Upper Occoquan Service Authority

Leader in Water Reclamation and Reuse

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RE: EPA Water Docket ID No. EPA-R03-OW-2010-0736, Draft Total Maximum Daily Load ("TMDL") for the Chesapeake Bay; and Virginia Chesapeake Bay Watershed Implementation Plan ("WIP")

To Whom It May Concern:

The Upper Occoquan Service Authority (UOSA) appreciates the opportunity to provide comments on the Draft Chesapeake Bay Total Maximum Daily Load (TMDL) document dated September 24, 2010. UOSA is an advanced water reclamation plant located in Centreville, Virginia and it serves the western portions of Fairfax and Prince William Counties, and the Cities of Manassas and Manassas Park.

In the draft TMDL the UOSA total nitrogen waste load allocation (WLA) was reduced from 1,315,682 pounds/year (in short, 1.316 million pounds/year) to 657,841 pounds/year. This reduction appears on Page 9-36 of the draft TMDL, and it is consistent with the backstop allocations and measures EPA imposed on the Commonwealth of Virginia, as discussed in Chapter 8 of the TMDL draft document. The comments and exhibits submitted herein provide unequivocal information that shows that reducing the UOSA TN WLA in any future Bay TMDL would be detrimental to Northern Virginia's water supply and would also result in increased loads of phosphorus and nitrogen delivered to the Potomac River and the Chesapeake Bay. Such detrimental effects are contrary to the purpose and restoration goals of the Bay TMDL.

Historical Background

The TN WLA assigned to the UOSA water reclamation plant in its VPDES Nutrient General Permit VAN010019, namely, 1.316 million pounds/year, recognizes that the highly nitrified UOSA reclaimed water has benefited the water quality of the Occoquan Reservoir, which is a critical component in a drinking water supply system that serves nearly 1.7 million people in Northern Virginia.

In the 1960's the Occoquan was afflicted by serious water quality problems such as:

- Massive algal blooms (including blue-green algae) due to over-enrichment with plant nutrients;
- Periodic episodes of taste and odor problems in the finished drinking water;
- Periodic fish kills; and
- Generation of hydrogen sulfide in the sediments due to anaerobic decomposition of organic matter.

At that time the Virginia State Water Control Board took several bold actions aimed at correcting the water quality degradation of the reservoir. Engineering studies conducted under the auspices of the Board identified substandard discharges from secondary effluent wastewater treatment plants and nonpoint source runoff as major culprits. The Board's efforts culminated in the promulgation of the Occoquan Policy (9VAC25-410).

The Policy mandated corrective actions including the creation of a regional advanced water reclamation plant, UOSA, and an independent entity for the purpose of water quality surveillance and evaluation, the Occoquan Watershed Monitoring Laboratory (OWML). OWML is operated by the Virginia Tech Department of Civil Engineering, and it is overseen by the Occoquan Watershed Monitoring Subcommittee (OWMS) on behalf of the State Water Control Board.

UOSA has operated its water reclamation facility for over 30 years meeting very stringent permit limitations imposed by the Occoquan Policy. For example, since 1978 the UOSA plant has consistently complied with a total phosphorus permit limit of 0.1 mg/L, which is considered the limit of technology for phosphorus removal. Research and water quality surveillance conducted by OWML indicates that the UOSA discharge has substantially improved the water quality of the Occoquan Reservoir.

Summary of Research and Surveillance Results

OWML's research has unequivocally shown that nitrate provides an oxidizing environment in the lower layers of the reservoir during times of thermal stratification. In other words, the Occoquan Reservoir is a natural denitrification system. As summarized in the OWML report entitled *An Assessment of the Water Quality Effects of Nitrate in Reclaimed Water Delivered to the Occoquan Reservoir, April 2005*, the nitrate-rich

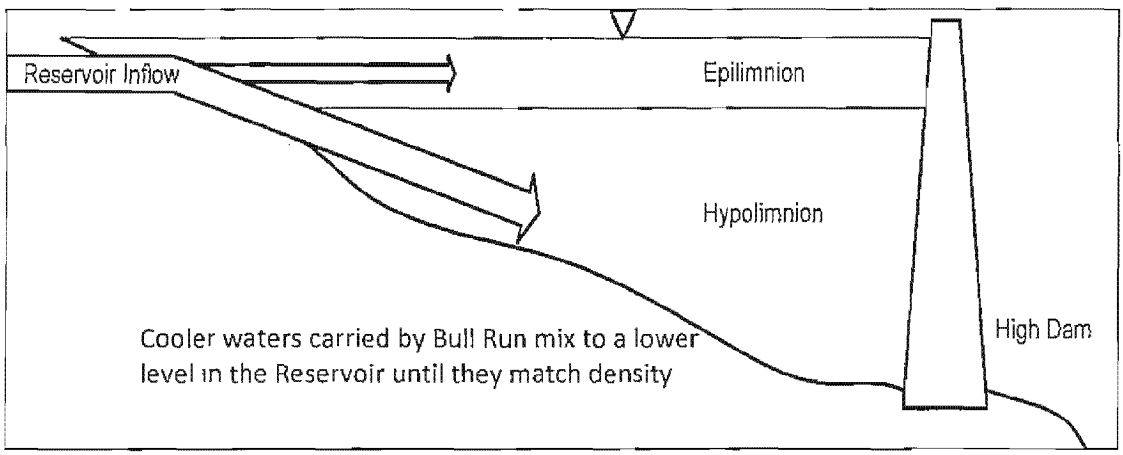
UOSA reclaimed water has benefited the Occoquan Reservoir water quality, specifically by:

- Preventing the release of sediment bound phosphorus;
- Reducing the release of ammonia from reservoir sediments;
- Preventing the reduction of sulfate to sulfide in the bottom layers of the reservoir;
- Possibly preventing the release of manganese (II) from sediments; and
- Maintaining green algae and diatoms species dominance and preventing the proliferation of less desirable blue-green algae.

The 2005 OWML report was endorsed by the OWMS on June 9th, 2005. A copy of the OWML 2005 report is included as Exhibit 1.

The process by which the UOSA highly nitrified reclaimed water exerts a protective action on the Occoquan is fortuitous and it occurs when the reservoir is thermally stratified. Under thermal stratification the cooler water is kept at the bottom and warmer water in the top layer. Under normal weather conditions these two layers do not mix due to differences in temperature and density and, therefore, dissolved oxygen from the atmosphere does not reach the bottom water layer. As summer progresses, dissolved oxygen is depleted in the bottom layer due to biological activity and, without another source of oxygen, water quality deteriorates. Fortunately, the cooler, nitrate-rich water of Bull Run, where the UOSA effluent is discharged, mixes downward in the reservoir until temperature and density match providing nitrate as an oxygen equivalent to the dissolved oxygen deficient lower layer. Figure 1 is a schematic showing this natural phenomenon. As long as nitrate persists in the bottom layer of the reservoir, the phosphorus and ammonia supply to the water column is reduced preventing the proliferation of nuisance algae and water quality degradation. The positive effect of nitrate on the control of sediment-bound phosphorus and ammonia has been documented by OWML in both laboratory scale experiments utilizing reservoir sediments and by data collected at the reservoir over many years. Exhibit 1 provides a summary of OWML's research and long term water quality surveillance.

Figure 1



Source: OWML

Recent Water Quality Effects Due to TN Loads Reduction

Exhibit 2 provides details on detrimental water quality effects recently observed during a period where the UOSA nitrate load to the Occoquan Reservoir was reduced. During 2007 – 2008 UOSA reduced its nitrate load to the Occoquan while operating its nitrogen removal system for the purpose of gaining operational experience. Summer data collected during that period showed near zero nitrate levels in the lower levels of the reservoir and increased levels of nutrients released from the sediments. For example, in the summer of 2007 as the nitrate concentration in the bottom layer of the reservoir was near zero, the Occoquan Laboratory detected a maximum of 5 mg/L of ammonia nitrogen and over 1 mg/L of phosphorus, much of it in the dissolved form. During the fall season circulation (turnover), such conditions are known to cause algae blooms due to nutrient over enrichment, which in turn lead to water quality degradation. The data in Exhibit 2 also indicates that removing nitrates from the reservoir may result in increases of nitrogen and phosphorus delivered to the Potomac River and the Chesapeake Bay.

UOSA's Waste Load Allocation in the VPDES General Permit and Further Reduction Due to Backstop Measure

During the VPDES Nutrients General Permit (9VAC25-820) public comment period, Dr. Grizzard, OWML's Director, expressed concern that the current allocation of 1.316 million pounds/year of nitrogen (8 mg/L at 54 mgd capacity) in the UOSA Nutrient General Permit may not be adequate at all times to prevent nitrate deficiencies and the resultant consequences discussed previously. However, UOSA accepted its VPDES General Permit with that TN allocation and has committed to manage nitrate discharges to match what is best for Occoquan water quality to the extent practicable and still not exceed its allocation. If UOSA's allocation were reduced to 657,841 pounds/year, UOSA would be in a position of having to conduct a year-round maximum denitrification effort which would undoubtedly result in nitrate deficiencies and a significant release of phosphorus, ammonia and manganese from reservoir sediments. The backstop measure of reducing UOSA's TN WLA from 1.316 million pounds/year to 657,841 pounds per year could result in the degradation of the Occoquan Reservoir's water quality similar to the pre-UOSA 1960s condition and also increase nutrient loads to the Potomac River and the Bay.

Dr. Grizzard, OWML's Director, and Dr. Randall, an Emeritus professor at the Virginia Polytechnic Institute and State University (Virginia Tech) and Chairman of the OWMS, will submit comments to the EPA docket opposing the reduction of the UOSA TN WLA. Mr. Charles M. Murray, Fairfax Water's General Manager, in his letter dated October 20, 2010 also expressed concerns regarding the reduction of the UOSA TN WLA in the draft Bay TMDL. Fairfax Water is the purveyor who owns and uses the Occoquan Reservoir to supply drinking water to most of Northern Virginia. In his letter Mr. Murray agrees that research and monitoring shows a strong relationship between reduced nitrate levels

in the Occoquan Reservoir and increases in ammonia and phosphorus in the water column, which expose Fairfax Water to increasing water quality challenges. A copy of his letter is provided as Exhibit 3.

EPA's Draft TMDL Backstop Actions on the Virginia Draft Phase I Watershed Implementation Plan (WIP)

UOSA believes that the Virginia draft WIP is based on solid guidance principles such as equity and cost effectiveness. The Virginia Phase I WIP also provides the regulatory stability point sources need to continue reducing nutrients loads to the Bay. Virginia (via its Water Quality Improvement Fund) and publicly owned treatment works (POTWs) have made and continue to make large investments in capital projects to reduce the inputs of nutrients to the Bay. Capital projects design and construction need to be based on firm long term water quality treatment goals. Continuously changing water quality goals will result in wasted public funds during one of the worst economic recessions in the Commonwealth and the nation and it also defies fiduciary responsibility.

UOSA has already invested $1.8 million in the design of the secondary treatment upgrades (a subset of a $94 million nutrient reduction capital project) to be able to meet the TN WLA of 1.316 million pounds/year (based on 8 mg/L and 54 mgd) as flows increase. Reducing the UOSA TN WLA, as shown in the EPA Bay Draft TMDL, would require a delay and additional costs to allow UOSA to re-direct and re-start the design process. Such a re-direction would be a waste of scarce public funds and, as explained above, would be contrary to the protection of the Occoquan Reservoir, the Potomac River and the Chesapeake Bay.

UOSA agrees with Virginia that the proposed expanded Chesapeake Bay Watershed Nutrient Credit Exchange Program as presented in its Draft Phase I WIP would result in meeting pollution reductions and cap load allocations cost-effectively and as soon as possible. Virginia's demonstrated successful track record implementing the current Nutrient Credit Exchange Program should be considered reasonable assurance in EPA's evaluation of the VA WIP.

We have significant concerns with EPA's Draft TMDL and object to EPA's threatened "backstop" actions against waste water treatment plants (WWTPs). EPA currently proposes to cut Virginia's stringent nutrient waste load allocations ("WLAs") currently set forth in Virginia's EPA-approved Water Quality Management Planning Regulation, 9VAC25-720, and Chesapeake Bay Watershed General Permit Regulation, 9VAC25-820 (collectively, the "Virginia Regulations"). EPA also threatens to cut WWTP allocations further to so-called "full backstop" levels, which would decrease the concentration basis further (3 mg/L TN and 0.1 mg/L TP at design flow) and possibly even the flow basis to past flow levels (2007 to 2009 average flow rather than design flow). This would reflect an unfair, punitive action by EPA that would do little to advance the Bay cleanup, which

necessarily depends on major nonpoint source reductions because the Bay is a nonpoint source dominated system with roughly 80 percent of the nutrient load attributable to nonpoint sources.

Given Virginia's good track record of achieving nonpoint reductions, we disagree with EPA's initial view that Virginia did not provide sufficient reasonable assurance on nonpoint loads reduction.

What is distinctly missing from EPA's Draft TMDL is any appreciation for the major commitments very recently made by EPA and Virginia (the State's adoption and EPA's approval of the Virginia Regulations in 2005 and 2007) and the major financial commitments that local governments have made to implement those requirements including incurring significant public debt (typically with 20 to 30 year repayment terms) and constructing major new facilities (typically built to last 20 to 30 years). As an organization with a demonstrable commitment to clean water, we object to the waste inherent in EPA's threatened override of the Virginia Regulations and Virginia WIP through the Draft TMDL and its elements that relate to our WLAs.

