horn with a new pump and transmission line.
- Continue to investigate a cooperative dilution feed route to Rocky Ford Arm.

The implementation plan included negotiating with the USBR for dependable delivery of dilution waters, applying for financial assistance to construct the Pelican Horn pump station, and conducting an Environmental Impact Statement for the Pelican Horn project.

4. Draft Environmental Impact Statement, Moses Lake Restoration Project (Brown and Caldwell, 1980)

This report summarized the impacts of the proposed dilution restoration alternatives identified in the previous 1977 pilot study. The stated objectives of the dilution restoration project were to improve water color and clarity in several parts of the lake and prompt substantial reduction in blue-green algae growth, understanding that the algae would not be completely eliminated and Moses Lake would remain eutrophic. It was also pointed out that the supply of Columbia River irrigation waters would be sporadic or unavailable at times during which algae blooms would return.

Introducing Columbia River water to Moses Lake was originally proposed in the 1960s as *flushing*. Downstream irrigation users viewed this proposal as *flushing* of contaminated water into their irrigation water supply. This perception, based on semantics and the resulting opposition, halted earlier development of a dilution restoration method. The environmental impact statement (EIS) concluded that irrigation waters going through Moses Lake would have no effect on downstream irrigation use. In fact, findings showed that the Moses Lake discharge, following dilution, would most likely improve water quality to the Potholes Reservoir because inflow nutrient concentrations would be lowered.

5. Phytoplankton and Nutrient Responses to Dilution In Moses Lake (Patmont, 1980)

This master's thesis completed at the University of Washington Department of Civil Engineering was conducted in conjunction with the Moses Lake 1977 Pilot Project (Brown and Caldwell, 1978), but the author continued the data collection for the 1978-79 season with funding from EPA. Complete water and nutrient budgets were constructed, and estimates of internal loading were calculated and presented for both years.

Dilution waters were found to mix into nearly all of Moses Lake as the result of wind-induced circulation. Phytoplankton biomass was reduced following dilution without an expected proportional decrease in TP, suggesting an N-limiting effect of the added dilution water. This was confirmed later by Welch et al. (1984). Blue-green algae were found to have declined from a position of exclusive dominance in the summer plankton (96% by volume) to a position of co-dominance with diatoms (55% blue-greens by volume).

6. Moses Lake Dilution Project, Summary Report (Brown and Caldwell, 1984)

This report summarized the results of the dilution projects begun in 1976 as part of the Moses Lake Rehabilitation Project. The authors reported that chlorophyll *a* averages were 60% lower, and the SD transparency nearly doubled over the six years of dilution releases compared to the pre-dilution years of 1969-70. **Despite these impressive improvements, intense algal blooms continued to occur during August and September, with maximum chlorophyll *a* in excess of 60 ug/L and SD transparency less than 1 meter. The blooms occurred in the months following the cessation of dilution flow, which occurred in July of most years.** Lack of irrigation demands and storage space in Potholes Reservoir made the supply of dilution water to Moses Lake from the USBR undependable during the late summer.

Grant funds to facilitate the dilution projects outlined in the draft EIS were provided by the Ecology and EPA to the MLIRD. In 1982 a pumping plant was built to transfer water from Parker Horn to Pelican Horn at a cost of approximately \$875,000. However, an additional dilution project for the Rocky Ford Arm of the lake was determined to be unfeasible. Therefore, grant funds originally allocated for this project were used instead to assist in removing the city of Moses Lake WWTP effluent from Pelican Horn and to fund nutrient control evaluations and techniques in the watershed. The Moses Lake WWTP effluent was diverted from Pelican Horn to a land infiltration site southeast of Moses Lake in 1984.

7. Moses Lake Clean Lake Project, Summary Report Stage I, March 1984 (Forster, 1984)

Although the dilution restoration project was successful in improving water quality in Moses Lake, it was understood that the benefits did not mitigate the pollution sources within the watershed. The Moses Lake Clean Lake Project was initiated in July 1982 to develop solutions for the long-term control, maintenance, and restoration of water resources within the Moses Lake drainage basin. A grant agreement was signed between EPA, Ecology, and the MLIRD. The MLIRD also entered into an agreement with the Moses Lake Conservation District to identify

nutrient sources and to develop potential water pollution control practices on agricultural lands in the Moses Lake watershed.

The Moses Lake Clean Lake Project was conducted in three stages:

- Stage I included additional work to identify and monitor the lake's nutrient sources with emphasis on agricultural land use practices.
- Stage II included an evaluation of potential lake and watershed nutrient control alternatives (i.e., BMPs).
- Stage III focused on the implementation of nutrient control alternatives and monitoring improvements to the lake water quality.

Stage I monitoring results indicated that farmers were generally over-irrigating their crops and causing nitrogen and other nutrients to percolate into the ground and surface waters flowing into Moses Lake. Over a third of the contribution to the deep percolation of nitrogen was estimated to be from furrow irrigation practices though only one-fifth of the farms irrigated this way. The results also showed that the TN losses from the nearly 28,000 acres of irrigated cropland located along Crab Creek near Moses Lake were from 23.6 to 26.2 pounds per acre. Irrigated cropland was found to account for about half of the nitrogen loading to the lake. The water quality monitoring results also showed that Rocky Ford Creek and effluent from the Moses Lake WWTP were the lake's major surface water sources of phosphorus. Agricultural activities in the Brooks Lake-Adrian area of upper Crab Creek were identified as the probable source of high phosphorus levels in the springs feeding Rocky Ford Creek.

8. Moses Lake Clean Lake Project, Stage II Report, March 1985 (Bain, 1985)

Stage II of the Moses Lake Clean Lake Project focused on the feasibility of several lake and watershed nutrient control alternatives. Recommended watershed nutrient control alternatives focused on: irrigation water and fertilizer management practices, sediment detention ponds, carp eradication (Rocky Ford Creek), runoff controls at livestock feeding operations, stream protection from livestock damage, a septic tank control program for homes along the lake, and post project monitoring.

9. Moses Lake Clean Lake Project, Irrigation Water Management, Final Report (Bain, 1990)

Stage III of the Moses Lake Clean Lake Project was to implement the nutrient control alternatives and monitor the lake and watershed for water quality improvements. The costs of implementing the nutrient control alternatives were shared among participating farms, local government, USBR, EPA, and the Agricultural Stabilization and Conservation Service.

In 1987 the Moses Lake Clean Lake Project entered an operational phase entitled Irrigation Water Management, a three-year management program. The dominant on-farm improvements involved a special cost-share program designed to improve irrigation systems and irrigation

management. By 1989 34 farms representing 7,357 acres were using the irrigation water management system. Activities included upgraded irrigation systems, soil moisture testing, split fertilizer applications, irrigation system performance evaluations, irrigation scheduling, and evaluations of water and fertilizer savings and crop yield assessments.

Other projects were carried out during this phase of the project. An aquatic weed harvester was purchased and operated beginning in 1985. Increased water clarity had permitted macrophytes to establish in Parker Horn, whereas earlier hypereutrophy (i.e., before dilution) had prevented macrophytes due to light limitation. In early 1987 a detention pond was constructed on Rocky Ford Creek at the mouth of Moses Lake. The detention pond was designed to trap nutrients associated with suspended sediments entering the pond. A secondary benefit of the detention pond structure was to prevent carp from migrating into the creek from Moses Lake. Later in 1988 the state Department of Wildlife eradicated carp in Rocky Ford Creek, resulting in extensive aquatic plant growth in the creek during 1989. Public information programs were developed and a weather station and lake temperature recorder were installed on the lake. In addition, the University of Washington completed an in-lake monitoring study evaluating lake dilution, sewage diversion and nutrient controls.

10. Moses Lake Quality: Results of Dilution, Sewage Diversion, and BMPs – 1977-1988 (Welch et al., 1989)

During 1986-88 Moses Lake was re-evaluated by the University of Washington Department of Civil Engineering to determine the effect of implemented nutrient controls and restoration efforts on lake water quality. The study indicated that the lake was no longer hypereutrophic as it was in the late 1960s, although the lake was still considered eutrophic. Figure 3 presents the mean May-September TP from transect samples in three sections of Moses Lake. Average TP and chlorophyll *a* levels had decreased nearly 70%, with overall means of 45 ug/L TP and 17 ug/L chlorophyll *a* in Lower Parker Horn and South Lake in 1986-88, compared to 154 ug/L TP and 57 ug/L chlorophyll *a* in 1969-70. The average SD transparency increased about 200% when compared to monitoring conducted before the nutrient control alternatives were implemented, from 0.8 meters in 1969-70 to 1.6 meters in 1986-88.

Middle Pelican Horn experienced dramatic declines in TP following wastewater diversion, with a mean of 77 ug/L of TP in 1986-88 compared to 920 ug/L TP in 1969-70. Chlorophyll *a* levels also improved (i.e., 11 ug/L in 1988 compared to 48 ug/L in 1969-70). However, a hypereutrophic state still existed in Pelican Horn (indicated by the 77 ug/L of TP and a low SD transparency of 0.8 meters), which the investigators hypothesized was due to non-algal turbidity from its shallowness, large carp population, and wind-induced mixing. Further improvements in water quality to Pelican Horn were deemed unlikely.

The study also concluded that Moses Lake had shifted from being nitrogen-limited to phosphorus-limited, demonstrating the long-term benefit of phosphorus reduction in spite of the severe nitrogen limitation of growth during the hypereutrophic state. As a result, dilution was having a less (but still favorable) effect in controlling algal growth, because of the less favorable

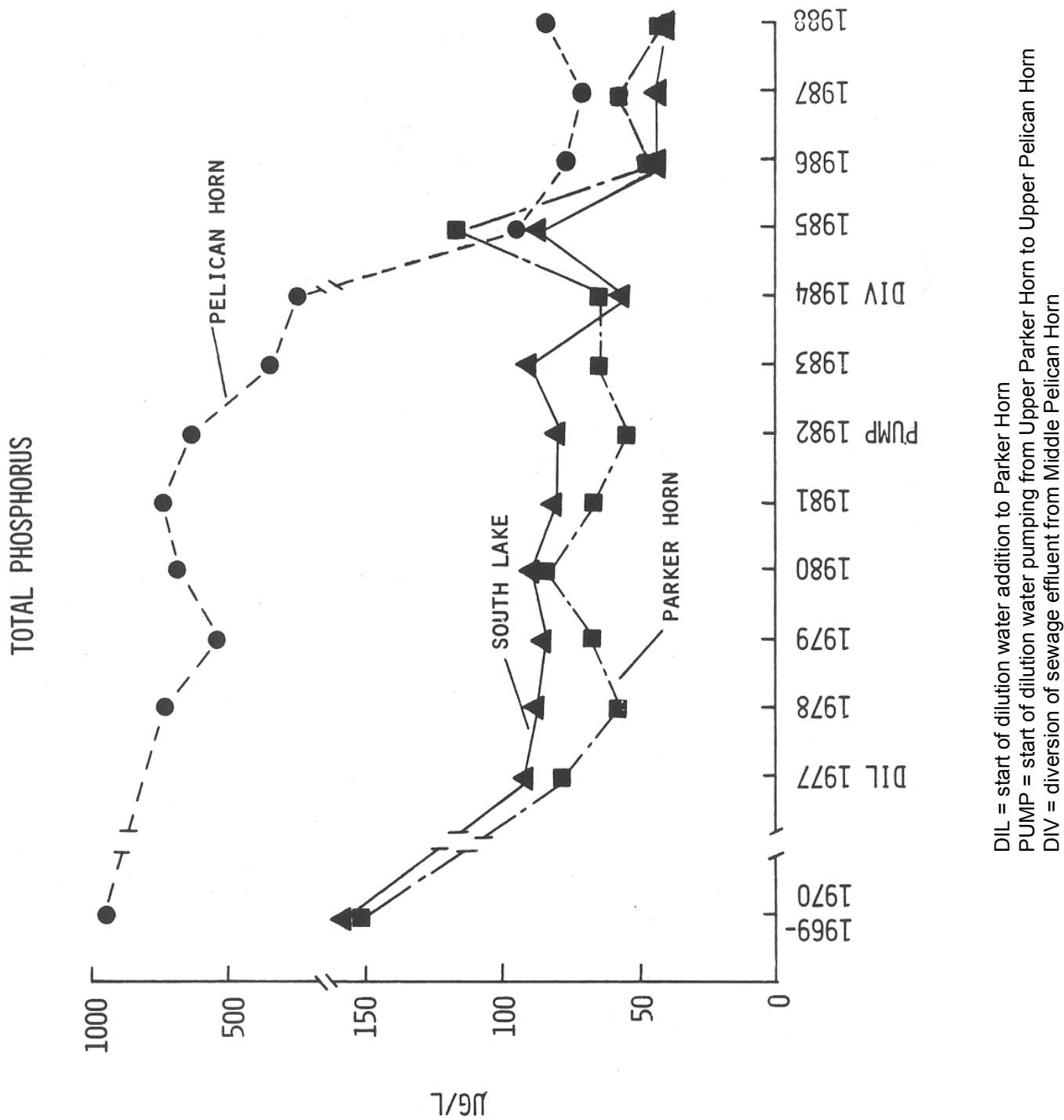


Figure 3. Mean total phosphorus concentrations from transect samples (0.5m depth) in three sections of Moses Lake (7,9,11) during May-September in pre-treatment years (1969-70) and post-treatment years (1977-88). (Welch, 1989)