Incorporation by Reference

We understand that the Draft TMDL is fundamentally and materially flawed. These deficiencies are thoroughly documented in the comments of the Virginia Association of Municipal Wastewater Agencies, Inc. ("VAMWA"). We request that EPA fully consider and address all of VAMWA's comments, which we generally support and hereby incorporate by reference as if fully set forth herein.

Summary

UOSA requests that the TN WLA of 1.316 million pounds/year be preserved in any future Chesapeake Bay TMDL. Research and water quality surveillance have unequivocally shown that reducing UOSA's TN WLA will result in water quality degradation of the water supply.

The draft TMDL document Executive Summary states:

> "It is important to note that the pollution controls employed to meet the TMDL will also have significant benefits for water quality in tens of thousands of streams, creeks and rivers throughout the region." (Executive Summary, Page 3)

As it stands, the draft Bay TMDL is not protective of the Northern Virginia water supply. EPA officials, in public meetings have acknowledged that the broad brush backstop provisions may not be the smart way to address local considerations such as the protective nature of the nitrate in UOSA's discharge. We strongly encourage EPA to do the correct and smart thing for the Occoquan, its 1.7 million drinking water customers,

the Potomac and the Bay and remove from the TMDL any further consideration of the backstop provision as it applies to UOSA. We urge EPA to restore the UOSA's TN WLA to 1.316 million pounds/year.

If you have questions regarding this mailing, please contact Evelyn Mahieu, UOSA Regulatory Affairs Coordinator at (703) 227-0202 or me at (703) 227-0204.

Sincerely,

Charles P. Boepple
Executive Director

cc: Department of Environmental Quality, Virginia

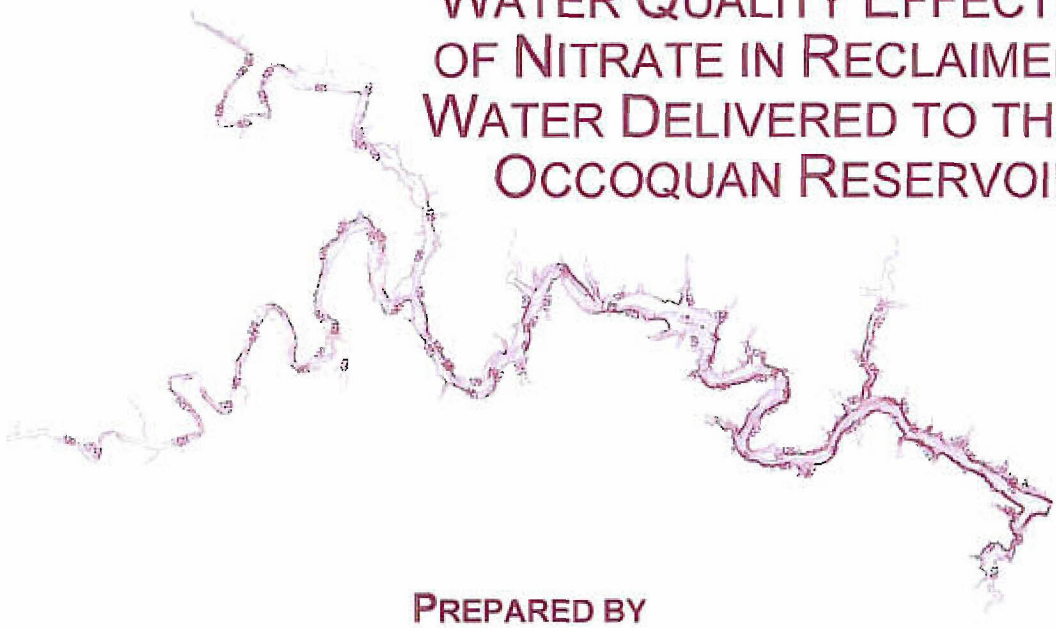
EXHIBIT 1

OWML report - *An Assessment of the Water Quality Effects of Nitrate in Reclaimed Water Delivered to the Occoquan Reservoir, April 2005*

Exhibit 1

Virginia Tech

An Assessment of the Water Quality Effects of Nitrate in Reclaimed Water Delivered to the Occoquan Reservoir



Prepared by

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April, 2005

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INTRODUCTION

GENERAL

The U.S. Environmental Protection Agency (US EPA) has designated portions of the Chesapeake Bay and its tidal tributaries as impaired waters under the definitions of the Clean Water Act (as amended through PL 107-303), largely due to the occurrence of low dissolved oxygen conditions and other problems related to nutrient pollution.

In 2000, in order to further the objective of restoring and protecting the Chesapeake Bay and its tributaries, key watershed state governments, EPA, and the Chesapeake Bay Commission entered into an agreement known as *Chesapeake 2000*. One of the goals of the document related to nutrient pollution is that by 2010, the signatories will correct the nutrient-related problems in the Bay and its tributaries sufficiently to remove them from the EPA list of impaired waters.

In moving towards meeting its commitments under the Chesapeake 2000 Agreements, the Commonwealth of Virginia has taken a number of steps:

- The Commonwealth has accepted nutrient load allocations assigned for its waters as a result of modeling studies performed by the EPA Chesapeake Bay Program;

- The Commonwealth, in consultation with local governments and other groups, has developed Tributary Strategies for the reduction of nutrient loads from its five major watershed draining to the Bay;

- Following development of the Tributary Strategies, the Secretary of Natural Resources for the Commonwealth issued a policy statement regarding new requirements for nutrient removal from point source discharges in Virginia;

- Following the policy directive from the Secretary of Natural Resources, the Virginia Department of Environmental Quality (Va DEQ) Quality has issued drafts of two proposed regulatory actions:

    - To amend the Policy for Nutrient Enriched Waters (9 VAC 25-40) which will set nutrient concentration limitations for point sources;

    - To amend the Water Quality Management Planning Regulation (9 VAC 25-720) which sets nutrient load allocations for point sources;

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The proposed regulatory actions were approved by the Virginia Water Control Board to be released for public comment in late 2004

The Board is currently holding public meetings on the proposed regulations and anticipates receiving comment until 25 April, 2005.

ISSUES FOR THE OCCOQUAN WATERSHED

The draft regulations cited above have been formulated with specific Chesapeake Bay restoration goals in mind, namely the reduction of nutrient loads delivered to the Bay in point source discharges. While this is an arguably simple and direct approach to dealing with point source contributions to the nutrient enrichment of the Bay and its tributary tidal estuaries, it should be examined for applicability to and unanticipated consequences for other waters of the Commonwealth.

The Occoquan Reservoir plays a unique role in northern Virginia with respect to public water supply and the indirect potable reuse of reclaimed water to supplement that supply. The draft regulations being considered by DEQ have some specific performance requirements for point sources related to nitrogen removal. Because a unique approach to nitrogen treatment has been a key component of the successful management of water quality in the Occoquan Reservoir, serious questions have been raised about the effects of implementing the new point source regulations, particularly with respect to the nitrogen removal requirement.

As currently envisioned, the point source nutrient control requirements would, at least, require the Upper Occoquan Sewage Authority Water Reclamation Facility (UOSA WRF) to remove total nitrogen (TN) to an average of 8 mg/L in the plant discharge. It also appears possible that future expansions of the WRF would require nitrogen removal to the currently-accepted limit of technology (LOT), which is 3 mg/L. Because the UOSA WRF has, for over a quarter century, provided a highly nitrified discharge to the Occoquan Reservoir, and because that discharge has produced well-understood water quality benefits, it seems prudent to thoroughly assess the chemistry and biochemistry of the system prior to initiating any major changes in operating protocols.

In order to provide relevant information, the Board of Directors of the Upper Occoquan Sewage Authority and representatives of local governments in the UOSA service area have made the following requests of the staff of the Occoquan Watershed Monitoring Program:

- To conduct an evaluation of existing data regarding the impacts of the UOSA WRF discharge on the Occoquan Reservoir, particularly as it relates to nitrogen management and any attendant effects on water quality;

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- To provide an assessment of the possible water quality risks of altering current UOSA WRF operations to conform with the nitrogen management strategy being proposed by DEQ.

- To identify information deficiencies, and to recommend additional studies that will be necessary to remedy those deficiencies.

THE OCCOQUAN WATERSHED

The Occoquan Watershed, which is shown on the location map in Figure 1-1, is situated in northern Virginia on the southwestern periphery of the Virginia suburbs of the City of Washington, D.C. The basin encompasses six political subdivisions of the Commonwealth of Virginia, including portions of four counties, and the entire land area of two independent cities, as follows:

- County of Fairfax
- County of Fauquier
- County of Loudoun
- County of Prince William
- City of Manassas
- City of Manassas Park

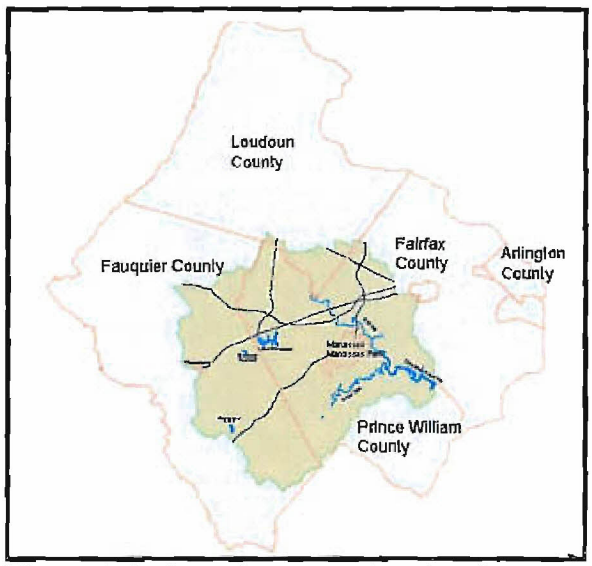

Figure 1-1. Location map showing the Occoquan Watershed in northern Virginia.

Following the end of the Second World War (WWII), the Washington Metropolitan Region experienced unprecedented growth. In the early years of the post-war period, that growth was mostly centered in the close-in jurisdictions of both the Maryland and Virginia suburbs. In Virginia, development was initially most pronounced in Arlington County and the City of Alexandria. In time, however, development continued to move away from the central urban core, reaching westward into Fairfax County, and towards Prince William County to the south. Growth was facilitated initially by the completion of I-95, the north-south interstate highway of the region, and in later years by the extension of I-66, which traverses northern Virginia in an east-west alignment. In the last three decades of the 20th century, substantial urban growth took place in the Occoquan Watershed upstream of the Occoquan Reservoir.

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THE OCCOQUAN RESERVOIR

The earliest documented use of the Occoquan Basin for public water supply took place in 1950 when the Alexandria Water Company constructed a low head (30-foot) dam and reservoir impounding a water storage volume of approximately 55 million gallons upstream of the small town of Occoquan, Virginia. In response to growing regional water supply needs, the low head facility was replaced in 1957 by a high dam and reservoir, which was located upstream of the low-head dam, and constructed to impound nearly 10 billion gallons. Backwater from the new reservoir pool extended to a point upstream of the confluence of the two principal tributaries, Bull Run and Occoquan Creek.

In 1967, ownership of the Reservoir and associated treatment works passed to the Fairfax County Water Authority (FCWA), which continues to operate the system as of this date, albeit as Fairfax Water (FW). In the years following its completion, the Occoquan Reservoir has come to be a major component of a drinking water system that services most of the Virginia suburbs of the national capital region. With its combined raw water sources from the Occoquan Reservoir and the Potomac River, FW now serves a customer base in excess of 1.2 million.

When initially constructed, the Occoquan Reservoir had an estimated storage capacity of 9.8×10^9 gallons, and a computed safe yield of about 65 million gallons per day (MGD). At the time of its completion, the 570 square mile watershed tributary to the reservoir was principally of an undeveloped rural character, which was anticipated at the time to contribute to the long term maintenance of a high quality source water. This assumption, did not of course, foresee the level of development, and the attendant wastewater flows and nonpoint source pollution that was to take place in later years.

Figure 1-2 shows a 1977 aerial view of the Reservoir and high dam looking westward towards the City of Manassas and western Prince William County. The photograph also illustrates the long and narrow shape of the reservoir, a feature which contributes to the plug-flow nature of water flow in the impoundment. At the present time, much of the southern shoreline of the Reservoir (left in the photograph) has been developed. As a result of a downzoning decision in Fairfax County in 1982, much of the northern shore remains in low density uses or park land.

Figure 1-2. Aerial view of Occoquan Reservoir and high dam, 1977.

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WATER QUALITY CONSIDERATIONS

As the aforementioned suburban expansion began to reach into the upper Occoquan Watershed in the 1960's, a variety of unanticipated water quality problems were experienced. Coincident with the accelerated population growth, a number of small wastewater treatment plants were constructed and/or expanded in western Fairfax County and central Prince William County, resulting in substantial increases in the discharge of domestic wastewaters to the surface waters of the watershed. By the late 1960's, eleven (11) publicly owned treatment works (POTWs) of conventional secondary design were discharging an average of nearly three (3) million gallons per day (MGD) of treated wastewater to the basin. The quality of the plant effluents was quite variable, and no provisions had been made at the time for the removal of plant nutrients such as nitrogen and phosphorus from the discharges.

The pace of watershed development also resulted in increases in urban stormwater runoff in the watershed. Increased conventional agricultural activity in the western basin, along with the application of chemical fertilizers, resulted in greater soil erosion, and the accompanying loss of nutrients in surface runoff.

By the mid- to late-1960's, with scarcely a decade of service as a municipal raw water supply, the consequences of the changes in basin activity were readily apparent in the Occoquan Reservoir, resulting in:

- Massive algal blooms (including blue-green algae of the genus *cyanobacter*) due to over-enrichment with plant nutrients;
- Periodic episodes of taste and odor problems in the finished drinking water;
- Shortened filter runs due to clogging with algal cells during bloom conditions;
- Rapid hypolimnetic deoxygenation due to the accumulation of allochthanous and autochthanous organic material in the reservoir;
- Periodic fish kills due to oxygen depletion during periods of algal respiration;
- Generation of hydrogen sulfide in the bottom waters of the reservoir during anaerobic decomposition of accumulated organic matter;

In later years, viable human enteric viruses were also detected in watershed tributaries, particularly Bull Run, and also in the Reservoir (Hoehn, *et al.*, 1977).

Several photographs from the late 1960's and early 1970's provide a useful illustration of the intensity of the algal blooms experienced at the time. Figure 1-3 is a photograph

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of a bloom of the blue-green algae *Microcystis*, at a mid-reservoir location in June, 1969. Note the presence of clumps of algae floating on the water surface.

Figure 1-4 is a photograph of a *Microcystis* bloom in the summer of 1973. Note that the algal mat is essentially continuous across the entire surface of the Reservoir.

Figure 1-5 is an additional photograph of the summer, 1973 *Microcystis* bloom, and also shows the contrast from the wake of a sampling boat moving through the algal mats on the reservoir surface.

Figure 1-3. *Microcystis* bloom at Jacob's Rock (mid-reservoir), 24 June, 1969. (Photograph courtesy of Metcalfe and Eddy.)

Figure 1-4. *Microcystis* bloom in the Occoquan Reservoir, summer, 1973.

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Figure 1-5. Boat wake through *Microcystis* bloom, summer, 1973.

As the conditions described previously became commonplace, and because the Occoquan Reservoir had become an irreplaceable component of the long-term water supply planning for the suburbs of northern Virginia, it was apparent that action would be required to insure the long-term viability of the impoundment as a raw water source.

In 1968, in recognition of the seriousness of the water quality problem, the Virginia State Water Control Board (VSWCB) imposed a sewer connection moratorium pending development of an acceptable management plan for the Reservoir that would protect its principal use as a major public water supply. The Board commissioned a study of the Reservoir and its tributary streams by the consulting engineering firm of Metcalf and Eddy (1969), with the goal of developing a management plan for the surface waters of the basin. That study, completed in 1970, stated that the reservoir was "highly eutrophic...", and further, that "the sewage plant effluents are mainly responsible for the advanced stage of eutrophication occurring..." Following completion of the 2-year study, the engineering firm formulated three alternative management approaches for the watershed, which are listed below in the proposed order of preference (Metcalf and Eddy, 1970):

- ...total containment of all sewage treatment plant effluents and their export out of the Occoquan Watershed."
    - The recommendation also called for strict sanitary sewer separation and rehabilitation, as well as control of agricultural nonpoint sources and soil erosion.

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- "Provision for the most advanced methods of wastewater treatment to accomplish removal of carbonaceous matter, harmful organisms, and algal nutrients..."

    - The recommendation also called for water purveyors in the watershed to be contracted to accept highly treated wastewaters pumped to their water treatment plants for direct reuse, and to limit the basin population to that number of individuals whose wastewater could be sold.

- "...total population within the Occoquan Watershed be restricted to 100,000 people, and all wastewaters ... subjected to the highest degree of treatment known to accomplish nutrient removal..."

    - The recommendation also stated that sewage overflow and agricultural nonpoint source controls would be required as in the first recommendation. It was also noted that such strict controls, including removal of both inorganic phosphorus and nitrogen from wastewater to concentrations of 0.02 mg/L and 0.35 mg/L, respectively, might make it possible to ultimately accommodate up to 10 MGD of highly reclaimed wastewater in the watershed.

After considering the Metcalf and Eddy report and recommendations, VSWCB, led by its Chairman, Noman M. Cole, Jr., rejected the first recommendation, principally because it entailed a loss of reclaimed wastewater that would be a future resource in the watershed. It is fair to say that, having taken that view, the Board had concluded that the Occoquan Program would eventually be built around a philosophy of indirect potable reuse.

The second recommendation was deemed unacceptable, principally because it called for direct potable reuse of reclaimed wastewater using technologies that had never, at the time, been proven at the full plant scale.

The third recommendation, with the exception of the population limitation proposal, is very similar to what was ultimately adopted by the Board in *A Policy for Wastewater Treatment and Water Quality Management in the* Occoquan Watershed (VSWCB, 1971).

THE OCCOQUAN POLICY

In July of 1971, after considering the recommendations of the Metcalf and Eddy report, the SWCB adopted *A Policy for Waste Treatment and Water Quality Management in the Occoquan Watershed* (VSWCB, 1971). As noted above, recognizing the practical

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limitations imposed by both the inter-basin transport of wastewaters and the imposition of population limitations, the *Occoquan Policy*, as it has come to be known, was based on a modification of the third option shown above. A milestone in water quality management in the Commonwealth of Virginia, the United States, and internationally, the *Policy* included an implicit recognition of the value of highly reclaimed wastewater as a resource, and that indirect potable reuse of reclaimed water would become the operational norm in the Occoquan Watershed.

The *Policy* also recognized that extraordinary measures would be required to protect the public health in a situation where reclaimed water was to be intentionally retained in a water supply reservoir. In addressing this, the document not only specified the type of waste treatment practices to be adopted on a watershed-wide scale, but it provided for an ongoing program of water quality surveillance to quantify the success of the water quality protection effort.

THE UPPER OCCOQUAN SEWAGE AUTHORITY

The creation of the Upper Occoquan Sewage Authority (UOSA) was mandated by the *Occoquan Policy*, and the local governments of the central basin participated in its constitution as a public service authority. UOSA was formed with voting representation from the Counties of Fairfax and Prince William County; and the Cities of Manassas and Manassas Park. The other jurisdictions with land area in the basin, the Counties of Loudoun and Fauquier, were not included in the UOSA service area, because at the time, they did not contribute significant wastewater flows to the watershed.

The *Occoquan Policy* did, however, recognize that future development might require the construction of water reclamation facilities (WRFs) to serve other parts of the watershed, and provisions were included to allow for up to two additional plants to be constructed at later dates.

The *Occoquan Policy* required that the initial WRF to be constructed by UOSA represent, and in some cases, go beyond what was then understood as the state of the art in water reclamation process design. This was necessary because of the requirement for high reliability, high efficiency removal of particulate matter; degradable organic matter; potentially toxic synthetic organics; the algal nutrients nitrogen and phosphorus; and pathogenic organisms, including bacteria and viruses. In addition to the unique process design requirements imposed by the special considerations of indirect discharge to a public water supply, the plant was also designed with unusual requirements for redundancy in treatment capacity, units, and power supplies. The result of the design effort by UOSA and the consulting firm of CH_2M-Hill was a plant of extraordinary treatment capability. At the time, it represented a unique full-scale application of biological/physical/chemical treatment technology that was unparalleled in the Commonwealth of Virginia, the United States, and perhaps the entire world.

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The UOSA Advanced Wastewater Reclamation Facility was placed in service in the summer of 1978, replacing the previously mentioned 11 POTW's providing secondary treatment in its service area. From that time forward, the pollutant loads contributed to the Occoquan Basin directly from treated wastewater sources have ceased to be a significant factor in the determination of stream or reservoir water quality. In fact, as will be seen later in this report, the inputs of at least one constituent, oxidized nitrogen, contained in the UOSA discharge have had the unusual effect of actually improving and protecting water quality in the Occoquan Reservoir.

At the present time, UOSA is just completing an expansion of its treatment works to accommodate flows of 54 MGD. As noted earlier, the safe water supply yield of the Occoquan Reservoir (from natural stream flow) has been estimated to be approximately 65 MGD. The supply of a base reclaimed water flow of approximately 38 MGD from the UOSA WRF may be expected to increase the safe yield by over 50 percent. In fact, Fairfax Water, recognizing the importance of the reclaimed water supplement to water supply yield, is constructing a new treatment works (the Fred W. Griffith Water Treatment Plant) adjacent to the Occoquan Reservoir to replace existing facilities that date back to the 1950s. The new treatment works has been designed to provide state-of-the-art water treatment, and to have production capacity of approximately 120 MGD in order to take full advantage of the supply of reclaimed water.

THE OCCOQUAN WATERSHED MONITORING PROGRAM

The *Occoquan Policy*, in addition to mandating the adoption of advanced water reclamation practices at all new regional wastewater treatment plants in the Basin, also included an innovative requirement for the establishment of an independent entity for the purpose of water quality surveillance and evaluation. In the words of the Policy, "to insure that performance levels are maintained at the ... plant, and that the effects of discharges and urban run-off (*sic*) are known." The Occoquan Watershed Monitoring Subcommittee (OWMS) was established under the auspices of the VSWCB, and was charged with the responsibility of implementing and overseeing the monitoring program.

The Occoquan Watershed Monitoring Program (OWMP) is funded by the counties and cities in the Basin, and by Fairfax Water. The Occoquan Watershed Monitoring Laboratory (OWML) is operated by the Virginia Tech Department of Civil and Environmental Engineering. The laboratory began operation in 1972, and has conducted comprehensive studies of receiving water quality, and effects of the reclaimed water discharges to the present time.

Over the years, OWML has developed a comprehensive database of water quality in the Occoquan Watershed, and has been instrumental in conducting studies which have proven to be critical to the ongoing management of water quality.

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UOSA WRF

Since beginning operation in the summer of 1978, the UOSA WRF has discharged reclaimed water of very high quality to the Occoquan Watershed. Figure 2-1 is a summary of the median values of selected discharge measurements for the 20 year

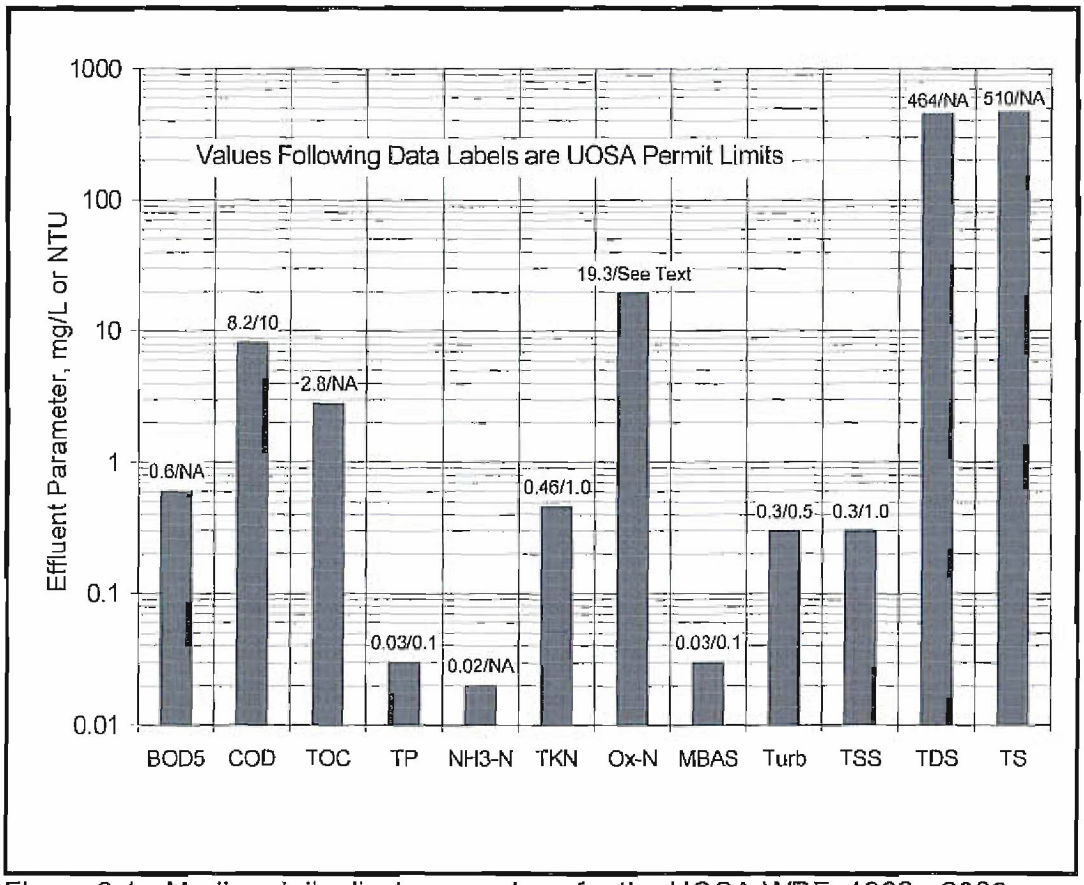

Figure 2-1. Median daily discharge values for the UOSA WRF, 1982 - 2002.

period from 1982 - 2002. Where discharge limits exist for constituents, the permit value follows the median value in the legend. As may be seen, WRF performance has been extraordinary over the entire period of plant operation. With regard to total phosphorus (TP), the plant has a limit of 0.1 mg/L, and the long-term median discharge value has been 0.03 mg/L. For oxygen-demanding materials in the discharge, UOSA has a permit limit of 10 mg/L COD, and has produced a long-term median value of 8.2 mg/L. It should be noted that the UOSA WRF produces a discharge of such high quality with

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respect to degradable organic matter removal that the most widely used measure of oxygen demand (Biochemical Oxygen Demand or BOD) is no longer included in the permit for the simple reason that the values are too low to reliably quantify.