ratio of phosphorus between East Low Canal water (i.e., dilution feed) and Crab Creek than for nitrogen. Further, the study indicated that internal phosphorus cycling from bottom sediments was often exceeding the external source loading. The year-to-year variation in internal loading was nearly 100% of the mean, making it difficult to characterize. A strong correlation was found between wind-induced mixing of Moses Lake and internal loading. The flushing rate was also found to correlate to internal loading, but with less effect than mixing. Dilution seemed to increase internal loading due to a reduced concentration of phosphorus and a consequent larger diffusive gradient between sediment and water.

As part of the study, predictive nitrogen and phosphorus models were developed to assess the lake response to changes in nutrient loading. However, the nitrogen model was not pursued, because phosphorus was identified as limiting and the most effective nutrient to manage, and a more empirical approach was viewed as more reliable. A steady-state TP model including internal loading was developed. In order to apply the model, the lake was divided into four segments based on observed differences in nutrient concentrations, chlorophyll *a*, and limiting nutrient (i.e., P). The study concentrated on Lower Parker Horn and the South Lake, because these areas could be most influenced by dilution water, and they were the areas of major concern for recreation. The model was used to predict May-September phosphorus concentrations. The model was calibrated using 1980-84 data, and the results confirmed with 1985-88 data.

The detention basin built on Rocky Ford Creek had not shown any detectable removal of phosphorus as of this study. Decreased SRP and TP levels found in Crab Creek may have been due to irrigation management during the 1970s, and probably contributed to the reduction of lake TP and increased P-limitation.

11. Moses Lake Area, Water Quality Monitoring Report (1991-92 Water Year), (Bain, 1993)

This water quality monitoring study of Moses Lake, funded by the MLIRD, was conducted from October 1991 to September 1992. The purpose of the study was to provide comparative data and additional background information following inception of the water quality control projects in 1977. The results of this study suggested a continued general trend of improvement to the lake water quality, as indicated by Welch et al. (1989), although the sampling plan was limited ($n=2$ for each lake transect) which makes it difficult to compare with earlier data sets. The study also reported a 50 percent drop in the TP concentrations in Crab Creek from earlier data sets, but again the sampling plan was limited. The study suggested possible changes in Crab Creek TP levels were attributed to the irrigation management practices implemented under Stage III of the Moses Lake Clean Lake Project.

12. Moses Lake Area, Water Quality Monitoring Report (1997), (Bain, 1998)

A follow-up study using the same monitoring plan (limited in scope) as used in the earlier monitoring report (Bain, 1993) found increasing nitrate-N and phosphorus concentration levels in Crab Creek and Rocky Ford Creek. Reference wells and springs on the eastside of Crab Creek generally showed increased or unchanged nitrate levels, as well as elevated TP levels, compared

to 1992 levels. TP levels from two sampling surveys in Moses Lake during June and August of 1997 were nearly double those found in 1992, averaging 100 ug/L in 1997. Average chlorophyll *a* levels were elevated over earlier years. The report indicated that the decreasing water quality in Moses Lake from that reported during earlier 1992 monitoring (Bain, 1993) was due to low dilution releases during 1997, which were less than 10% of those in 1992.

13. Rocky Ford Creek TMDL Study (Cusimano and Ward, 1998)

This report examined the water quality of Rocky Ford Creek with respect to 303(d) listings for pH, dissolved oxygen, and temperature. The original intent of the study was to set TMDL limits for the causes of the listings. The listings for pH and dissolved oxygen were suspected to be due to excessive plant productivity caused by high nutrient concentrations. However, the authors noted that deriving a direct quantitative link between nutrient loading, concentrations in the water column, and dissolved oxygen or pH levels in the creek may not be possible, because of the nature of wetlands and rooted submerged plants that dominate the creek. They found mean TP concentrations to be 69 ug/L in August, and 231 ug/L in November, in the springs that feed the creek. Average TN was found to be 2.29 and 1.89 mg/L in the springs for the same periods, respectively. The investigators also noted that phosphorus levels increased below the fish hatcheries and that the discharge mean phosphorus concentration to Moses Lake was 50 – 70% greater than the mean spring concentration for the August and November surveys. In addition, they found that nitrogen levels decreased from the springs to Moses Lake during August (i.e., the growing season) from 2.29 to 0.815 mg/L, but they did not significantly change during November.

The detention pond on Rocky Ford Creek, located near Moses Lake, was found to have no significant effect on nitrogen or phosphorus concentrations being discharged to the lake. The investigators did find that the creek flows in 1997 were higher than the previous 30 years, which they suggest could be due to increased water availability for irrigation.

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Summary of 30 Years of Studies and Restoration on Moses Lake

Effects of Restoration Projects

The major restoration measures applied to Moses Lake to date are:

- Dilution of Parker Horn, Main Lake, and Pelican Horn
- Sewage diversion from Pelican Horn
- Agricultural BMPs in Crab Creek watershed
- A detention pond on Rocky Ford Creek

In general, the water quality in Moses Lake has improved since applying the various restoration measures. Particularly, dilution and diversion have been shown to be individually successful at improving water quality (Welch et al., 1992; Welch et al., 1989; Welch et al., 1986). The proportionate contribution in improved water quality of other control measures, particularly the agricultural BMPs, is unknown. Ideally, the effectiveness of each restoration measure could be quantified and tracked in order to explain how water quality management practices affect year-to-year changes in lake water quality. Successful and efficient management of Moses Lake may depend upon better knowledge and continued monitoring of each restoration measure and practice. The following is a summary of the individual major restoration projects:

Lake Dilution

Dilution water has been added annually to Moses Lake via Crab Creek since the 1977 Pilot Project study. Lake dilution has had a positive, visible effect on Moses Lake, though its effectiveness in reducing algae was more apparent in earlier years when nitrogen was more limiting in Moses Lake (Welch et al., 1989). Still, there is a favorable effect on phosphorus in Moses Lake when dilution additions are available.

The highest annual dilution flow was about 290,000 acre feet in 1994 (Figure 4). The mean annual dilution flow from 1977 to 1998 was roughly 138,000 acre feet, or just over one lake volume. The 90th percentile annual dilution flow for the same period was about 250,000 acre feet or about two lake volumes. The dilution period generally occurred from April through June, though many years also had a period of dilution flow around October.

Generally, the water quality goals established during the dilution pilot project have been accomplished. For TP, pre-dilution levels of 152 ug/L in 1969-70 were reduced to a low of 43 ug/L (in Lower Parker Horn) in 1988, averaging 66 ug/L during the 12 years of dilution from 1977-1988. While dilution has been established as part of the permanent restoration plan for Moses Lake, operationally it has been difficult to set the needed amount of dilution flows at the

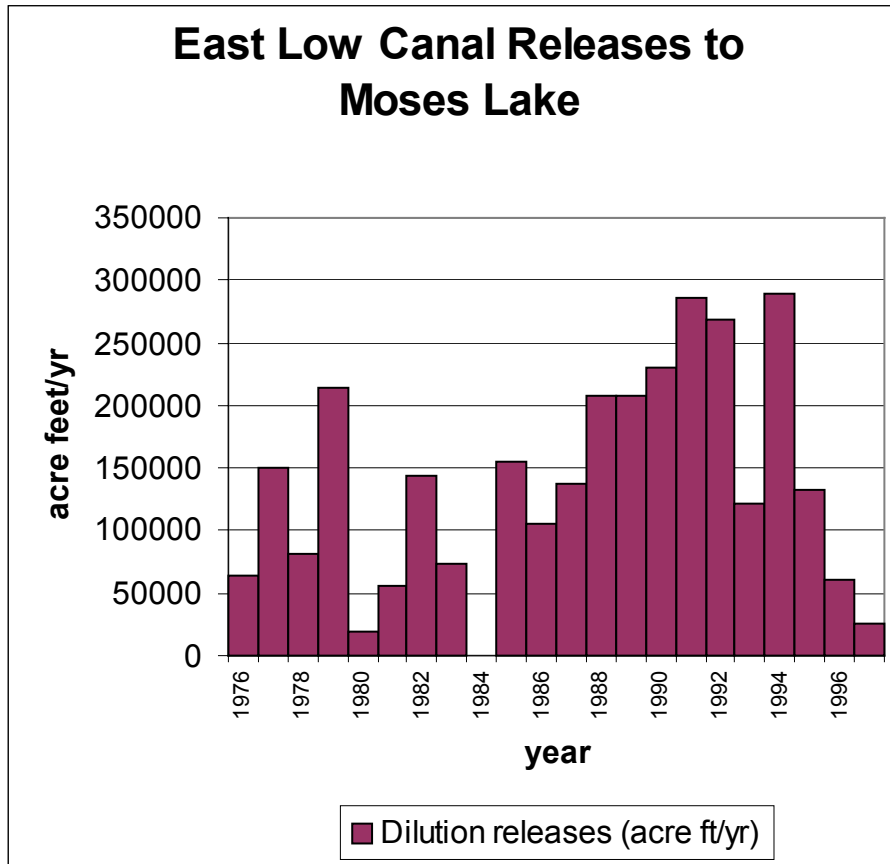


Figure 4. Dilution releases to Moses Lake, 1976-1997.

desired times. The historical studies suggest an optimum annual dilution input of 80,000 acre feet distributed throughout the summer or about 16,000 acre feet per month (May-Sept). In 1980 the USBR agreed to provide a minimum dilution flow of approximately 15,000 acre feet for each month April through August. However, a review of dilution flows through Moses Lake in the past 22 years indicates that during most of the summer inadequate dilution took place (Figure 5).

Several factors affect the dependability of dilution water additions to Moses Lake. The amount of water released from the East Low Canal to Moses Lake is controlled by the USBR. They release water based on the supply and demand at Potholes Reservoir. Presently, the lower CBIP (i.e., the area downstream of Moses Lake and Potholes Reservoir) is fully developed, with the lower canal system running at capacity, so additional demand because of increased development is unlikely (O’Callahan, 1998). If the upper CBIP (i.e., the area upstream of Moses Lake) were to fully develop the upper Crab Creek watershed for irrigation farming (i.e., the East High Canal and branch canals), it is unclear whether dilution water would continue to be available for

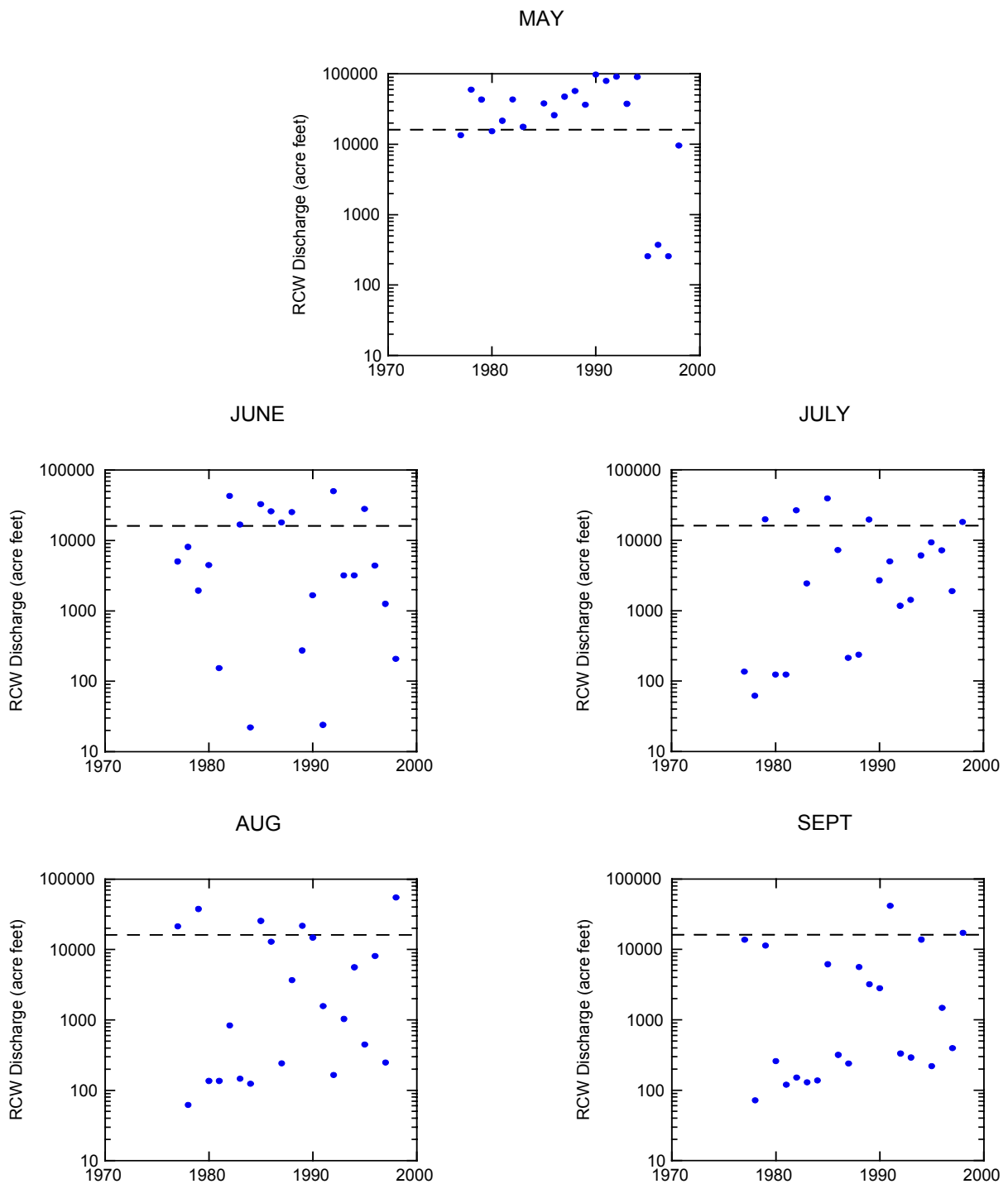


Figure 5. Dilution flow by month for 1977-1998. RCW denotes Rocky Coulee Wasteway, and dashed line indicates optimum flow of 16,000 acre feet per month.

Moses Lake. Completion of the East High Canal would increase the irrigation return waters from the upper Crab Creek watershed, possibly eliminating the need to use East Low Canal water to recharge Potholes Reservoir via Moses Lake. However, nearly 60 years have elapsed since CBIP began pumping irrigation waters. The East High Canal area has not been developed; it is unlikely to be developed given the capital costs involved. In essence, irrigation demand and supply based on development are in a relatively static condition.

Nevertheless, dilution water to Moses Lake has proven undependable in the short term, mainly due to climate variation. Climatic trends affect irrigation demand and supply. Cool, wet weather during the growing season lowers demand below Potholes Reservoir, whereas wet weather in winter provides enough winter runoff to fill Potholes Reservoir, both negating a need to route East Low Canal water through Moses Lake. This explains the decreased East Low Canal releases to Moses Lake since 1995 when cool, wet weather prevailed. Alternatively, a hot and dry weather pattern increases growing season water demand and lowers springtime runoff and recharge to Potholes Reservoir, thereby increasing the need for East Low Canal releases to Moses Lake. Figure 6 depicts the relationship between annual Crab Creek flow and dilution flow, illustrating a dilution flow operational response to the magnitude of Crab Creek inflow (i.e, the winter runoff). This inconsistency in dilution releases to Moses Lake diminishes the effectiveness of dilution as a dependable restoration technique.

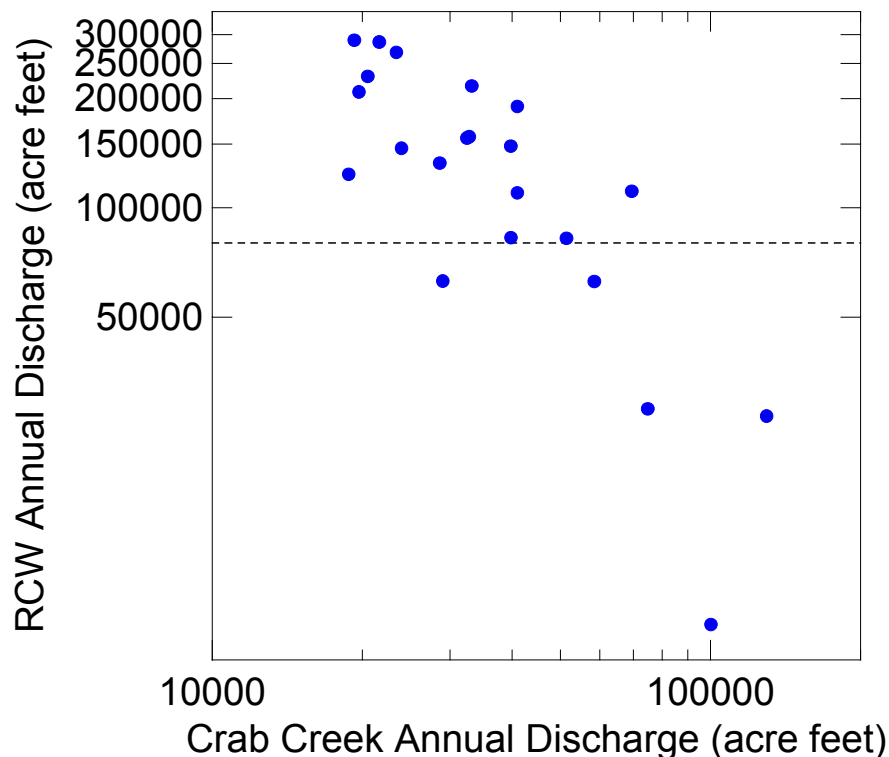


Figure 6. Relationship between annual dilution flows (RCW denotes Rocky Coulee Wasteway) and Crab Creek annual flows for 1977-1998. Dashed line indicates optimum dilution flow of 80,000 acre feet per year.

Dilution water has been pumped to Pelican Horn since 1982 via a pump station and transmission line from Parker Horn. The pumps are maintained by the MLIRD and generally operate from May through September of each year, coinciding with the expectant East Low Canal dilution releases. Operating costs are on the order of \$10,000 per month during operation. Following the beginning of pumping in 1982, Pelican Horn showed a 35% decrease in TP. However, there was little change in chlorophyll *a* and no change in transparency, despite a considerable washout of algal cells due to the increased flushing rate.

Sewage Diversion

Sewage diversion from Pelican Horn was completed in 1984, using over \$3 million in Washington State Referendum 39 funds and residual from the initial \$6 million EPA grant. The effluent was diverted from Pelican Horn to a land infiltration site southeast of Moses Lake. As expected, sewage diversion did result in a dramatic decrease in phosphorus levels in Pelican Horn, as indicated above; however, Pelican Horn continues to remain hypereutrophic. Diversion of the sewage has also improved phosphorus levels in South Lake and possibly Lower Parker Horn, which was apparent in 1984 when there was no dilution flow concealing these changes. It is unlikely, given the groundwater flow directions in the area of the new discharge site, that nutrients from the Moses Lake WWTP effluent reach Moses Lake via groundwater. However, the Lawson WWTP and on-site treatment systems most likely eventually discharge to Moses Lake through groundwater recharge. One estimate is that at least half of the current urban population (approximately 30,000) contribute to this load (Bain, 1998).

Agricultural Best Management Practices (BMPs)

With over 75% of the phosphorus load to Moses Lake estimated to originate from agricultural fertilizers and farm animal wastes (Welch et al., 1973), it has been important to try to mitigate these sources to Moses Lake. Beginning in 1987, the Moses Lake Clean Lake Project initiated irrigation and fertilizer controls and management, at a cost of over \$220,000 plus federal cost-share monies for irrigation system conversions. However, implementing BMPs has not been as effective or extensive as hoped within the Moses Lake watershed. Welch et al. (1989) reported that only 20% of irrigated lands in the immediate Crab Creek watershed had implemented water and nutrient controls, amounting to a potential nutrient concentration reduction of less than 2% in the Crab Creek inflows to Moses Lake.

The effects of nonpoint BMPs as currently implemented are difficult to quantify. Short-term, in-lake water quality changes are unlikely, because Moses Lake and its watershed have been sediment and phosphorus traps for years, and dilution and internal loading mask the effect of external loading changes within the watershed. However, if BMPs can be implemented and maintained, reductions in external loads will likely have long-term visible benefits. For now, changes in Crab Creek water quality would best indicate the effectiveness of agricultural BMPs, as this tributary is recharged by groundwater and agricultural runoff, and a majority of the implemented BMPs have taken place in the Crab Creek watershed. Current data from Crab Creek suggest insignificant nutrient concentration changes from pre-BMP data (Bain, 1998).

Detention Pond

The nutrient detention pond was built on Rocky Ford Creek in 1987, partially funded by Ecology through Referendum 39, at a cost of about \$130,000. Additional resources by the state Department of Wildlife eradicated the carp in Rocky Ford Creek following construction. To date, the detention dam does not seem to afford a reduction in phosphorus loading from that tributary. Various reports (Welch et al., 1989, Cusimano and Ward, 1998) have shown there has not been a significant difference in phosphorus concentrations between samples taken above and below the detention pond. In addition, the dam has been the object of vandalism in recent years and a source of contention among local landowners. Carp have repopulated Rocky Ford Creek and the state Department of Fish & Wildlife is considering further rehabilitation measures.

Other Major Findings from Previous Studies

- The hydrology of the Moses Lake watershed has been significantly altered by the development of the Columbia Basin Irrigation Project (CBIP), primarily through the extent and quality of groundwater recharge which contributes the bulk of inflow to Moses Lake and its tributaries. In fact, Moses Lake itself has become a part of the CBIP irrigation flow system. The present agricultural development represents a permanent, uncontrollable (presumably) change to the watershed. Anthropogenic activities, mostly agricultural, have increased nutrient loads to Moses Lake and are responsible for the accelerated eutrophication or hypereutrophication of Moses Lake.
- There are definite restoration limitations for Moses Lake. Along with watershed and climatic factors, the morphology of Moses Lake affects its lake dynamics and productivity. Controlling algal biomass and SD transparency is more difficult in shallow, unstratified lakes than in deep, stratified lakes (Welch and Cooke, 1995). Mean depth is regarded as the single best index of morphometric conditions and shows a clear inverse relationship to productivity within large lakes (Wetzel, 1983). Additionally, long and sinewy lakes have a greater potential for development of littoral areas in proportion to their lake volume resulting in greater zones of productivity. As described above, Moses Lake is a relatively shallow (mean depth = 5.6 m; Osgood Index = 1.07), polymictic, dendritic lake with extensive littoral areas at the head of the Rocky Ford Arm and in Parker Horn and Pelican Horn.
- The dendritic nature of Moses Lake has allowed investigators to view the lake in a more complex manner, segmenting the different basins and arms for modeling purposes. Lake responses to loading changes and dilution may vary in different parts of Moses Lake, suggesting the importance of regarding localized effects when evaluating management decisions. For instance, Parker Horn was specifically modeled and evaluated for responses to dilution, because a majority of recreational activity on the lake takes place there. Likewise, sewage diversion and dilution were specifically applied to Pelican Horn, intending to improve water quality there.