As may also be seen from the figure, the UOSA WRF produces a highly nitrified discharge, which, over the 20 year period of record depicted in Figure 2-1, has had a median value of 19.3 mg/L NO_2^--N+NO_3^--N (Ox-N). Essentially all of the Ox-N from the UOSA WRF is in the form of nitrate (NO_3^--N) with very little nitrite (NO_2^--N). Along with the high values of nitrate, it may be seen that the median discharge concentrations of NH_4^+-N and TKN were quite low, with values of 0.02 and 0.46 mg/L, respectively. Given the UOSA liquid stream treatment processes, including nitrifying activated sludge, and granular activated carbon contactors operated in a biologically active mode, it is also likely that a large fraction of the organic nitrogen in the TKN measurement is recalcitrant (difficult to biodegrade) and contained in soluble microbial products.

At the time of the completion of the Metcalf and Eddy Study (1970) of the Occoquan Reservoir, it was assumed that successful control of nuisance growths of algae would require the joint (and high performance) removal of both nitrogen and phosphorus from any future WRF discharges to the watershed. For that reason, the planning for the UOSA WRF assumed that limit of technology performance would be required for both nutrients. When the *Occoquan Policy* (1971) was adopted by the VSWCB, TP and TN limits of 0.1 and 1.0 mg/L, respectively, were established for the WRF discharge, even though such performance was beyond the (then) state-of-the art in full scale nutrient removal treatment processes.

The original plan was for the UOSA WRF to remove nitrogen with an ion exchange process (SWCB, 1971), in which NH_4^+-N ions would be exchanged for Na^+ ions on a natural zeolite resin known as clinoptilolite. Subsequent treatment steps (ion exchange resin regeneration with a salt brine, pH adjustment to 10.8, gas stripping in a packed tower, and acid absorption) were to designed to allow recovery of the nitrogen as a solution of $(NH_4)_2SO_4$. Construction problems, however, delayed the start-up of the system, and the plant was placed into service without the nitrogen removal facilities in operation. In order to avoid potential problems with the depletion of dissolved oxygen from the oxidation of ammonia in Bull Run, the plant was, instead, successfully operated in a nitrification mode at start-up.

In the early years of plant operation, studies by OWML revealed that there were water quality benefits being realized in the Occoquan Reservoir as a result of receiving the nitrified WRF discharge. As a result, a change in the nitrogen management requirements for the UOSA WRF was instituted in a revision to the *Occoquan Policy* (VSWCB, 1980).

For the period from July, 1978 through the present, this mode of operation has continued, with the exception of a period to study the ion exchange process

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performance, some minor periods of upset, and recent tests of a biological nitrogen removal capability. As shown previously in the summary in Figure 2-1, The plant has generally produced a discharge containing approximately 20 mg/L of NO_3^--N. After treatment, the reclaimed water flows directly to a final effluent reservoir (FER), which effects some nitrogen removal, and at the time of entry into Bull Run, the discharge generally contains 15 - 18 mg/L NO_3^--N.

OCCOQUAN RESERVOIR INPUT-OUTPUT MONITORING RESULTS

Figure 2-2 is a map of the Occoquan Watershed showing the major tributaries, other waterbodies; and OWML stream and reservoir monitoring stations, which have "ST" and "RE" prefixes, respectively.

The location of the UOSA WRF discharge is also shown, as are Lake Jackson and Lake Manassas, which are located in the central and upper watershed, respectively.

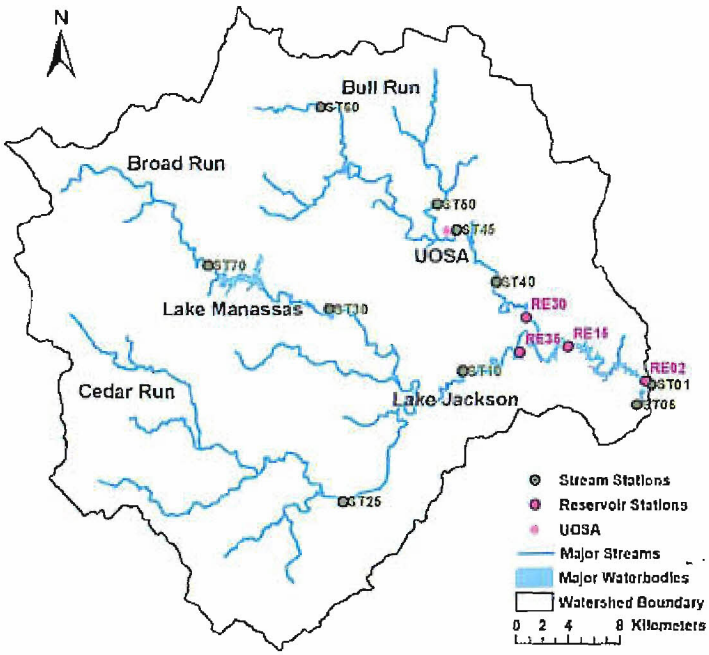

Figure 2-2. Map of the Occoquan Watershed, showing key water bodies and monitoring stations.

Figures 2-3 through 2-6 each present a period of record time series of seasonal average concentrations of a key nutrient (TP, Ox-N, TKN) at automated OWML monitoring stations on the principal tributaries entering the Occoquan Reservoir (ST10 and ST40) and in the release from the Occoquan Dam (ST01).

Phosphorus

Figures 2-3 and 2-4 show, respectively, seasonal average time series plots of total soluble phosphorus (TSP) and total phosphorus (TP) concentrations in the inflows and outflows of the Occoquan Reservoir for the period of record through 2004. It is important to note the changes observed in both TSP and TP concentrations in Bull Run downstream of Manassas (ST40) in the periods before and after mid-1978. It should be recalled that the Bull Run stream reach below Manassas received all the 11 existing POTW discharges prior to the completion of the UOSA WRF. In 1976 and 1977, as may be seen in Figure 2-3, average TSP concentrations in Bull Run exceeded 0.2 mg/L in five seasons out of eight, and in the fall of 1977, during an extreme drought,

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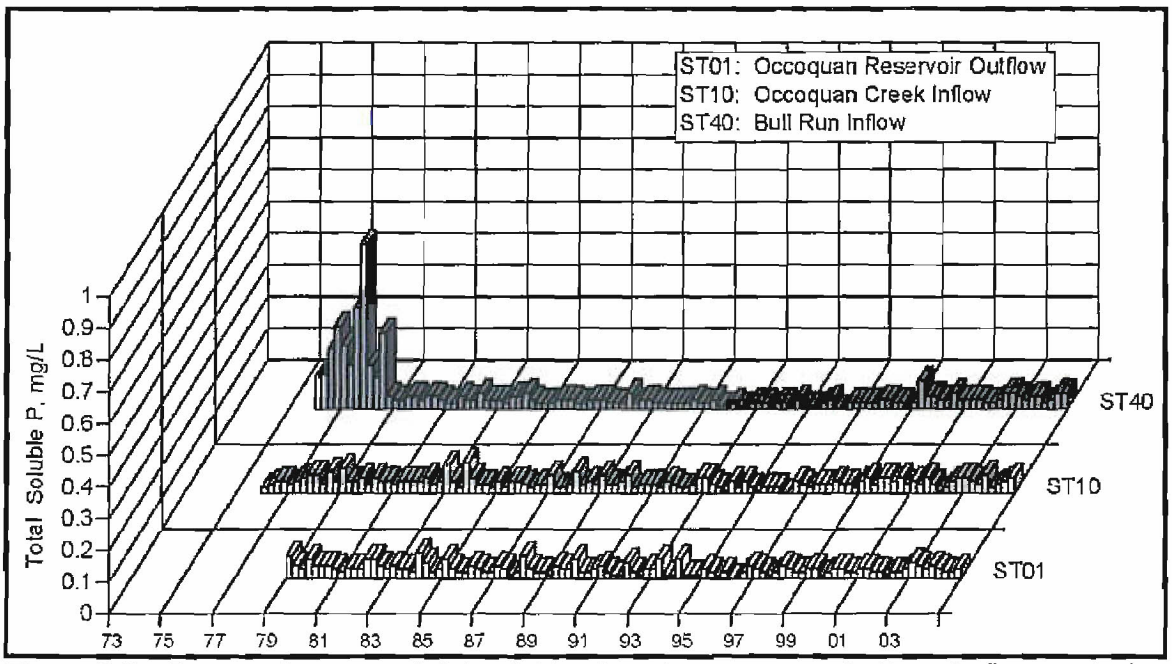

Figure 2-3. Seasonal average total soluble phosphorus concentrations in flows entering and leaving the Occoquan Reservoir, 1973 - 2004.

exceeded 0.5 mg/L. The TSP analysis is generally taken to include inorganic phosphates and soluble organic phosphates, and therefore represents the forms most immediately biologically available. Put in the context of the concentration set forth as a desirable goal (0.02 mg/L as P) in the Metcalf and Eddy study (1970), it may be seen that the observed seasonal average stream values often exceeded the recommendation by a factor of 10. For TP, the observed average concentrations in 1973 - 1977, exceeded 0.2 mg/L for 16 out of 19 seasons for which data were available, as may be seen in Figure 2-4.

Because the stream was highly effluent-dominated during the 1973-1977 period, the in-stream concentrations for both TP and TSP were generally inversely affected by seasonal flow, with the highest concentrations being observed in the summer and fall seasons.

Following start-up of the UOSA WRF in 1978, it may be seen in the two figures that seasonal average concentrations of both TSP and TP rapidly declined to much lower values. In fact, for the period 1979 - 2004, the seasonal average value of TP in Bull Run (ST40) was only 0.036 mg/L. Interestingly, the mean value of TP in the Occoquan Creek tributary (ST10) to the reservoir was slightly higher (0.044 mg/L) for the same period. At the reservoir outlet (ST01), the average value from 1979 - 2003 was slightly higher (0.055 mg/L) than that observed in either principal tributary, which may indicate that stored sediment phosphorus was, on occasion, being liberated to the water column.

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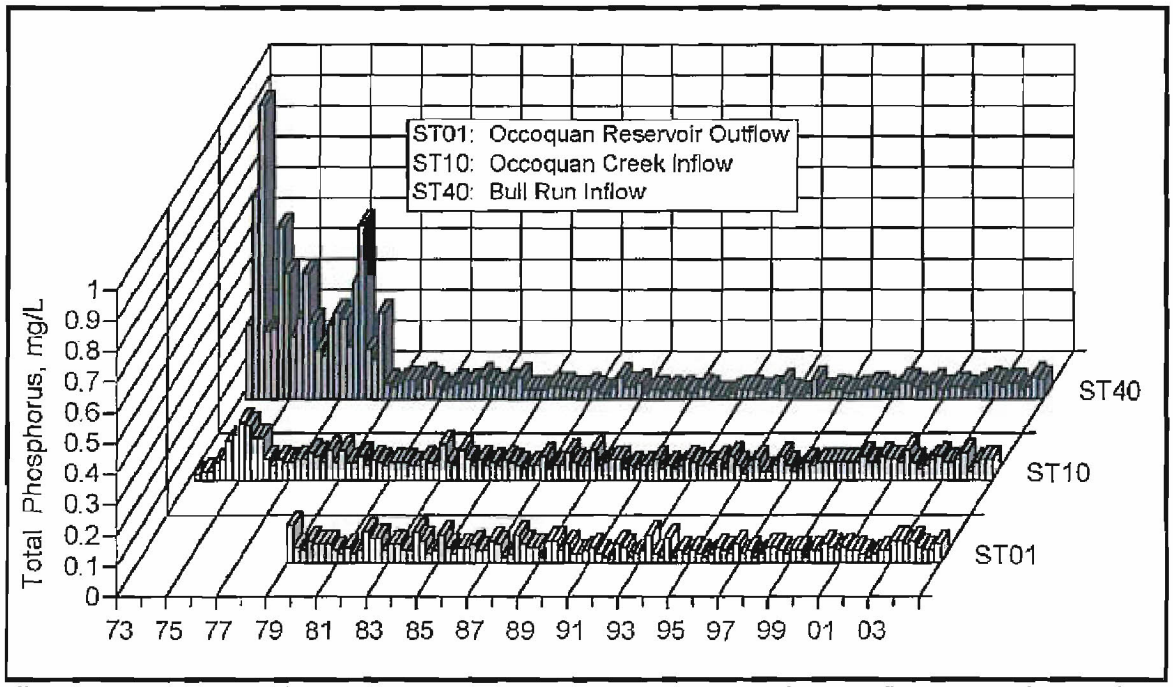

Figure 2-4. Seasonal average total phosphorus concentrations in flows entering and leaving the Occoquan Reservoir, 1973 - 2004.