- The nutrients of primary importance are phosphorus and nitrogen, as they have been shown to limit growth in freshwater lakes (Wetzel, 1983). In the studies performed on Moses Lake over the last 30 years, there has been uncertainty as to whether nitrogen or phosphorus limit algal growth in Moses Lake. It seems, at times, one or both may have been limiting, depending on which time period and which part of the lake was observed. Early on, Sylvester and Oglesby (1964), Welch et al. (1973), and others found the water column nearly devoid of nitrate-N during the growing season reflecting a nitrogen limitation, but recommended managing phosphorus loading because the blue-green algae causing the blooms were capable of nitrogen fixation. Nutrient enrichment studies by EPA (1977) using algal assays indicated nitrogen limitation in Parker Horn and phosphorus limitation in Rocky Ford Arm during a spring and fall sampling. Nutrient enrichment studies by Welch et al. (1973) revealed that phosphorus was the controlling nutrient in Moses Lake, and an algal assay by Patmont (1980) suggested phosphorus limitation in Parker Horn. Pelican Horn remains nitrogen limiting, though, due to excessive amounts of phosphorus present, even after sewage diversion.

The ratio of TN to TP in lake waters is generally accepted as an indicator of which nutrient may be more limiting to algal growth (Forsberg, 1980; Healy and Hendzel, 1980). While the critical TN:TP ratio for nitrogen or phosphorus limitation varies in the literature, a higher ratio indicates that phosphorus is more likely to limit. There was a trend of increasing TN:TP ratios in Moses Lake from 1977 to 1988, indicating a switch to phosphorus limitation within Moses Lake (Welch et al., 1989). This increasing trend was correlated to sewage diversion and possibly phosphorus reduction in Crab Creek due to a switch to spray irrigation. In cases of cultural eutrophication, it is not uncommon to have excessive loads of phosphorus creating short-term or occasional nitrogen limitation in a lake with an historical phosphorus limitation. In such cases, the control of phosphorus as the limiting nutrient (possibly with additional control of N) may still impart the greatest regulation of algal activity (OECD, 1982). For Moses Lake, TP is the recommended nutrient to control.

- Wind mixing was found to greatly affect the magnitude of summertime internal loading in Moses Lake (Jones, 1988; Jones and Welch, 1990). In the absence of dilution water, it was predicted that column-weighted TP in Lower Parker Horn for May through September should vary from approximately 70 to 120 ug/L, due solely to differences in wind mixing. Therefore, the variability in wind from year to year was expected to cause large differences between actual and predicted summertime water quality, due to the resulting variability in summertime internal loading.

In addition, though the water movement is generally from the north end of the lake (i.e., where the tributaries enter) to the south end (i.e., where the outlet exits), the prevailing wind is generally from the south and seems to provide a counter, northward water movement. It was originally thought that dilution water entering into Parker Horn would have no effect in Rocky Ford Arm; however, conductivity tracer studies by Patmont (1980) showed that dilution water traveled well up into Rocky Ford Arm, achieving roughly a 40% proportion in that basin by the end of the dilution period. Thus, wind probably helps spread localized restoration measure effects throughout the entire lake.

- Macrophytes are becoming a problem, particularly associated with the increased clarity afforded by the dilution releases to Parker Horn. A macrophyte weed harvester was purchased in the late 1980s and used extensively. Problems with macrophyte production will continue to have an inverse relationship to water quality improvements to Moses Lake, because of the large area of shallow depths in the lake.

Review of Major Nutrient Loading Components to Moses Lake

In an effort to develop a nutrient allocation strategy to improve Moses Lake's water quality, it is important to first characterize the various loading components to Moses Lake. The major external loading components considered are groundwater inflow, Rocky Ford Creek, and Crab Creek. In addition, sediment release of nutrients acting as an internal loading component is considered.

Groundwater Inflow

Groundwater has a significant influence on Moses Lake. Pre-dilution estimates of annual water inflow contributions attributed to groundwater have ranged from 30-45% of inflows. A post-dilution estimate of 26% groundwater contribution to water inflows was made by Patmont (1980). Groundwater phosphorus loads have been estimated to be 5-11% of annual external TP load to Moses Lake (Sylvester and Oglesby, 1964; Welch et al., 1973 and Patmont, 1980). The groundwater contribution of the total external nitrogen load to Moses Lake has been estimated to be 70% (Patmont, 1980).

The average concentration of phosphorus in groundwater entering Moses Lake has been estimated by Jones (1988) to be 51 ug/L which is significantly higher than expected. This is probably reflective of the high agricultural and cultural influences on groundwater water quality around Moses Lake. Based on earlier groundwater sampling, Patmont (1980) estimated the average TN concentration of groundwater to be 5.1 mg/L, implicating groundwater as the major source of nitrogen to Moses Lake. Concerns are increasing about pollutants in the groundwater of the highly-conductive, gravelly-outwash formation. Nitrate contamination in Columbia Basin aquifers is now being investigated by federal, state, and local agencies, with agricultural and cultural influences suspected of causing elevated nitrate concentrations exceeding the 10 mg/L maximum contaminant level (MCL) threshold for drinking water.

Based on residuals from monthly water budgets, Patmont (1980) found that groundwater flow entered Moses Lake primarily in the fall and winter, coincident with an increase in groundwater levels in the upper aquifer northeast of Pelican Horn and the annual drawdown of Moses Lake for the winter. The majority of groundwater seemed to enter Pelican Horn based on these findings. In constructing a phosphorus model for Moses Lake, Welch et al. (1989) allocated 80% of groundwater flow into Pelican Horn based on work by Carlson (1983). The remaining

20% was divided equally between Parker Horn and Rocky Ford Arm, based on groundwater contour maps and assuming a constant hydraulic conductivity around the lake. Earlier, Brown and Caldwell (1980) reported that the principal source of groundwater flows into Moses Lake was thought to be along the east shore of the Rocky Ford Arm near the Grant County airport. Much earlier, Sylvester and Oglesby (1964) reported extensive groundwater additions in this area, based on observations of an ice-free area south of Airman's Beach during the winter; this may have been the reference source for Brown and Caldwell (1980).

Rocky Ford Creek Loading

Rocky Ford Creek is one of two tributaries to Moses Lake. It is unique as a tributary because of its small watershed size (104 km²) and yet relatively large mean annual flow, contributing from 21% to 35% of inflow to Moses Lake (Sylvester and Oglesby, 1964; Welch et al. 1973; Patmont, 1980). Figure 7 shows flows for Rocky Ford Creek and Crab Creek from 1960 to the present. The creek obtains most of its flow from springs that are its headwaters. Rocky Ford Creek flows south from the springs for approximately 8 miles and then discharges to the north end of the main arm of Moses Lake. A U.S. Geological Survey (USGS) discharge monitoring station, located 1.5 miles downstream of the springs, provides a long-term flow record for Rocky Ford Creek. The mean annual flow from Rocky Ford Creek to Moses Lake is 69.0 cfs, although Cusimano and Ward (1998) found flows increased approximately 20% from the USGS monitoring station to the lake, suggesting groundwater inflows to Rocky Ford Creek en route to Moses Lake.

Because of the consistently high flow and the elevated nutrient levels, Rocky Ford Creek contributes significantly to the annual nutrient loading to Moses Lake. Patmont (1980) estimated the annual TP and TN contributions to Moses Lake to be 30% and 8%, respectively. Nutrient concentrations have remained high in Rocky Ford Creek since water quality monitoring began in the early 1960s. Based on samples taken from before 1989, the annual mean TP concentration was 167 ug/L and the annual TN concentration was 1.35 mg/L. The origin of the particularly high phosphorus levels has been the subject of speculation and inquiry. Bain (1985) found the source of phosphorus to be from the headwater springs. This study hypothesized that the source of phosphorus in the springs might be seepage from impoundments that serve as nutrient sinks in the Crab Creek drainage, located northeast of the springs in an agricultural area.

Cusimano and Ward (1998) summarized nutrient data from Rocky Ford Creek and surveyed the creek in 1997. During 1997 the fish hatcheries on Rocky Ford Creek were estimated to contribute 21% and 7% of the TP and TN load to the creek, respectively. The report also indicated that the fish hatchery percent contributions to the Rocky Ford Creek nutrient load could be significantly higher than survey data suggest. This would be the case in years with lower creek flows and higher fish hatchery production levels. Fish hatchery contributions could approach 100% of the nutrient load in extreme cases.

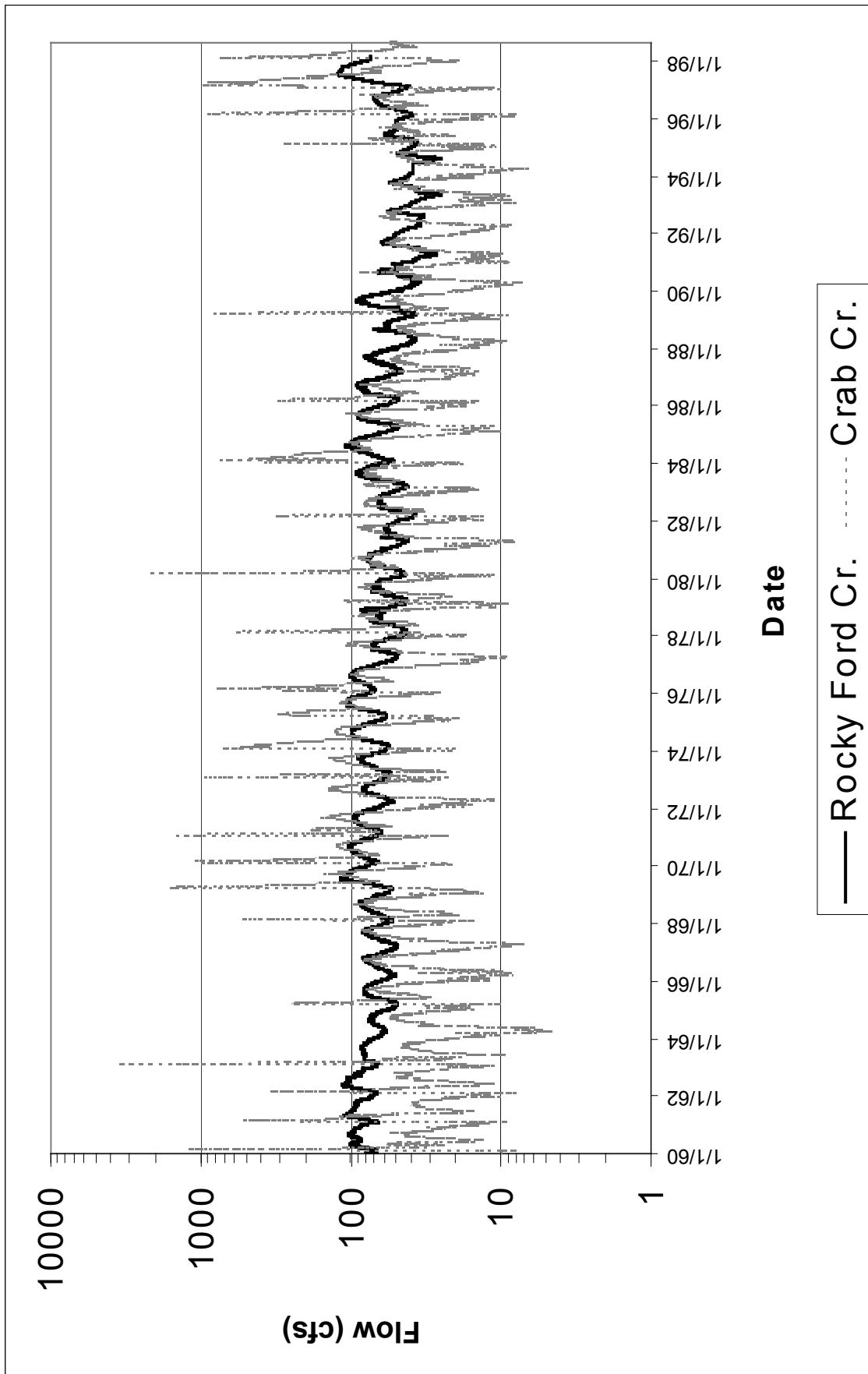


Figure 7. Rocky Ford Creek and Crab Creek daily flows at USGS stations #12470500 and #12467700, respectively. Flows for Rocky Ford Creek after June 1991 are estimated from bimonthly measurements.

Crab Creek Loading

Crab Creek is the more variable tributary to Moses Lake. Figure 7 shows flows for Crab Creek and Rocky Ford Creek from 1960 to the present. Although it has a drainage area of 2,040 mi², Crab Creek has a lower annual mean flow than Rocky Ford Creek. Much of Crab Creek flow is underground; prior to the beginning of the CBIP in 1952, Crab Creek surface flow was negligible except during periods of heavy runoff. A USGS discharge monitoring station, located 3.2 miles upstream of Moses Lake, provides a long-term flow record for Crab Creek. Since 1960 the mean annual flow has been 44.5 cfs. Sylvester and Oglesby (1964) found a flow increase of approximately 10 cfs from the USGS monitoring station to the lake, indicating groundwater inflows to Crab Creek en route to Moses Lake.

Major flows can occur from January through April and these large winter run-off events have produced flows greater than Rocky Ford Creek. Table 1 presents mean monthly flows and monthly mean and 90th percentile nutrient loads for Crab and Rocky Ford creeks. From October 1968 to September 1969, approximately 60% of the flow from Crab Creek occurred during March and April of 1969, exceeding the entire annual flow of Rocky Ford Creek for the same period (Welch et al., 1973). Additionally, nearly 83% of the phosphorus load and 56% of the nitrogen load from Crab Creek for this same period occurred in March and April. Accordingly, nutrient loads from Crab Creek to Moses Lake have varied as a function of flow. Different flow regimes during different study years have resulted in Crab Creek contributing from 11% (Sylvester and Oglesby, 1964) to 49% (Welch et al., 1973) of the TP load to Moses Lake. The mean annual TP and TN concentrations in Crab Creek (from data collected 1960 to 1989) were 97 ug/L and 882 ug/L, respectively.

Most of the agricultural BMPs have been implemented within the Crab Creek drainage, because a significant area of irrigated agriculture occurs in the watershed. As mentioned above, these BMPs were implemented in the late 1980s. Bain (1998) reported a mean of 140 ug/L TP and 1,370 ug/L TN from a 1997 Crab Creek survey, suggesting no improvements from established BMPs.

Internal Phosphorus Loading

Internal sediment release of phosphorus is an important loading source to Moses Lake. In lakes with an anoxic hypolimnion, vertical entrainment of phosphorus from the hypolimnion is usually not significant during the growing season, affording a decrease in epilimnetic phosphorus concentration after a decrease in external phosphorus loading. However, in eutrophic, shallow, mixed lakes (like Moses Lake) nearly all of the phosphorus released from the sediments may be available in the epilimnion during the growing season, often resulting in unchanged in-lake phosphorus concentrations following external phosphorus diversion (Welch and Cooke, 1995).

Some of the highest in-lake phosphorus concentrations in Moses Lake have occurred in the summer when external loading was at its minimum and net internal loading at its maximum (Patmont, 1980). During 1977 and 1978, approximately 85% of the annual net release of

Table 1. Estimated monthly total phosphorus (TP) and total nitrogen (TN) loading budget for Moses Lake tributaries (1960-1989).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rocky Ford Creek												
mean flow (cfs)	59.9	54.9	55.0	58.4	64.2	71.9	77.6	82.5	82.2	80.6	74.8	67.2
mean TP mg/L	0.187	0.184	0.176	0.168	0.157	0.159	0.157	0.161	0.162	0.183	0.195	0.183
TP mean (kg/month)	849.4	689.5	733.7	719.4	763.8	837.9	923.6	1006.3	1009.1	1117.3	1069.4	932.6
TP 90th%tile (kg/month) ^a	1205.1	950.8	1013.5	1059.5	1140.1	1377.9	1346.4	1408.7	1356.1	1476.1	1331.0	1217.8
mean TN mg/L	1.61	1.51	1.55	1.14	1.20	1.23	1.17	1.28	1.54	1.53	1.64	1.65
TN mean (kg/month)	7312.8	6278.4	6461.1	5044.1	5838.0	6698.0	6882.9	8000.6	9593.0	9341.7	9293.6	8408.6
TN 90th%tile (kg/month) ^a	9170.6	7830.2	8648.2	7776.4	9618.4	9637.7	10006.7	11339.8	13338.6	13070.8	11373.5	10407.8
Crab Creek												
mean flow (cfs)	21.8	43.2	51.8	43.0	39.4	45.7	58.3	67.9	70.8	60.9	38.2	24.8
mean TP mg/L	0.118	0.158	0.16	0.13	0.074	0.066	0.056	0.056	0.068	0.05	0.069	0.078
TP mean (kg/month)	195.0	466.2	628.2	410.0	221.0	221.2	247.4	288.2	364.9	230.8	193.3	146.6
TP 90th%tile (kg/month) ^a	643.9	3554.5	3710.9	1898.1	596.1	462.1	444.9	557.2	747.3	429.1	457.2	276.9
mean TN mg/L	1.215	1.137	0.681	0.399	0.477	0.6	0.74	0.683	0.93	0.889	1.206	1.343
TN mean (kg/month)	2007.5	3722.7	2673.6	1300.3	1424.4	2078.2	3269.7	3514.8	4990.3	4103.3	3491.6	2524.3
TN 90th%tile (kg/month) ^a	6315.6	25520.6	15568.8	5692.4	3978.0	4192.3	5530.7	6416.1	8065.9	6478.2	5890.4	4710.0

^a= percentile estimate includes propagation of error estimate for flow and concentration.

phosphorus from the sediments took place during May through September. May-September phosphorus budgets from 1977 through 1988 showed calculated net internal phosphorus loading averaging $33\% \pm 15\%$ of the total load for the 10 years showing a net release, including two years (1985 and 1987) where internal loading exceeded the seasonal external load (Welch et al., 1989). There was no net internal loading in 1978 (for unknown reasons) and in 1980, probably due to the ashlayer from Mt. St. Helens that blocked the release of phosphorus from the sediments (Welch et al., 1985). The May through September calculated net internal loadings from 1977 to 1980 ranged from -2,010 to 19,845 kg of TP with a mean of 6,588 kg of TP, and a year-to-year variation of nearly 100% of the mean.

Greater littoral zones of photosynthetic production and decomposition are associated with a greater ratio of sediment surface to lake volume and increased lake nutrient concentrations of sediment-released nutrients. Moses Lake, with its shallow arms, provides a high ratio of sediment surface to lake volume for internal recycling. Although water columns are usually aerobic in shallow lakes, several mechanisms (i.e., wind resuspension, high pH, periodic anoxia, macrophyte senescence) can combine to cause a release of phosphorus from the sediments to the water column (Welch and Cooke, 1995). Internal phosphorus loading within Moses Lake appears to increase when the water column is less stratified; wind was reported to be the predominant factor affecting vertical stratification in Moses Lake (Jones, 1988). Increased flushing rates (i.e., dilution) were also correlated to increased sediment phosphorus release within Moses Lake (Okereke, 1987).

In conclusion, the internal loading processes in Moses Lake seem to be controlled by the morphology and climate of the lake. Current restoration methods to control sediment phosphorus recycling, such as alum treatments, are unfeasible given the areal extent involved, and dredging was eliminated as a practical consideration because of the uniform consistency of nutrient concentrations throughout the sediments (Welch et al., 1973).

Other Influences

Estimates for loads from atmospheric deposition and direct precipitation were made in various reports. Base flow and concentration data from Rocky Coulee Wasteway were presented by Patmont (1980), and were assumed to be constant as the major source of the flow was from springs. Loading estimates from the East Low Canal dilution releases were also made by Patmont (1980).

Other loads not considered in this evaluation because of lack of data are: (1) On-site septic and sewage leachate (both might be accounted for in the relative high nutrient concentrations of the groundwater); (2) Stormwater runoff (unknown contributions from city of Moses Lake stormwater collection system); (3) Waterfowl contributions (more than 50,000 waterfowl winter on Moses Lake each year); and (4) Net pen fish production by the state Department of Fish & Wildlife in the south basin.

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TMDL Assessment

Nutrient Criteria Evaluation

It is necessary to establish in-lake nutrient target concentrations for Moses Lake to develop a TMDL. This proposed TMDL assessment is designed to address impairments to the characteristic uses of Moses Lake caused by excessive phosphorus loading, and the resulting eutrophication and algal blooms.

While there seems to have been a combination of both phosphorus and nitrogen limitation within Moses Lake, with the limiting factor occasionally being only phosphorus or nitrogen in the short term, there has been a trend of increasing N:P ratios, suggesting more phosphorus limitation, and an historical preference to impart phosphorus control. Even though Moses Lake is listed for both TP and TN on the 303(d) list, the historical studies on Moses Lake have shown that TP is the favored nutrient to control to limit algal biomass. This strategy of managing TP to control algal growth is supported in literature even for lakes where nitrogen may be limiting growth. On this basis, this report recommends that Moses Lake be de-listed for TN from the 303(d) list, and that future lake management activities and decisions focus on the control of TP to manage algal biomass in Moses Lake.

The protection of characteristic uses by the adoption of water quality standards and criteria lies under the authority of Ecology pursuant to Chapter 173-201A of the Washington Administrative Code (WAC) revised November 1997.

Characteristic uses protected for lake class waters are listed as follows:

“Characteristic uses. Characteristic uses shall include, but not be limited to, the following:

- (i) Water supply (domestic, industrial, agricultural).*
- (ii) Stock watering.*
- (iii) Fish and shellfish:
Salmonid migration, rearing, spawning, and harvesting.
Other fish migration, rearing, spawning, and harvesting.
Clam and mussel rearing, spawning, and harvesting.
Crayfish rearing, spawning, and harvesting.*
- (iv) Wildlife habitat.*
- (v) Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).*
- (vi) Commerce and navigation.”*

[WAC 173-201A-030(5)(b)]

The water quality criterion for phosphorus in lake-class waters is as follows:

“(viii) Aesthetic values shall not be impaired by the presence of materials or their effects excluding those of natural origin, which offend the senses of sight, smell, touch, or taste.”

[WAC 173-201A-030(5)(c)(viii)]

The code provides guidance for establishing an in-lake TP criterion. For Moses Lake, in the Columbia Basin Ecoregion, the water quality standards set an action value of 35 ug/L. If ambient TP levels exceed this level, additional study and activities are required to be initiated to protect the lake. Moses Lake ambient TP levels exceed the action value criterion of 35 ug/L. Additional study and actions required include:

1. Conducting a lake-specific study to evaluate the characteristic uses of the lake and to distinguish the source or threat of impairment to the lake.
2. Determining appropriate TP or other nutrient criteria to protect the characteristic lake uses.
3. Determining if the proposed criteria are achievable.

(WAC 173-201A-030 (6)(c)).

Similarly, the EPA provides guidelines on developing site-specific nutrient criteria for a lake (EPA, 1984). The specific steps to develop site-specific nutrient criteria for a lake are summarized as follows:

1. Determine the designated uses of the lake.
2. Determine the endpoint indicators and target levels that are to be used to determine whether the lake meets the designated uses.
3. Determine the total nutrient concentration (standard) that can be assimilated into the lake without violating the endpoint target.
4. Model the lake to determine the nutrient load that will meet the nutrient standard.
5. Set the criteria for nutrients and develop the site-specific water quality standards for the lake.

Both methods require that the characteristic or designated uses of Moses Lake first be determined in order to establish what level of lake protection will be necessary.