It is also interesting to note that between the UOSA WRF start-up in the summer of 1978 and the end of the period of record displayed Figures 2-3 and 2-4, there was an approximately 5-fold increase in the UOSA discharge, with virtually no change in ambient conditions in Bull Run with respect to phosphorus.

Nitrogen

Figures 2-5 and 2-6 are, respectively, seasonal average time series plots of TKN and Ox-N, respectively, in the major tributary inflows and the principal outflow of the Occoquan Reservoir from 1973 - 2004. The impacts of the 1978 start-up of UOSA in removing TKN, which is the sum of ammonium and organic nitrogen, from the Bull Run Tributary, may clearly be seen in Figure 2-5. From 1979 until 2003, the seasonal average concentration of TKN has been approximately 0.56 mg/L, and has not changed appreciably during the 5-fold increase observed in the UOSA WRF discharge flow. In the Occoquan Creek tributary (ST10), the TKN has averaged approximately 0.70 mg/L in the 1979 - 2004 period, with virtually no temporal trend. TKN at the reservoir outlet (ST01) has likewise displayed little change in the 1979 - 2004 period, and has averaged 0.65 mg/L. The similarity of inflow and outflow concentrations of TKN at all three stations suggests that very little of any observed nitrogen removal in the reservoir is attributable to a net reduction of ammonium or organic nitrogen flux through the system.

Figure 2-6 shows is a time series of the seasonal average concentrations in the principal inflows and outflows of the Occoquan Reservoir for NO_3^-+NO_3^--N (Ox-N) over

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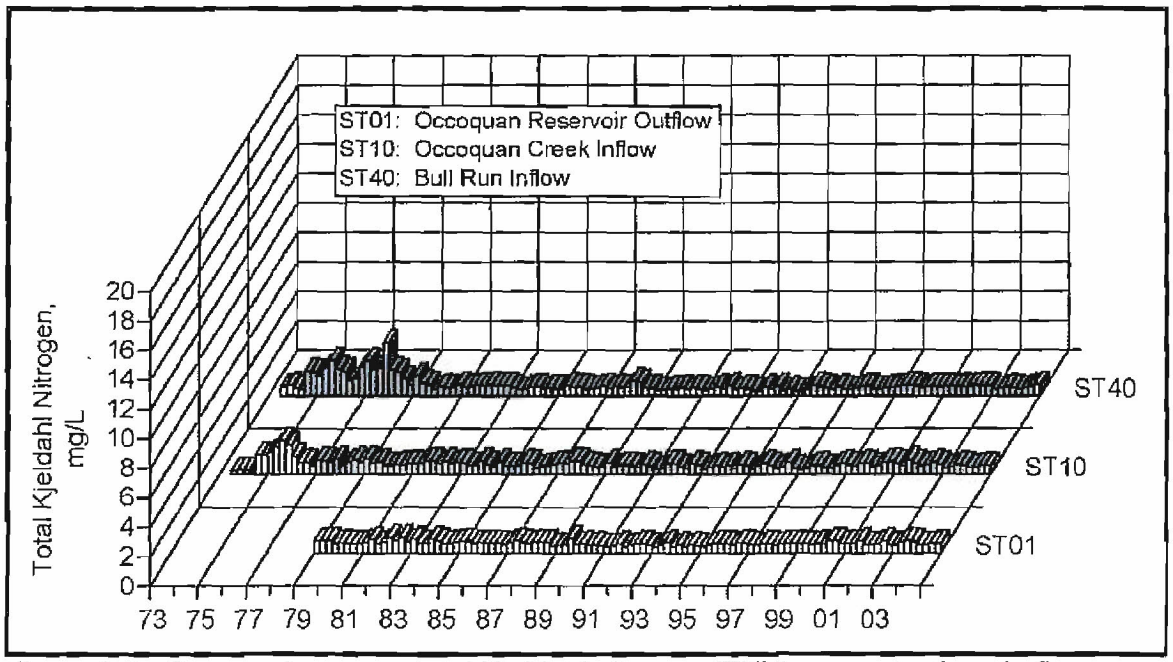

Figure 2-5. Seasonal average total Kjeldahl nitrogen (TKN) concentrations in flows entering and leaving the Occoquan Reservoir, 1973 - 2004.

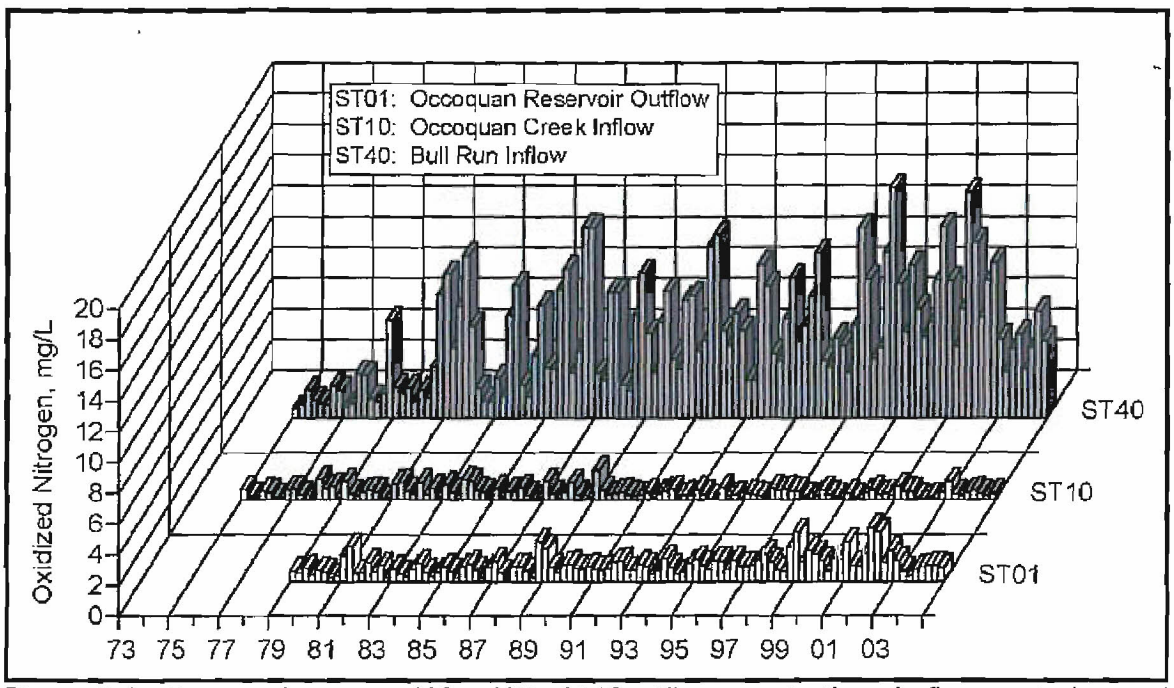

Figure 2-6. Seasonal average NO_3^-+NO_3^--N (Ox-N) concentrations in flows entering and leaving the Occoquan Reservoir, 1973 - 2004.

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the period of record. Beginning in late 1978, the effects of the start-up of the UOSA WRF in a nitrification operating mode may be clearly seen in the seasonal concentration data for Bull Run (ST40). As may be seen, the in-stream Ox-N concentrations have generally varied inversely with seasonal flows, because the nitrate originates almost exclusively from the UOSA WRF discharge, which is essentially continuous during all seasons of the year. The 5-fold UOSA flow increase in the 1978 - 2003 period is the most straightforward explanation of the general upward trend in the seasonal averages for Bull Run Ox-N.

Even though seasonal average Ox-N concentrations have continued to slowly rise in Bull Run due to UOSA flow increases, it is also apparent from Figure 2-6 that concentrations at the Reservoir Outlet (ST01) have, with a few exceptions, remained relatively stable. If one examines the average concentrations for the 10 year period from 1993 - 2004, it may be seen that the outflow average concentration displayed low variability in the first 5 years (1993-1998), and much more variability in the second 5 year period (1999-2004).

- 1993 - 1998 Ox-N average at ST01: 1.11 mg/L
- 1993 - 2003 Ox-N average at ST01: 1.67 mg/L

The approximately 0.5 mg/L increase in average Ox-N concentration observed in the second 5 year period was very likely due to the occurrence of some unusual hydrologic conditions. Figure 2-7 shows an annual and seasonal summary of Occoquan Watershed rainfall from 1951 - 2004. Overall, rainfall was approximately 20% below normal in 1999, 2000, and 2001. In addition, the seasons that were observed to have high Ox-N concentrations during the period were either (1) during seasons of low rainfall, or (2) immediately following seasons of low rainfall. If the higher average Ox-N concentrations at ST01during these anomalous hydrologic periods are treated as outliers, then the entire 10-year period from 1993 - 2004 appears to exhibit relatively stable reservoir outlet concentrations.

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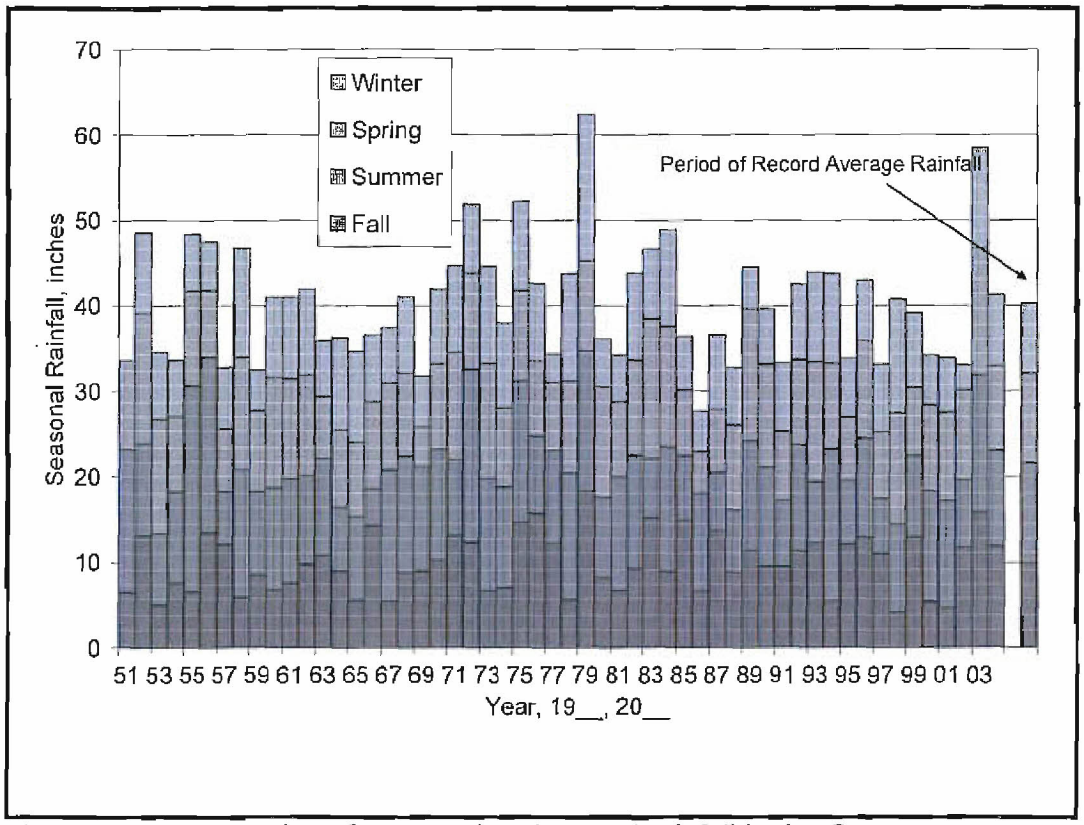

Figure 2-7. Time series of seasonal and annual rainfall in the Occoquan Watershed, 1951 - 2003.

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CONSTITUENT FLUX MONITORING

The Occoquan Watershed Monitoring Laboratory (OWML) operates a network of nine automated stream gaging and sampling stations on the major tributaries to the Occoquan Reservoir. The locations of the stations were shown earlier in this chapter in Figure 2-2. The four principal stations used in establishing inflow-outflow fluxes of constituents to and from the Occoquan Reservoir are shown in Table 2-1.

Table 2-1. Monitoring stations used in computing mass balances of constituents entering and leaving Occoquan Reservoir.

Station No.	Station Name	In service since	Drainage Area (mi.^{2})
ST01	Occoquan Dam Outflow	01/82	570
ST10	Occoquan Creek near Manassas	01/72	343
ST40	Bull Run at Yates Ford	09/72	185
ST45	Bull Run at Manassas	01/84	149

Stream Gages and Chemical Constituent Monitoring

Automated stream monitoring stations in the Occoquan Watershed are equipped with conventional stream gaging instrumentation which is interfaced with automated water samplers and refrigerated storage. The stream gages are supervised by on-site microcomputers, which communicate directly with a central server located at OWML in Manassas, Virginia. The on-site computers are programmed to begin collecting flow-weighted composite samples at the onset of a storm event. The sampling strategy is based on an equal time - variable flow protocol previously described by OWML (1993), wherein the objective is to produce a sample that is truly representative of the entire storm flow for all the constituents of interest. Collected in this way, a final composite sample is representative of the entire volume of a storm event should it be captured and completely mixed. The concentration is also known as the Event Mean Concentration, or EMC.

The method is illustrated with a schematic of a runoff hydrograph in Figure 2-8. As may be seen, a fixed-volume sub-sample of the storm is retrieved at equal increments of total flow volume. This approach allows a very large number of sub-samples to be collected during an event, thereby assuring that any intra-event variations in flow, concentration, and load are captured. In addition, the method allows the complexity of

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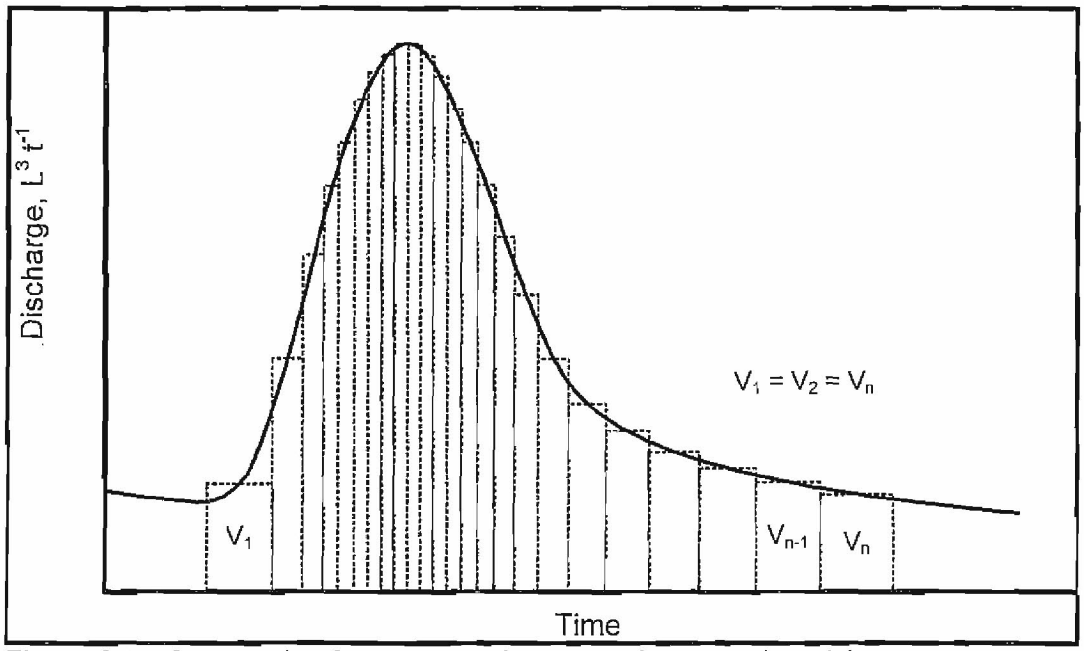

Figure 2-8. Schematic of the compositing technique employed for storm event monitoring at OWML stream monitoring stations.

sample collection to be assumed by the microcomputer device supervising the automated sampler. Stations are programmed to collect samples during all storm events, and at the onset and completion of an event, the equipment provides an electronic notification that sample collection should be scheduled. Generally speaking, the monitoring stations listed in Table 2-1 would be expected to collect 25 - 35 storm events (each) during the course of a normal hydrologic year.

Along with storm event sampling, ambient flow conditions are routinely sampled on a time schedule. This allows the non-storm component of constituent loads to be adequately characterized. During the course of a normal hydrologic year, non-storm sampling would be generally be conducted 35 - 45 times annually at the stations identified in Table 2-1.

The OWML reliance on all-event storm composite sampling, and time-based non-storm sample collection has produced a constituent flux database that supports a detailed and robust description of the movement of suspended and dissolved materials through the Occoquan Reservoir. Since the start-up of Station ST01 in 1982, it has been possible to construct annual and longer-term mass balances on the Reservoir for key constituents. Periodic atmospheric sampling studies by OWML have also made it possible to account for the wetfall and particulate dryfall contribution to constituent budgets in the watershed.

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Table 2-2 was developed from 21 years of watershed loading data, and shows a long-term budget for a nitrogen, phosphorus, and suspended sediment in the Occoquan Watershed for both point and nonpoint sources for the period 1983 - 2004.

Table 2-2. Summary of load sources and retention or conversion in the Occoquan Reservoir, 1983 - 2004

Constituent	Average Annual Load (lb.)	Nonpoint Sources (%)	POTW's (%)	Atmospheric Deposition (%)	Retention or Conversion in Reservoir (%)
Total Nitrogen	3.30E+06	67.4	32.2	0.4	26.9
Total Phosphorus	2.13E+05	98.2	1.7	0.1	56.2
Total Sediment	1.32E+08	100.0	0.0	0.0	82.3

Sediment. As may be seen from the 21 years of record summarized in Table 2-2, the Occoquan Reservoir is an extremely efficient trap for suspended sediment. Over the period of record presented, the Reservoir has removed 82% of the inflow sediment load, which is almost exclusively delivered from agricultural and urban nonpoint (NPS) sources in the watershed. The sediment removal performance is also very much in line with what would be predicted by an empirical relationship developed from an analysis of U.S. reservoirs by Brune (1953). The relationship developed by Brune is shown in Figure 2-9 with the capacity to annual inflow ratio for the Occoquan Reservoir superimposed. As may be seen, the predicted median removal of all inflow sediment would be 80%, which is in excellent agreement with the observed data.

Phosphorus. Essentially all of the phosphorus entering the Occoquan Reservoir is contributed by agricultural and urban nonpoint sources. Less than 2% of TP originates from the UOSA WRF, and only 0.1% is directly deposited from the atmosphere. A relatively large fraction of the TP carried by nonpoint sources is associated with suspended matter, so substantial removal of phosphorus in the Reservoir would be expected, and the average was 56% over the 21 year period summarized in Table 2-2.

Nitrogen. As may be seen in Table 2-2, the annual average load of nitrogen to the Reservoir was 3.3 million pounds over the 21 year period summarized. During that time span, atmospheric sources accounted for less than 0.5% of the total direct nitrogen inputs to the Reservoir. Of course, if it were possible to separate out the atmospheric contributions to the entire watershed nitrogen budget, this percentage would be expected to be considerably higher. Of the remaining inputs, nonpoint sources accounted for over twice as much of the N load (67%) as point sources (32%). It should be noted that the UOSA WRF and its highly nitrified discharge constitutes (at least at the present time) the only point source nitrogen load of any consequence remaining in the watershed. During the entire 21 year record summarized in the table, it may be seen that observed output loads of nitrogen were 27% lower than the input

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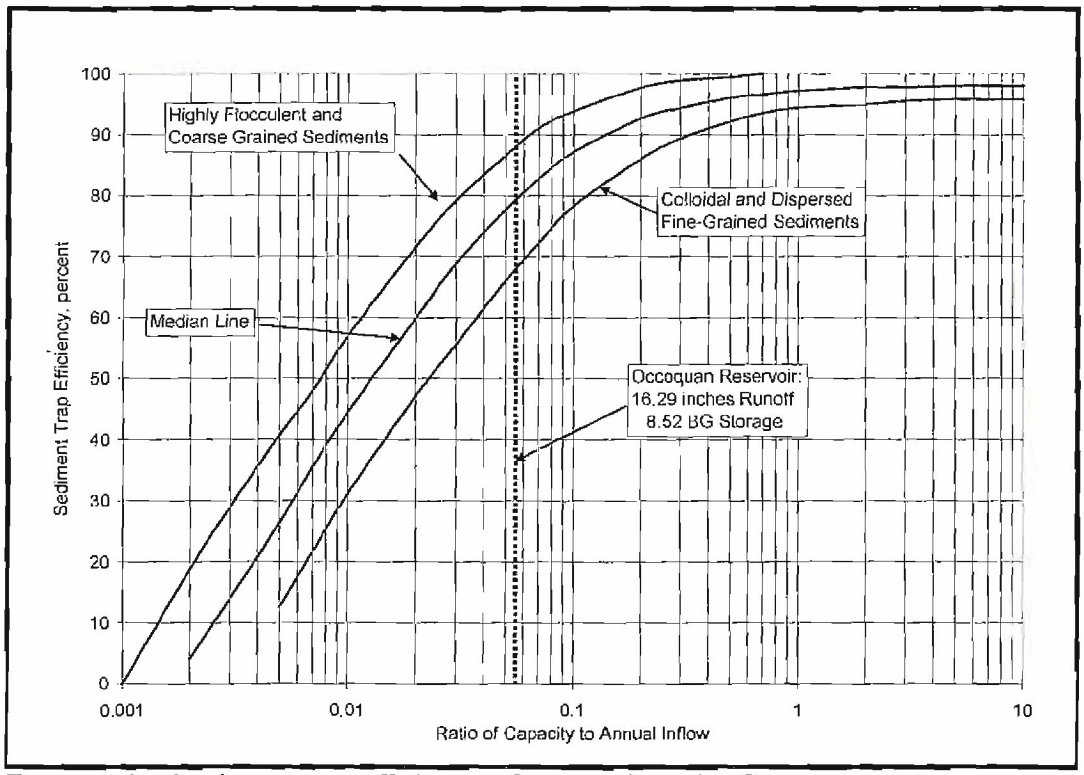

Figure 2-9. Sediment trap efficiency of reservoirs, with Occoquan data superimposed, after Brune (1953).

loads, indicating substantial removal of nitrogen in the Reservoir. The 27% N load reduction from 1982 - 2003 was lower than the 35-40% annual reductions that have been reported previously by OWML (1993; 1997). This is, at least in part, due to the unusual hydrologic conditions experienced in the years from 1997 to 2003.

Most of the nitrogen contributed nonpoint sources from both the Bull Run and Occoquan Creek sub-watersheds is in the reduced form (TKN). Conversely, the nitrogen from the UOSA WRF is almost exclusively in the oxidized form (Ox-N). Figure 2-10 is an illustration, in terms of concentrations, of the flow-weighted contributions (by source) to the species constituting the total nitrogen load to the Occoquan Reservoir. The load and concentration contributions in the figure were calculated from OWML data acquired in the period 1987 - 2002.

As may be seen in the figure, the UOSA WRF contributed over half the Ox-N entering the Reservoir, while the remaining 46% originated from nonpoint sources in the watershed. In the second column, it may also be seen that the UOSA WRF had virtually no contribution to the flow-weighted TKN concentration entering the Reservoir, while over 96% originated from watershed nonpoint sources. In terms of total nitrogen entering the reservoir, slightly over a third originated from the UOSA WRF.

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RESERVOIR MONITORING

In-Reservoir Transformations of Nitrogen

As was noted in the previous section, studies by OWML over the past 25 years have demonstrated a substantial removal of nitrogen in the Occoquan Reservoir. The observed loss of nitrogen between the inflow and outflow points have, of course, raised questions about the mechanisms responsible for the reduction. Unoxidized forms of nitrogen may be removed from the water column in aquatic systems by several physical, chemical, and/or biochemical mechanisms, including:

- Ion exchange of NH_4^+-N on sediments
- Hydrolysis of organic N and subsequent biological assimilation of NH_4^+-N
- Biological assimilation of NH_4^+-N
- Sedimentation of particulate biomass (organic-N)
- Sedimentation of particulate inorganics (organic-N or NH_4^+-N)

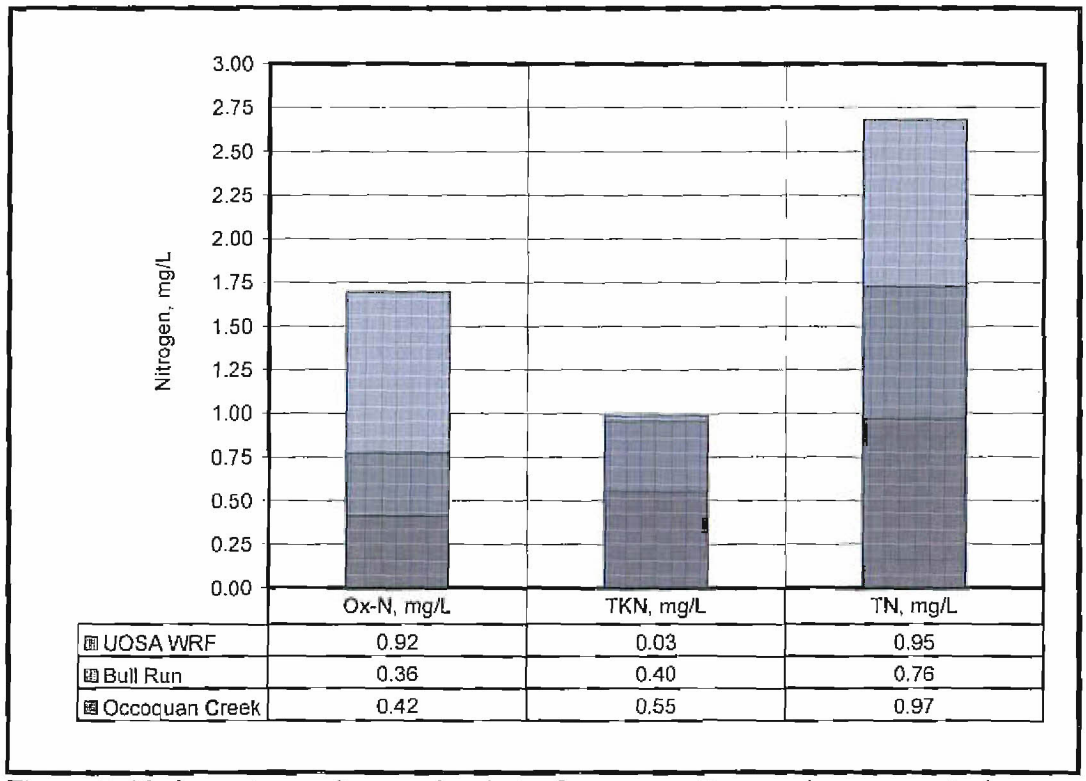

Figure 2-10. Long-term nitrogen loads to Occoquan Reservoir represented as flow-weighted concentrations by species and source, 1987 - 2002.