The extensive amount of study and restoration done on Moses Lake, most of which was reviewed above, qualify as site-specific diagnostic/feasibility lake studies conforming to Phase I and Phase II Federal Clean Lake Project requirements. They provide an evaluation that determines excessive phosphorus loading as the source of impairment to Moses Lake, with the impairment being the algae blooms which affect the characteristic uses of recreational and aesthetic enjoyment during the summer.

Characteristic or beneficial uses and perception of water quality are in “the eye of the beholder.” For people who do not have contact with the water, Moses Lake provides an aesthetic backdrop to the surrounding desert. As long as unsightly algal mats are not visible or detectable by odor, the lake quality as it exists probably meets their approval. Warm-water fishery proponents are also happy with a productive lake that supports a strong warm-water fishery, if again, blue-green

algae blooms do not dominate the lake productivity. Non-contact, aesthetic appreciation and warm-water fisheries seem to reflect some historical beneficial uses of Moses Lake. As such, present management, when it successfully controls hypereutrophic conditions, meets the requirements of a certain number of the public.

While there are members of the public who believe Moses Lake has been successfully restored, there are those who think Moses Lake is still degraded beyond use. Some of these perceptions are based on different views of the beneficial uses of Moses Lake. Those with direct contact with the water (e.g., water skiers, swimmers) are probably the least satisfied with the existing water quality conditions, as the water often maintains a murky, green color through the summer. Like-wise, cold-water fishery proponents (e.g., trout anglers) find the existing conditions in Moses Lake not conducive to supporting a thriving trout population. As stated before, though, Moses Lake has been fundamentally altered by human activities over the last 50 years, such that it does not have an historical reference condition. However, nothing indicates that Moses Lake has had anything but a highly productive past.

Based on relationships between the total nutrient loading and the mean depth of many lakes, Vollenweider (1968) suggested dangerous loading limits for nitrogen and phosphorus into lakes which, if exceeded, could promote accelerated eutrophication. Based on these loading limits, Welch et al. (1973) indicated that an order of magnitude reduction in nitrogen and phosphorus loading to Moses Lake would be required to bring it below dangerous limits, suggesting that background (or natural) conditions were sufficient to cause eutrophication in Moses Lake. Additional studies suggest Moses Lake has most likely been following a long-term natural process of eutrophication, even prior to cultural impacts. A review of sediment profiles from Moses Lake revealed large and consistent phosphorus and nitrogen loads for at least 100 years, suggesting the lake probably experienced algal blooms even in its “natural” state (Patmont, 1980). Therefore, management of Moses Lake for other than a eutrophic condition has been deemed impracticable, and has not been the focus or objective of rehabilitation measures to date (Welch et al., 1973; Brown and Caldwell, 1980; Patmont, 1980).

It seems clear that halting the accelerated hypereutrophication and restoring Moses Lake to a pre-impacted condition would most likely result in a continued eutrophic state, with the associated characteristic uses of a productive lake. Characteristic uses proposed by Mancini et al. (1983) and OECD (1982) for eutrophic north temperate lakes suggest reduced aesthetic properties, diminished enjoyment from water contact recreation, and generally very productive warm-water fisheries. These reflect the current and historical characteristic uses and conditions of Moses Lake, and suggest a level to protect and manage.

Both the EPA and Washington State guidelines next require an endpoint indicator and target level be established to protect the designated uses of the lake. Several studies, particularly those under the direction of Eugene Welch at the University of Washington, have been conducted in accordance with these guidelines to develop site-specific nutrient criteria for Moses Lake. These studies have drawn a link between TP concentration and an endpoint indicator, chlorophyll *a* concentration. They found that a maximum concentration of 50 ug/L TP would limit

chlorophyll *a* concentrations to an endpoint target of 20 ug/L during the growing season (May-September) in Parker Horn. Accordingly, the endpoint target of 20 ug/L chlorophyll *a* maximum concentration would significantly reduce the likelihood of hypereutrophic conditions (i.e., blue-green algae blooms) in Moses Lake.

Water quality goals for Moses Lake were reported for the 1977 Pilot Project (Brown and Caldwell, 1978). These mean annual targets were established as goals, based on earlier studies by Welch, for the dilution restoration project begun in 1977. The mean annual targets were 50 ug/L TP, 20 ug/L chlorophyll *a*, and SD transparency of 1.2 meters. Again, the goals were adopted as achievable targets to manage the hypereutrophic conditions in Moses Lake. It was accepted that these water quality goals would leave Moses Lake in a eutrophic state. The primary intent for setting the targets was to control the algae blooms which impaired the aesthetic and recreational uses during the summer. The SD transparency goal of 1.2 meters served as a gross measure of aesthetic conditions as well as a minimum standard for swimming safety. These management goals have continued to be used in the last 20 years as a basis for assessment and evaluation in subsequent water quality monitoring of Moses Lake.

Assuming the goal is to protect Moses Lake from hypereutrophic conditions (i.e., the 150 ug/L TP, 47 ug/L chlorophyll *a*, and 0.8 SD transparency seen in the 1970s), a probability distribution scheme of trophic categories proposed by OECD (1982) estimates that a 50 ug/L TP concentration represents a less than 5% chance of hypereutrophic conditions developing in Moses Lake. Mancini et al. (1983) and Reckhow and Chapra (1983) proposed TP concentration ranges for different trophic states and lake uses with 50 ug/L being the upper limit of a eutrophic state, just below a hypereutrophic state. Given these guidelines and the historical management intent to maintain Moses Lake in a eutrophic condition, while protecting against excessive hypereutrophic conditions, the 50 ug/L TP criterion seems reasonable.

Ecology proposes adopting the in-lake TP criterion of 50 ug/L to develop a nutrient TMDL for Moses Lake. Based on available knowledge, this nutrient criterion seems to protect the characteristic lake uses, has a basis in the historical lake restoration efforts as an achievable target, and probably best reflects the historical development of Moses Lake. Although a 50 ug/L TP level exceeds the action value of 35 ug/L TP in the lake nutrient criteria of WAC 173-201A-030 (6)(a), Ecology recommends setting 50 ug/L of TP as the phosphorus criterion for Moses Lake as per WAC 173-201A-030 (6)(c)(ii). Again, this section of the WAC is for lakes that exceed the action value and states; “...*If the existing total phosphorus concentration is not protective of the existing characteristic lake uses, then set criteria at a protective concentration.*”

Lastly, the EPA and Washington State guidelines require that the lake be modeled to establish and allocate TP loads necessary to achieve the nutrient standard. To monitor and implement a restoration lake plan, the ability to assess the effectiveness of the restoration measures is needed. Setting nutrient criteria in the form of a mean in-lake TP concentration is a way of addressing a measurable outcome. However, a whole-lake mean TP concentration is a difficult and costly measurement to ascertain. Traditionally therefore, lake managers have relied on lake modeling to relate a whole-lake mean TP concentration to a certain amount of incoming TP load to the lake, which is easier to measure.

In selecting targets for nutrients during the Moses Lake 1977 Pilot Project dilution study, consideration was not only given to what was necessary to deter algae blooms and enhance the characteristic uses of Moses Lake, but also to what appeared possible given the character of Columbia River dilution water used. These goals were meant to be attained through the use of dilution as a restoration technique. As proposed, dilution would have to constitute a permanent and reliable restoration plan to Moses Lake. The results from Welch et al. (1989) convey that the water quality goals are being met when dilution is available. However, adequate dilution water has not been available every year and also has not been available during the entire period of critical conditions. In addition, the established restoration plan may not provide a margin of safety to account for more extreme loading events during certain years. As such, loading reductions may be needed to meet the 50 ug/L in-lake TP criterion. To investigate this, the authors developed several loading scenarios using mean and 90th percentile loads and used a simplified, whole-lake, steady-state model to test total nutrient loading for compliance with the in-lake target concentration. The loading estimates are based on pre-1990 data collected from the lake and its hydraulic sources.

Preliminary Loading Assessment

Design Criteria for Loading Assessments

- In order to develop an allocation strategy to improve Moses Lake's water quality, all of the major loading components to Moses Lake were characterized. *Annual* loads were calculated for the major loading components and used to predict in-lake phosphorus concentrations using a whole-lake steady-state model. The Moses Lake summary report of Welch et al. (1989) reported only May through September data which did not account for the external loads during the rest of the year, especially the large external loads of Crab Creek during the late winter. Their focus was more on lake response to dilution during the growing season. However, lake dilution has not been reliable every year to mitigate winter runoff loadings, and therefore, it is important to develop allocation strategies that encompass all loadings to address this TMDL.
- In an effort to consider total loads to Moses Lake and provide a range of loading scenarios to manage within, assessments for each loading component were made in two ways. (1) The average annual mean load was calculated from the available flow and nutrient concentration data reported from 1960 to 1989, and (2) 90th percentile loads were calculated for each load component. Where applicable, 90th percentile load estimates include propagation of error estimates for flow and concentration as per Reckhow and Chapra (1983).
- Dilution additions are operationally not a reliable restoration measure for Moses Lake. Therefore, load assessments are made three ways: no dilution additions, the historical mean, and 90th percentile dilution additions.

Evaluation of Loading Assessments

- Rocky Coulee Wasteway annual base flow was estimated by Patmont (1980) to be 35 cfs. Annual loading to Moses Lake was calculated using this base flow and nutrient data collected from 1977 and 1978 (Patmont, 1980). The base flow was considered primarily spring-fed and thus assumed to be relatively constant throughout the year.
- Mean monthly and 90th percentile groundwater TP and TN loading contributions were calculated from monthly flow estimates (n=7-13 for each month) given in the reviewed reports (Sylvester and Oglesby, 1964; Welch et al., 1973; Patmont, 1980; and Jones, 1988) and reported average TP and TN concentration values of 51 ug/L (Jones, 1988) and 5.1 mg/L (Patmont, 1980), respectively. A coefficient of variation of 0.6 was assumed for the average concentration values. Annual mean and 90th percentile loads were calculated from the monthly values.
- Mean and 90th percentile internal loading was calculated from 12 annual loads reported by Welch et al. (1989).
- Nutrient loading by atmospheric deposition and direct precipitation onto Moses Lake was calculated from estimations by Patmont (1980) and Welch et al. (1989).
- Mean annual, 90th percentile, and 10th percentile TP and TN loads were calculated for Rocky Ford Creek and Crab Creek. Daily flow data from 1960 through the present were obtained from USGS who maintain flow monitoring stations on both creeks. Nutrient concentration data, reported from 1960 to 1989, were averaged monthly. Table 2 compares how significant study year flows and reported TP loads compare with the calculated mean, 90th percentile, and 10th percentile annual flows and TP loads.

The historical flow and loading perspective of Table 2 offers insight into the variable nature of Rocky Ford Creek's and Crab Creek's influence on Moses Lake and the different conditions between different study years. For example, the study year for Sylvester and Oglesby (1964) had approximately a 90th percentile flow and a mean P-load for Rocky Ford Creek while having below average flow and P-load for Crab Creek. Subsequently, Rocky Ford Creek was reported as the principal source of phosphorus contribution. However, a large P-loading to Moses Lake from 1968 to 1970 was observed by Welch et al. (1973), resulting from high flows for Rocky Ford Creek and very high flows for Crab Creek during those years (Figure 7). Accordingly, Welch et al. (1973) reported that Crab Creek was the principal source of phosphorus to Moses Lake. Likewise, Patmont (1980) examined Moses Lake from 1977 to 1979 when Rocky Ford Creek flows were low and Crab Creek flows were high, and he likewise found Crab Creek to be the principal source of phosphorus to Moses Lake.

Welch et al. (1989) and Bain (1993) reported generally improved water quality in Moses Lake with in-lake TP concentrations below the target goal of 50 ug/L during their

Table 2. Comparison of calculated mean, 90th percentile, and 10th percentile flows and phosphorus loads with historical study-year flows and loads.