Another transformation that, although it results in a change in chemical form, does not result in a net loss of nitrogen from the water column is the biochemical oxidation (in the presence of molecular oxygen) of NH_4^+-N to NO_3^--N. Certain classes of microorganisms

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obtain their cellular energy from this oxidation (*e.g. Nitrosomonas, Nitrobacter*). This oxidation, which takes place in the UOSA WRF biological treatment system, also somewhat reduces the utility of the nitrogen as an algal nutrient, as will be explained in a later section.

The removal of oxidized forms of nitrogen ({NO_2^--N+NO_3^-}-N) from the water column in aquatic systems may be accomplished by fewer mechanisms than enumerated above, including:

- Assimilatory denitrification
- Dissimilatory denitrification

In assimilatory denitrification, organisms reduce oxidized forms of nitrogen to ammonium in order to facilitate the formation of amino acids and proteins in the synthesis of biomass. In dissimilatory denitrification, which occurs only under conditions of anoxia, the oxidized forms of nitrogen act as alternate electron acceptors in place of molecular oxygen, resulting in the reduction of nitrate to nitrogen gas, which is then ultimately lost to the atmosphere.

As was noted earlier, the nitrogen in the UOSA WRF discharge is almost exclusively in the form of NO_3^--N, and any removal in the Occoquan Reservoir would be expected to occur *via* one of denitrification mechanisms listed above.

Reservoir Thermal Stratification Effects

In the years following startup of the UOSA WRF, data collected in the main body of the Occoquan Reservoir have clearly revealed some of the hydrodynamic and biochemical mechanisms affecting the transformations of nitrate in the system. These are, in part, due to the fact that the Occoquan Reservoir, as do most deep reservoirs in temperate climates, undergoes an annual thermal stratification. In the late spring, direct solar radiation and convection from the air begins to warm the surface waters of the Reservoir. Vertical mixing of these warmer (and lower density) waters with the underlying cooler waters occurs due to energy provided by both wind and stream inflows. After a period of time, the epilimnion, which is a layer of warm water from 10 - 20 feet in depth, develops on the surface of the Reservoir. The surface water layer becomes thermally isolated from the deeper waters because it is of significantly lower density. Figure 2-11 shows a set of vertical temperature profiles in the Occoquan Reservoir in 1998. As may be seen, very little vertical temperature variation was observed in the January - March period. Beginning in April, the surface waters began to become progressively warmer, culminating in a strong thermal stratification that spanned the June to September period. By October, cooling of the air in contact with the Reservoir surface, coupled with less direct solar radiation due the sun being lower in the sky, resulted in a breaking of the stratification, and the waters became vertically

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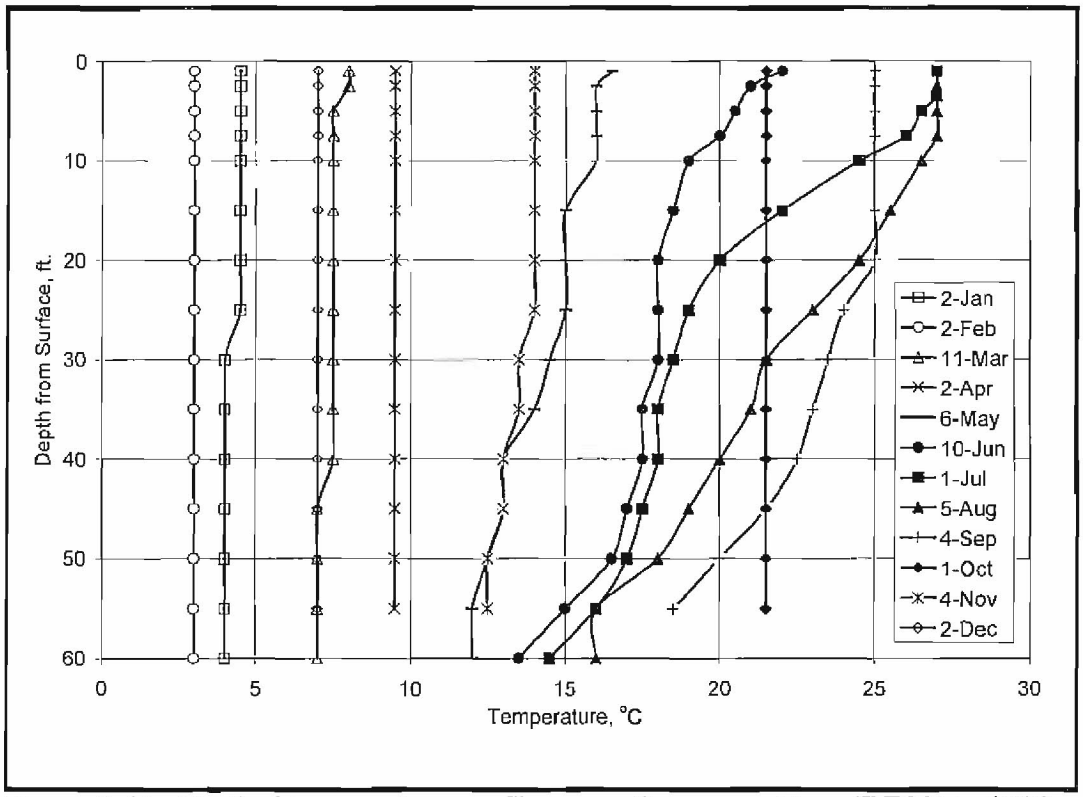

Figure 2-11. Vertical temperature profiles near Occoquan Dam (RE02) in 1998.

mixed again. By November and December, the entire water column had become much cooler, with temperatures dropping below 10 °C.

The effects of the annual thermal stratification on vertical profiles of dissolved oxygen (DO) in the Occoquan Reservoir are shown in Figure 2-12. During the stratification period, the cooler layer of higher density water, called the hypolimnion, cannot be replenished with oxygen from the atmosphere because the density differential forms an effective barrier to the diffusion of dissolved gases. As a practical matter, then, the oxygen supply present in the hypolimnion at the onset of stratification is all that is available until the Reservoir is again thermally homogeneous. As a result, oxygen-consuming biological activity in the hypolimnion progressively depletes the available dissolved oxygen until the concentration is eventually reduced to zero.

In Figure 2-12, the reduction of DO in the bottom waters may be seen to have begun between the April and May profiles. By June, oxygen was absent from the very deep waters, and by July, no oxygen was present below a depth of about 25 feet. Oxygen again penetrated into the deeper waters in October, which coincided with the disruption of the thermal stratification previously discussed in Figure 2-11.

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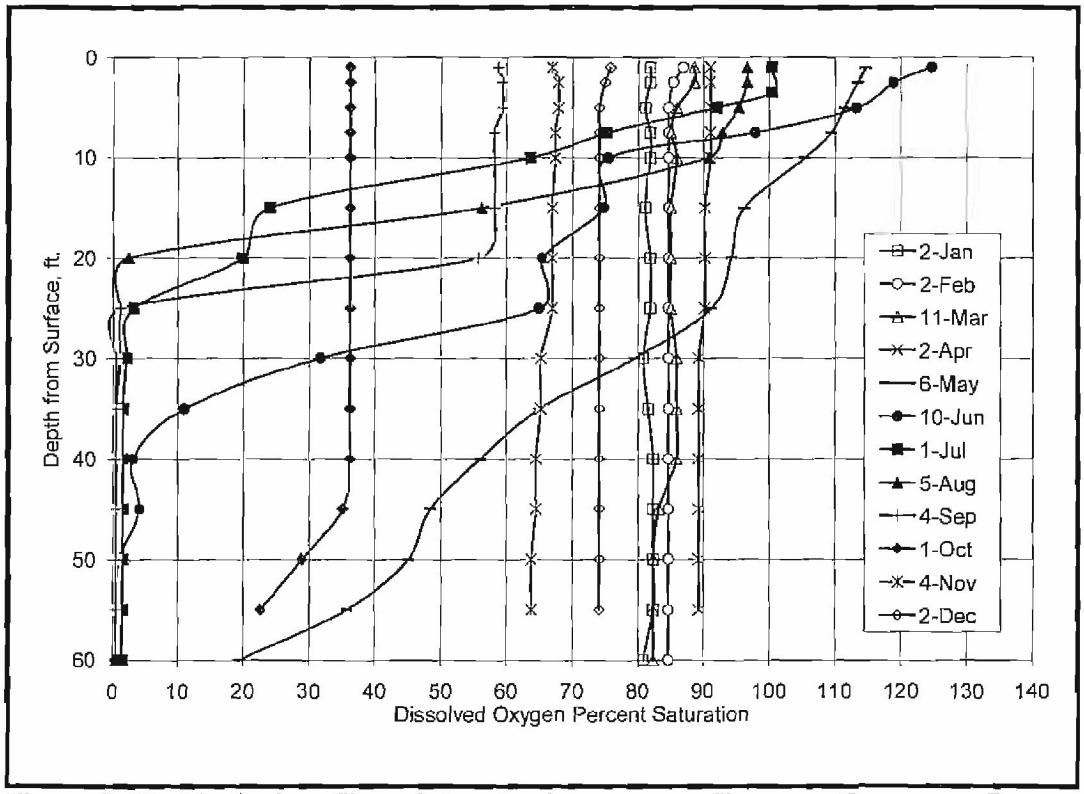

Figure 2-12. Vertical profiles of dissolved oxygen profiles near Occoquan Dam (RE02) in 1998.

In the absence of any other inorganic electron acceptor, the loss of oxygen from the water column is quickly followed by the establishment of anaerobic conditions, which have been long known to promote the release of phosphorus bound to deposited sediments in lakes and reservoirs (Mortimer, 1941). The phenomenon has also been observed in the Occoquan Reservoir for many years (OWML, 1993, 1998), where summer hypolimnetic phosphorus concentrations have regularly exceeded 0.1 mg/L throughout the monitoring history of the Reservoir, particularly during periods of low nitrate concentrations.

The high concentrations of phosphorus produced in hypolimnetic waters by release from deposited sediments may also be transported to the surface waters of the Reservoir in at least two ways:

- Short-term disruptions of the thermal stratification and mixing of the water column due to high flows events;
- Disruption of the thermal stratification in the fall following cooling of the epilimnetic waters.

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Whenever sufficient mixing occurs to disrupt the thermal stratification, any dissolved species present in the hypolimnetic waters may serve to increase concentrations at the water surface. In fact, this mechanism is often responsible for increasing the surface water phosphorus supply, and causing the intense fall algal blooms that often occur in eutrophic impoundments.

Stream Inflow Patterns During Thermal Stratification

During the period of thermal stratification of the Occoquan Reservoir, the flowing waters of Bull Run are generally at a lower temperature than the surface waters of the impoundment. One consequence of this temperature difference is that the stream waters tend to "plunge" to a lower depth until they encounter waters of similar temperature and density. This process is clearly illustrated by the data displayed in Figure 2-13. As may be seen, summer temperatures in the flowing waters of Bull Run, which are plotted on the abscissa, are lower than the surface temperatures of the Reservoir on common dates (open circles). The same stream waters are of a higher temperature than the near-bottom waters of the reservoir on the same dates (closed circles). As a result, the Bull Run flow, at least during the summer months may be expected to mix towards the bottom of the Reservoir. The flow distribution is illustrated schematically in Figure 2-14.

The streamflow of Bull Run, particularly during the summer months, contains high concentrations of nitrate due to the presence of the UOSA WRF discharge. Because of the mixing phenomenon described above, the nitrate is preferentially delivered to the bottom waters of the upper Reservoir, which tend to be anoxic due to dissolved oxygen depletion by the late spring or early summer, as was previously shown in Figure 2-12.