	Crab Creek		Rocky Ford Creek	
	Annual Flow ^b (cfs)	Annual TP Load (kg)	Annual Flow ^b (cfs)	Annual TP Load (kg)
90 th Percentile	120	13778	94	14883
Mean	45	3614	69	10654
10 th Percentile	15	118	46	6520
Mar 1963-Feb 1964; Sylvester and Oglesby (1964)	30.4	2355 ^a	93.4	9694
Oct 1968-Sep 1969; Welch et al. (1973)	153.9	29216	94.3	12846
Oct 1969-Sep 1970; Welch et al. (1973)	138.7	21142	106	14682
Mar 1977-Feb 1978; Patmont (1980)	60	13070 ^a	71.6	9328
Mar 1978-Feb 1979; Patmont (1980)	55.8	9434 ^a	68.9	10318
Oct 1991-Sept 1992; Bain (1993)	32.5	NA	NA	NA
Jan 1997-Dec 1997; Bain (1998)	179.2	NA	88.6	NA

^a Includes Rocky Coulee Wasteway

^b Flows measured at gaging stations; Rocky Ford Creek and Crab Creek appear to have a 20% (Cusimano and Ward, 1998) and 10 cfs (Sylvester and Oglesby, 1964) increase in flow, respectively, enroute to Moses Lake from their gaging stations, attributed to groundwater inflow. Increases were not included in the above flows.

study years. The improved water quality in Moses Lake from about 1986 through 1995, with some of the best levels of trophic status indicators reported, may be viewed in context with the historical flow record as a period exhibiting the best of all circumstances for improved water quality. The average annual flows for Rocky Ford Creek and Crab Creek during this 9-year period were 42.5 cfs and 30.0 cfs, respectively, well below their mean flows and containing the lowest flows for the past 37-year record (1960-97). Except for 1989, Crab Creek did not have any high, late-winter runoff flows during this period (Figure 7). These late-winter run-off flows typically deliver the bulk of the phosphorus load for Crab Creek. In addition, dilution flows from the East Low Canal through Moses Lake were very high during this period, as the USBR replaced the missing run-off water which normally recharged Potholes Reservoir (Figure 4). This combination of low flows (i.e., low phosphorus loads) and high dilution flows during this period most likely explain the improved water quality in Moses Lake during this period.

On the other hand, a particularly high-flow event in 1997 for Crab Creek, along with the subsequent lack of need for dilution water in Potholes Reservoir that year, most likely explain the deteriorating water quality in Moses Lake observed by Bain (1998), with average TP levels of 100 ug/L in Parker Horn and South Lake transects. Likewise, Ecology personnel found elevated levels of TP (mean of 79 ug/L) in Lower Parker Horn during June through September of 1998, another year with above average flows for Crab Creek and Rocky Ford Creek and no dilution (Hallock, 1999).

The variation in flow (and resulting variation in loads) from Rocky Ford Creek and particularly Crab Creek, suggests that year-to-year variation of water quality in Moses Lake may be, at least partially, flow-driven. A seasonal lake model would be needed to verify this relationship. High flushing of nutrients in the Crab Creek drainage during some winter run-off events can contribute additional, large P-loads and N-loads to Moses Lake.

The goal of the TMDL assessment for this present study is to set preliminary load allocations to protect the water quality of Moses Lake during years of high nutrient loading from Crab Creek and Rocky Ford Creek.

A summary of calculated annual mean TP loads and 90th percentile TP loads for the individual components is presented in Table 3. The calculated annual 90th percentile TP total load is 44,113 kg/yr. Figure 8 presents the percent contributions of TP from individual sources for calculated mean loads.

Table 3. Summary of annual mean total phosphorus (TP) loads to Moses Lake.

Source Component	Mean TP (kg/yr)
Rocky Coulee Wasteway	1890
Crab Creek	3614
Rocky Ford Creek	10654
Groundwater	5368
Net Internal Sediment Release	6588
Precipitation	369
Total of Individual Loads	28482

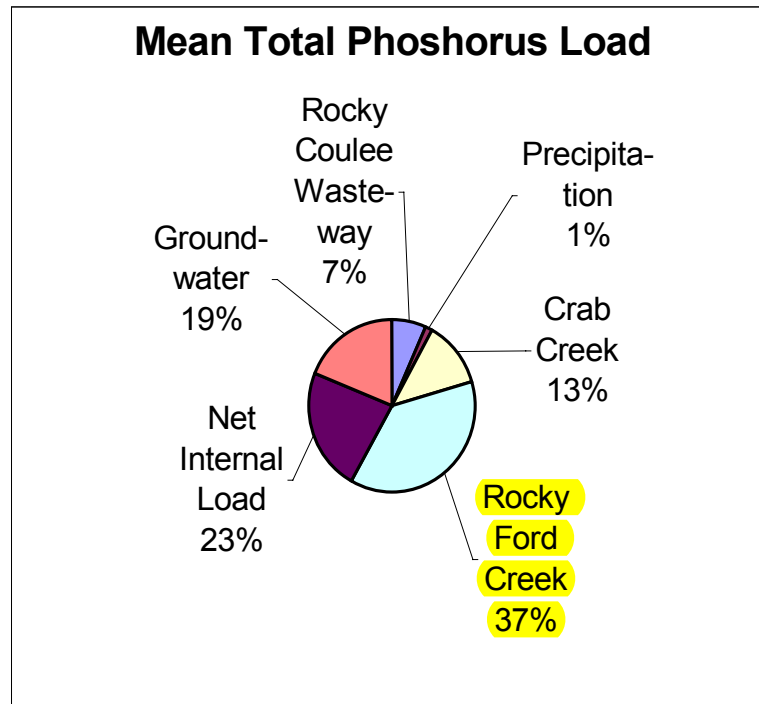


Figure 8. Percent contribution of individual loads to the mean total phosphorus (TP) load to Moses Lake.

Steady-State Model

A nutrient mass balance equation is an accounting of all the inputs and outputs, in this case, for TP. The steady-state solution to the mass balance equation presented by Reckhow and Chapra (1983) assumes that the average TP concentration in the lake is in equilibrium with the annual rate of input (external and internal loads) and output (sedimentation and outflow). The steady-state equation to solve for the average whole lake TP concentration is described as:

$$P = \frac{W + I}{vA + Q} = \frac{L}{v + q}$$

Where:

P = average whole lake TP concentration (mg/m³)

W = external TP load (mg/year)

I = net internal TP load (mg/year)

Q = inflow discharge rate (m³/year)

v = apparent TP settling velocity (m/year)

A = lake surface area (27.502 * 10⁶ m²)

L = (W+I)/A = areal TP load (mg/m²/year)

q = Q/A = areal hydraulic load (m/year)

The annual steady-state model is a simplified way to illustrate potential TP conditions based on different annual TP loading scenarios. The annual steady-state model was used to predict an average, whole-lake TP concentration in Moses Lake given changes in the relative magnitude of loading sources and dilution flows. The steady-state model provided an assessment of the annual total TP loading to Moses Lake and was used to develop preliminary TMDL allocation targets. A seasonal, whole-lake model could be developed, expanding on that done by Welch et al. (1989), and is recommended for further study.

The apparent settling velocity (v) describes the net settling velocity (in this case, for P) over the lake surface area and is used to calibrate the model to specific lakes as all the other terms are more readily measured. The steady-state solution equation was calibrated to Moses Lake by rearranging the equation to solve for the settling velocity (v) and then using study-year data from earlier reports to calculate a mean apparent net settling velocity. In this way, a mean net settling velocity for Moses Lake of 8.7 m/y was calculated. Table 4 presents the calibration data used to calculate the mean apparent net settling velocity used in the steady-state model. The year-to-year variation in the apparent net settling velocity was nearly 60% of the mean. The variation associated with the net settling velocity estimate most likely occurs because of the variability in year-to-year internal loading, linked to the variation in wind mixing and dilution water input.

The calculated mean apparent net settling velocity of 8.7 m/y for Moses Lake is low compared to reported values from literature. Mancini et al. (1983) reviewed published apparent settling velocities, and reported a range of averages from 12.4 to 16 meters per year based on a number of north temperate lake databases. While a mean apparent net settling velocity of 8.7 m/y for Moses Lake may be low, a margin of safety is provided by using this lower net settling velocity in the steady-state model, as this would reflect a more conservative, higher net release of TP from the sediments.

No correlation could be found between the calculated apparent settling velocities and hydraulic loads or the calculated apparent settling velocities and annual RTRs (relative thermal resistance or a dimensionless value reflecting thermal disruption of the water column primarily by wind) reported by Welch et al. (1989). A multiple regression of the above variables also showed no correlation. Perhaps a seasonal evaluation of these terms would correlate, as inclusion of the winter period may be affecting the correlation.

Preliminary Load Allocations

Using the calculated mean apparent net settling velocity of 8.7 m/y, the original steady-state solution equation was solved for the change in average, whole-lake TP concentration with mean loads, 90th percentile loads, and various dilution scenarios (e.g., mean dilution, 90th percentile dilution, and zero dilution). Table 5 presents a matrix of predicted in-lake TP concentrations based on the various loading and dilution combinations, as well as allocated load levels, needed to comply with the 50 ug/L TP in-lake criterion.

Table 4. Calibration data used to calculate apparent net settling velocity.

STEADY-STATE MODEL CALIBRATION	May through Sept only ⁴																
	1963-64 ¹	1968-69 ²	1969-70 ²	1977-78 ³	1978-79 ³	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Total Areal Nutrient Load (mg/m ² /yr)	1150	2493	2262	1622	1351	642	603	1125	527	545	729	1100	706	1273	561	599	850
Whole-lake Concentration (mg/m ³)	59	128	151	76	84	79	77	82	88	74	69	84	62	89	53	44	49
Areal Hydraulic Load (m/y)	8.0	10.7	11.6	16.2	14.1	4.4	6.2	9.6	3.9	3.6	8.9	6.1	4.8	12.0	7.5	10.1	8.1
Calibration Apparent Settling Velocity (m/y)	11.5	8.8	3.4	5.2	2.0	9.1	4.0	10.0	5.1	9.1	4.0	16.9	15.7	5.3	7.4	8.4	22.2
Mean and STD Deviation Apparent Settling Velocity:																	
	8.7	5.4															

¹ data from Sylvester and Oglesby (1964)

² data from Welch et al (1973)

³ data from Patmont (1980)

⁴ data from Welch et al (1989) - apparent settling velocities prorated to 12 months

Table 5. Predicted total phosphorus (TP) concentrations.

STEADY-STATE MODEL TP PREDICTIONS	Mean Load			90th% Load			Allocated Loads		
	Mean dilution	90th percentile dilution	Zero dilution	Mean dilution	90th percentile dilution	Zero dilution	30% Reduction dilution	18% Reduction dilution	11% Reduction dilution
Total Areal Nutrient Load (mg/m ² /yr)	1183	1326	1036	1752	1894	1604	1130	1435	1685
Mean Calibration Apparent Settling Velocity (m/y)	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
Areal Hydraulic Load (m/y)	15	20	8.8	20	25	13.9	13.9	20	25
Predicted Whole-lake Concentration (mg/m ³)	49.9	46.2	59.2	61.0	56.2	71.0	50.0	50.0	50.0

The matrix of loading scenarios provides managers with a range of possibilities to manage the in-lake TP concentration. As can be seen, a mean load entering Moses Lake is predicted to achieve the 50 ug/L TP criterion if a 90th percentile dilution flow occurs. The 50 ug/L TP criterion is also predicted to be barely achieved with a mean load and mean dilution flow. In the absence of a dilution flow, however, phosphorus levels will most likely not meet the 50 ug/L TP criterion, thus establishing the importance of dilution under the current management program.

Under no conditions is the TP criterion of 50 ug/L predicted to be achieved during a year with a 90th percentile load. Any dilution flows with 90th percentile loads are unlikely because the large inflows associated with 90th percentile loads fill up Potholes Reservoir, eliminating the storage capacity or need for either mean or 90th percentile dilution flows. The USBR has released only limited dilution water during very “wet” years; for this reason, dilution flows have not been a reliable restoration measure for Moses Lake. Whether Potholes Reservoir could be managed to allow dilution flows following high inflows is unknown to Ecology; this should be investigated further. Otherwise, these scenarios are not likely but are presented to provide a full spectrum of possibilities for comparison.

Total TP load allocations and reductions were established using the 90th percentile load and zero dilution scenario. This provides a level of safety where the characteristic uses of Moses Lake are protected to a level with only a 10% chance of exceeding the established water quality criterion, even during a year with no dilution. Dilution would reduce the amount of load reduction; however, as stated before, adequate dilution flow appears unfeasible given the hydraulic load involved with a 90th percentile load. A 30% total areal TP load reduction is required in order to meet the 50 ug/L in-lake TP criterion with no dilution (Table 5). This represents a maximum total annual loading capacity of 31,077 kg TP. As an alternative scenario, using a 90th percentile dilution flow, an 11% total areal TP load reduction would be required to meet a maximum total annual TP loading capacity of 46,341kg TP.

As an initial allocation strategy, all manageable loading sources were reduced equally until the maximum allowable incoming TP load of 31,077 kg was met. An additional 10% margin of safety (or reserve) was included in the budgeting to account for uncertainty related to estimation of loads and estimation of loading capacity for Moses Lake.

Rocky Coulee Wasteway, Rocky Ford Creek, and much of Crab Creek are supplied by groundwater. These, as well as groundwater directly entering Moses Lake, are all considered manageable sources. The water quality of the groundwater in the Moses Lake area is directly affected by land-use applications (e.g., agricultural fertilization, irrigation) in the Moses Lake watershed. Crab Creek, and Rocky Coulee Wasteway to a certain extent, are subjected to direct agricultural run-off (water and suspended particles) which could be managed by BMPs. In addition, within these general source components there are four regulatable fish rearing operations: one state Department of Fish & Wildlife fish hatchery on Rocky Coulee Wasteway, two private fish hatcheries on Rocky Ford Creek, and a Fish & Wildlife net pen facility in Moses Lake. Internal loading and precipitation were considered uncontrollable sources of TP to Moses Lake, although considering internal loading as uncontrollable also builds in a margin of safety, because eventually internal loads would be suppressed after external loads were reduced.

Table 6 presents load allocations for each of the major source components. Based on an annual loading capacity of 31,077 kg TP, an across-the-board load reduction of 50% from all of the manageable sources would be necessary to protect the characteristic uses of Moses Lake with a 10% exceedance of water quality goals. Table 7 presents a comparative load reduction of 31% for the same sources when combining a 90th percentile dilution flow with the 90th percentile load.

Table 6. Allocation of phosphorus for the major source components to Moses Lake for a year without dilution water input.

Source Component	Annual 90th Percentile TP Load Contribution (kg/yr)	% Contribution ¹	Control-able Source	Control-able TP Load (kg/yr)	Allocated TP Load (kg/yr)	Allocated Load % Contribution	TP Load Reduction Required %
Rocky Coulee Waste-way	2495	6%	Yes	2495	1257	4%	50%
Crab Creek	10400	24%	Yes	10400	5237	17%	50%
Rocky Ford Creek	11234	25%	Yes	11234	5657	18%	50%
Groundwater	8387	19%	Yes	8387	4223	14%	50%
Net Internal Load	11167	25%	No		11167	36%	0%
Precipitation	429	1%	No		429	1%	0%
10% Margin of Safety		0%			3108	10%	0%
TOTAL	44113	100%		32517	31077	100%	30%

¹ based on individual component's % contribution to the summation of all the individual component's 90th percentile TP loads.

In conclusion, even if dilution additions were a reliable restorative measure for Moses Lake, additional allocations and external load reductions would probably be needed to achieve the proposed phosphorus criterion 50% of the time (with a 10% margin of safety). Welch et al. (1989) reported success using dilution restoration measures to achieve water quality goals was apparently accomplished during a climatic “dry” period when external loads were low and dilution flows high. To achieve the proposed phosphorus criterion during a climatic “wet” period with high loading events, it appears that at least a 30% reduction in the total areal phosphorus load would be required for years without dilution flows. This corresponds to a 50% TP load reduction for Rocky Coulee Wasteway, Crab Creek, Rocky Ford Creek, and groundwater. With the exception of the regulatable fish hatchery operations, the majority of the load allocated to these four components is from nonpoint sources of which at least 75% are estimated to originate from agricultural operations. It is apparent that the success in achieving the proposed phosphorus criterion and maintaining the characteristic uses of Moses Lake will depend on the astute application of agricultural BMPs in the Moses Lake watershed.

Table 7. Allocation of phosphorus for the major source components to Moses Lake for a year with a 90th percentile dilution water input.

Source Component	Annual 90th Percentile TP Load Contribution (kg/yr)	% Contribution ¹	Control-able Source	Control-able TP Load (kg/yr)	Allocated TP Load (kg/yr)	Allocated Load % Contribution	TP Load Reduction Required %
Rocky Coulee Waste-way	2593	5%	Yes	2593	1796	4%	31%
Crab Creek	10806	21%	Yes	10806	7483	16%	31%
Rocky Ford Creek	11673	22%	Yes	11673	8083	17%	31%
Groundwater	8714	17%	Yes	8714	6035	13%	31%
Net Internal Load	11603	22%	No		11603	25%	0%
Precipitation	446	1%	No		446	1%	0%
Dilution Water	6262	12%	No		6262	14%	0%
10% Margin of Safety	0	0%			4634	10%	0%
TOTAL	52097	100%		33786	46341	100%	11%

¹ based on individual component's % contribution to the summation of all the individual component's 90th percentile TP loads.

Those managing Moses Lake will need to decide the reliability desired to protect the water quality of the lake (i.e., meeting the phosphorus target 50% versus 90% of the time or somewhere in-between). In addition, lake managers will need to determine the extent to which dilution flows will be used as a restoration measure in Moses Lake. Decisions on dilution may be based on what is possible (i.e., whether dilution flows can occur during “wet” periods) or negotiable. For example, it is not known the extent to which USBR would commit to providing consistent dilution flows to allow dilution to be used as a reliable restoration measure in Moses Lake).

Inadequacies of Historical Work

An initial review of the historical work on Moses Lake indicated that inadequacies in the historical data would not allow a thorough total maximum daily load (TMDL) assessment. In addition to publishing this report summarizing the historical studies of the lake, Ecology is proposing to conduct a study to assess the current status of nutrient loading to the lake and nutrient concentrations in the lake. This additional study will supplement the historical work to establish the load allocations for a final nutrient TMDL.

Ecology is planning to conduct this study during water year 2001 (October 1, 2000 to September 30, 2001). The major reasons for conducting this study are:

- No comprehensive water quality assessment of the lake has been done since the mid-1980s; multiple sources of data were used to develop the historical work, now 20 years old.
- Water quality data are needed to assign nutrient load allocations to the major nutrient sources. The historical work rarely addressed all the incoming loads at once and did not model the lake in a way to set a maximum incoming load of TP to achieve the 50 ug/L criterion.
- New water quality data, together with findings and recommendations from the historical studies, are needed to set nutrient TMDLs for the lake.
- A TP TMDL for Moses Lake is needed to satisfy the requirements of the federal Clean Water Act and to help meet the water quality goals established for the lake by the previous studies.

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Conclusions and Recommendations

1. Although Moses Lake is listed for both total phosphorus (TP) and total nitrogen (TN) on the 303(d) list, historical studies on Moses Lake have shown that TP is the nutrient to control to limit algal biomass. This strategy of managing TP to control the algal growth rate is supported in literature, even for lakes where nitrogen may be limiting growth. On this basis, Ecology recommends that Moses Lake be de-listed for TN from the 303(d) list and that future lake management decisions focus on the control of TP to manage algal biomass in Moses Lake.
2. Ecology proposes adopting the in-lake TP criterion of 50 ug/L to develop a nutrient TMDL for Moses Lake. Based on available knowledge, this nutrient criterion seems to protect the characteristic lake uses, has a basis in the historical lake restoration efforts as an achievable target, and probably best reflects the historical development of Moses Lake.
3. The dendritic nature of Moses Lake has allowed investigators to view the lake in a more complex manner, segmenting the different basins and arms for modeling purposes. Lake responses to loading changes and other restoration measures may vary in different parts of Moses Lake, suggesting the importance of regarding localized effects when evaluating management decisions. A dynamic computer model for Moses Lake should be developed to look at the seasonal and spatial effects of loading changes throughout the entire lake.
4. It is recommended to develop and maintain a sampling survey strategy to allow for a current annual assessment of nutrient loading to Moses Lake, including whole-lake nutrient concentrations. This will permit an evaluation of current restoration measures and their effects, as well as supplement historical work, in establishing TP load allocations for the major nutrient sources.
5. Currently under normal conditions, dilution (water addition) is critical to achieving water quality goals in Moses Lake. Historically, dilution has not been provided reliably as a restoration technique; dilution has been provided by the U.S. Bureau of Reclamation (USBR) on an as available basis. Moses Lake has been significantly altered by the Columbia Basin Irrigation Project. The hydrology and water quality of the inflows in the watershed have changed as a result of imported water and agricultural practices. As such, it would be cooperative if the USBR participated more in the responsibility of maintaining water quality in Moses Lake. Ecology recommends making binding agreements with the USBR to provide regular dilution on an annual basis, especially during critical conditions (May-September), so that dilution will be a reliable restoration technique used in the management of Moses Lake. It is also recommended to study the possibility of using dilution, even during high-flow years, for Crab Creek and Rocky Ford Creek.
6. Dilution can constitute a restorative management technique and be helpful in achieving water quality goals. However, to achieve these goals, particularly with a margin of safety, external loads will need to be reduced. A total external load reduction of 30% of manageable sources

will most likely ensure protection of water quality in Moses Lake. It is predicted that a load reduction of this order will result in a less than a 10% exceedance of the in-lake phosphorus criterion. A 30% load reduction should result in much better water quality during normal years, particularly if dilution water is available as well.

7. It is estimated that over 75% of the TP load to Moses Lake originates from agricultural fertilizers and farm animal wastes. As of 1989, it was reported that only 20% of irrigated areas had implemented water and nutrient controls, amounting to a potential nutrient concentration reduction of less than 2% in the Crab Creek inflows to Moses Lake. It is important to mitigate these agricultural sources to Moses Lake, as this is the key to reducing external phosphorus loads. The Moses Lake Clean Lake Project initiated irrigation and fertilizer controls concentrated in the Crab Creek watershed, but the study project concluded in 1990. Existing BMPs should continue to be monitored, and more extensive BMPs should be applied, within the Moses Lake watershed.
8. Rocky Ford Creek is generally driven by groundwater, either fed by springs or groundwater entering its channel enroute to Moses Lake. The average TP concentration of the spring source of this tributary is significantly elevated above the average TP concentration of groundwater elsewhere around Moses Lake (e.g., 98 ug/L versus 51 ug/L, respectively). An earlier study indicated that perhaps a direct conduit exists between Rocky Ford Creek's source springs and Brook and Round lakes, which serve as nutrient sinks in the Crab Creek drainage (Bain, 1985). Other agricultural blocks lying near Soap Lake were also indicated as a probable source of phosphorus. As the major source of TP during a normal year (37%), and given the unusual and yet consistent elevated TP levels, groundwater sources of TP for Rocky Ford Creek should be studied more fully to mitigate them. If controls can be designed for the groundwater TP sources, then TP limits for the fish hatcheries should also be established.
9. Crab Creek experiences variable flows. Large flow events can occur in late winter from run-off of melted snowfall and rain. These flow events carry large TP loads to Moses Lake, essentially flushing the Crab Creek drainage of nutrients. The necessary BMPs to help curb this late-winter flushing should be studied and implemented.
10. Ecology recommends that daily flow monitoring on Rocky Ford Creek be reinstated by the U.S. Geological Survey. Also, a discharge relationship for the mouth of Rocky Ford Creek and the gaging station should be developed.
11. It is unclear from the reviewed material what the impact of on-site septic and increased near-shore development is having on Moses Lake. It is recommended to study the effect of these as well as stormwater on Moses Lake because of the increased development around the lake.
12. The Larson wastewater treatment plant discharges to groundwater, eventually flowing in a southwesterly direction and most likely intercepting the Rocky Ford Arm of Moses Lake. The effect this facility is having on nutrient loading to Moses Lake should be studied.

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