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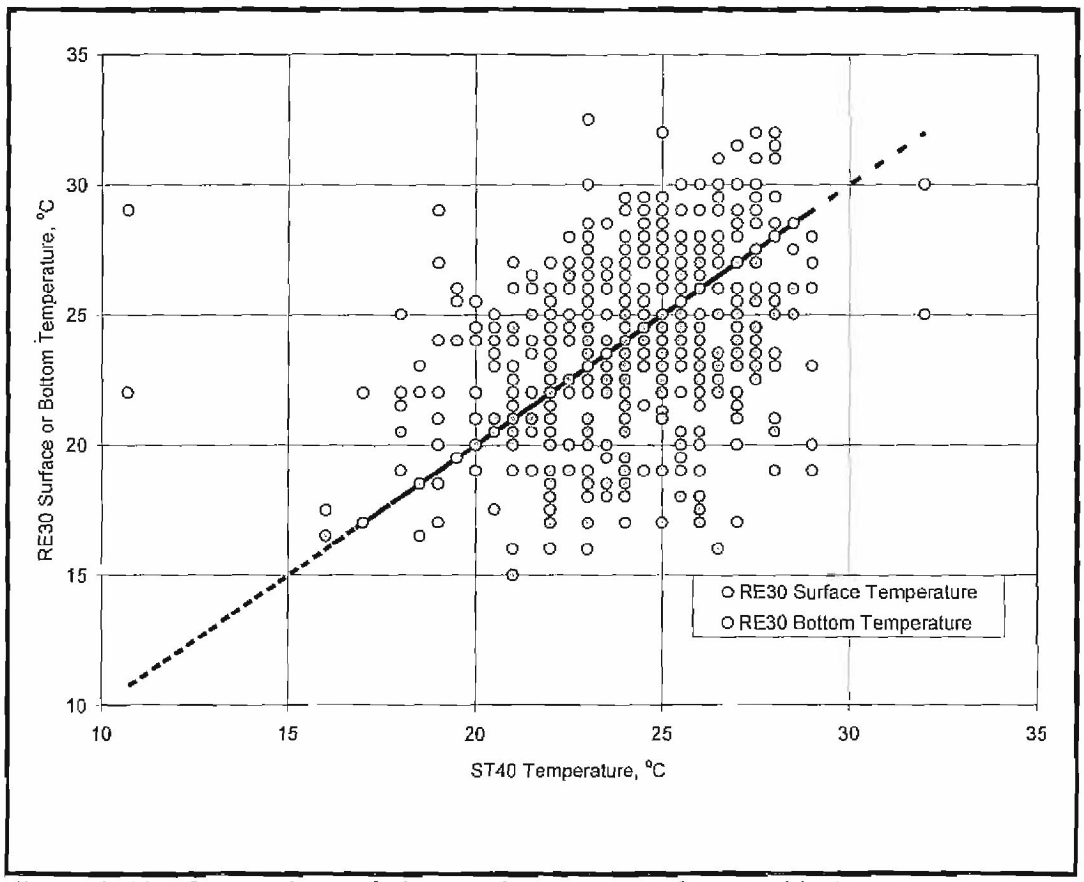

Figure 2-13. Comparison of observed summer surface and bottom temperatures at Bull Run Marina (RE30) to streamflow temperatures in Bull Run at Yates Ford (ST40) from 1973 - 1997.

Beneficial Effects of Nitrate in Anoxic Waters

The addition of nitrate to oxygen-depleted waters to produce an oxidized environment over deposited sediments has been previously proposed by several investigators (Lawrence, 1959; Ripl, 1976; McLaughlin, 1981; Andersen, 1982) as a lake and reservoir restoration technique. There are also early reports in the literature describing the use of nitrate to control odors arising from anaerobic conditions in cannery wastewaters and in river sediments. Lawrence (1959) found that addition of nitrates could be effective in poising the oxidation-reduction potential (ORP) of an aquatic system above the point at which sulfate could be reduced to sulfide. McKinney and Conway (1957) reported the role of nitrate as an alternate terminal electron acceptor in aerobic respiration rather than as a direct source of oxygen. Ripl (1976) showed that nitrate addition to the sediments of a Swedish lake resulted in the oxidation of the upper layer of sediment, and in a decrease in the soluble phosphorus concentration in the overlying water due to a retardation of sediment release. Andersen (1982), in an

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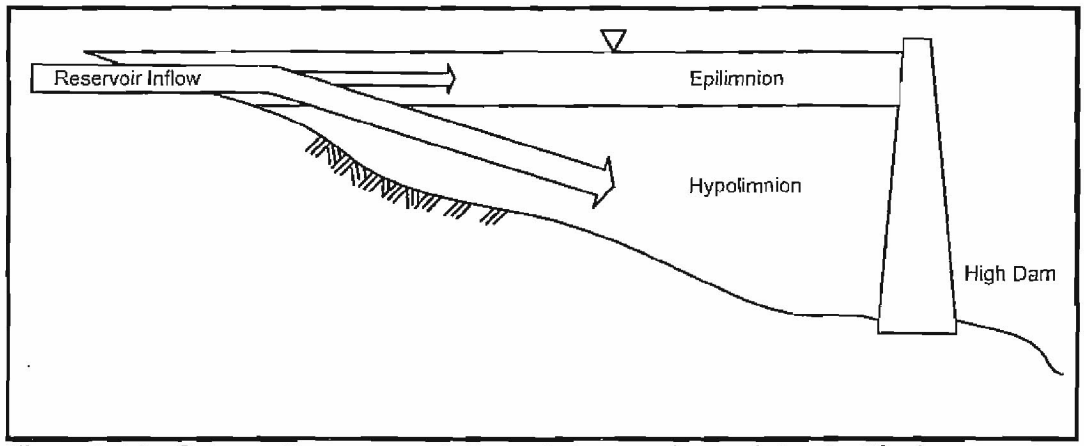

Figure2-14. Schematic representation of stream plunge into stratified reservoir during the summer stratification.

investigation of eutrophic Danish lakes, found that no sediment phosphorus release occurred if the oxidized nitrogen concentration in the hypolimnetic waters was at least 1.0 mg/L. The phenomenon takes place because, nitrate, in the absence of molecular oxygen, acts as an alternate terminal electron acceptor for certain bacteria. In that role, it delays the onset of truly anaerobic conditions, poises the system oxidation-reduction potential (ORP) at a sufficiently high level to delay the reduction of Fe(III), and thereby delays or inhibits the release of iron-bound phosphorus from the sediments. The succession of common electron acceptors with decreasing ORP is summarized in Table 2-3.

Table 2-3. ORP Couples of interest in the hypolimnetic reduction of nitrate in anoxic waters.

Redox Couple	E_7, mv	DO, mg/L
$NO_3^- \rightarrow NO_2^-$	450 - 400	4
$NO_3^- \rightarrow N_2 \uparrow$	450 - 350	0.4
$NO_3^- \rightarrow NH_4^+$	450 -350	0.4
$Fe^{3+} \rightarrow Fe^{2+}$	300 - 200	0.1
$SO_4^{2-} \rightarrow S^{2-}$	100 - 60	0

In order to illustrate the effect of the presence of nitrate in the waters of the Occoquan Reservoir, subsets of OWML data from Bull Run Marina (RE30), Ryans Dam (RE15), and Occoquan Dam (RE02) were prepared for the period following start-up of the

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UOSA WRF (1979-2004). The stations represent a longitudinal sequence along the main axis of the Reservoir, as may be seen in Figure 2-15. A dataset of total soluble phosphorus (TSP) and oxidized nitrogen (Ox-N) in the bottom waters was prepared for each monitoring for those occasions when the reservoir was thermally stratifiied and anoxic conditions existed, as evidenced by dissolved oxygen concentrations less than 0.5 mg/L.

Plots of the data subsets are shown in Figures 2-16 through 2-18, which show TSP as a function of hypolimnetic oxidized nitrogen at several monitoring stations. As may be seen, a strong negative relationship exists between the two variables at each station, and the clarity of the relationship may be seen to improve in the downstream direction. The relationships shown in Figure 2-16 through 2-18 suggest that maintenance of nitrate concentrations in the Reservoir in the 2 - 4 mg/L range can be expected to provide substantial protection against the liberation of sediment-bound phosphorus during periods of anoxia. Conversely, the data also suggest that naturally occurring periods of anoxia, without the ORP poising effects of nitrate, can be expected to be accompanied by substantial release of stored phosphorus from the bottom sediments.

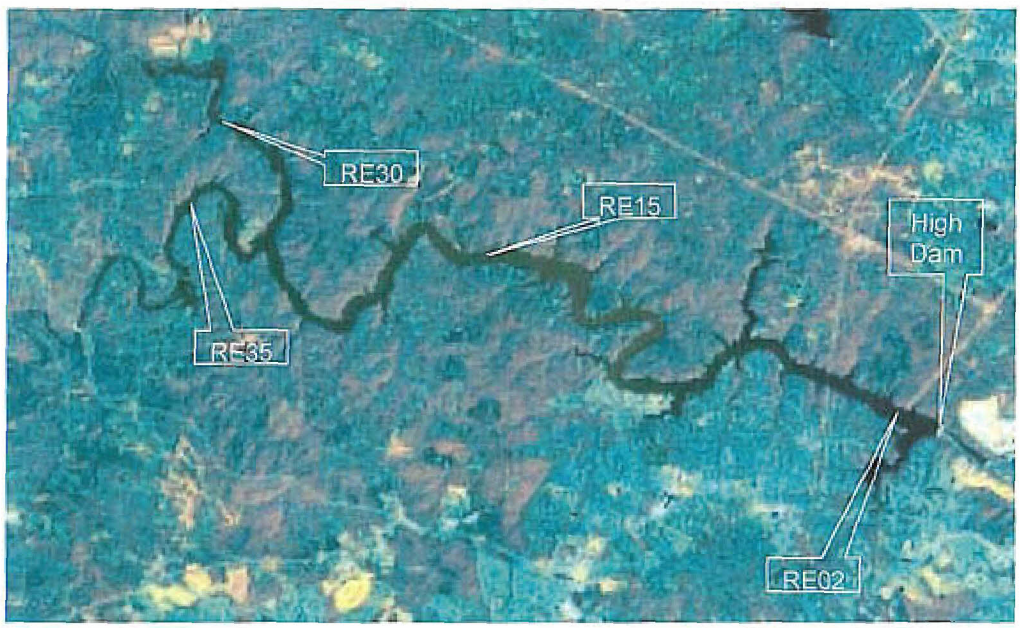

Figure 2-15. Aerial view of Occoquan Reservoir showing sampling station locations.

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A useful illustration of the utility of nitrate in managing water quality is provided in Figure 2-19, which presents a time series of Ox-N, TSP, NH_4^+-N, and total alkalinity in the bottom waters near Occoquan Dam (RE02) during the summer of 1998. As may be seen in the figure, concentrations of nitrate had declined to less than 1 mg/L early spring, and following a short period of increase, had completely disappeared (*via* dissimilatory denitrification) by early July. Although the data are not shown on the plot,

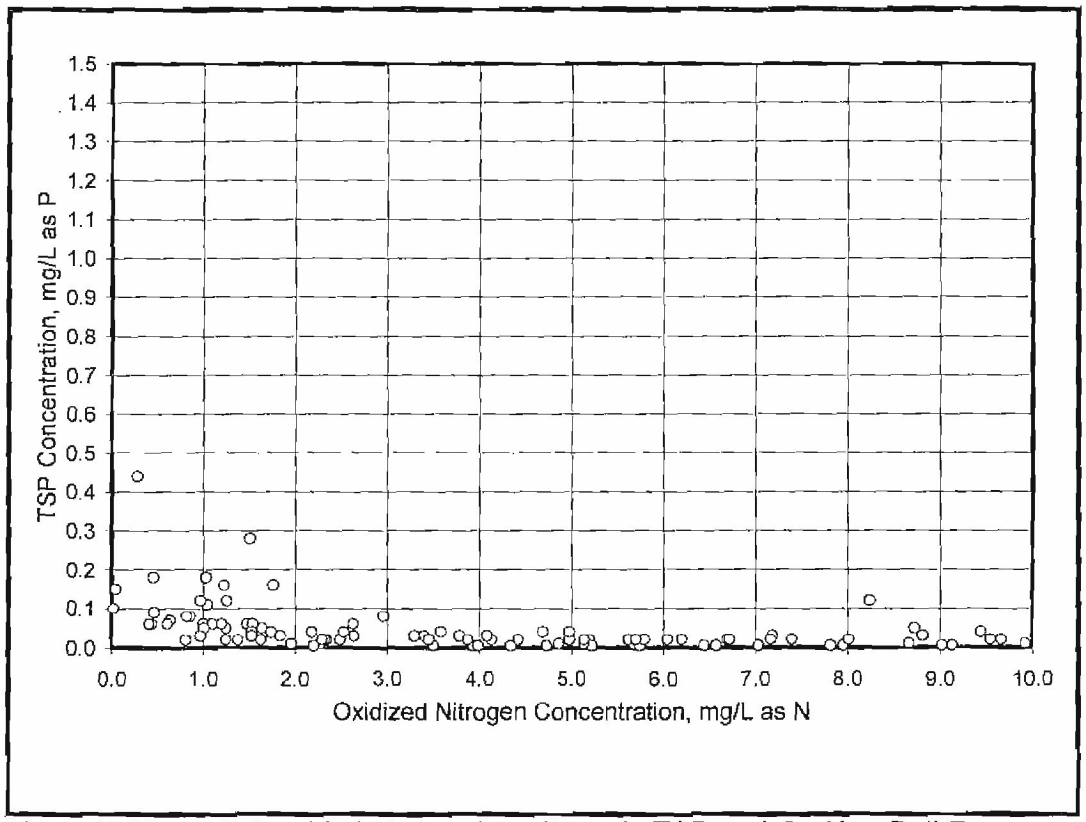

Figure 2-16. Relationship between hypolimnetic TSP and Ox-N at Bull Run Marina (RE30) for conditions of DO less than 0.5 mg/L, 1972 - 2004.

dissolved oxygen (DO) was absent from the bottom waters from early May through late September. The water quality consequences of the depletion of nitrate after loss of water column oxygen were dramatic. Beginning in April, when DO concentrations started to decline, NH_4^+-N began to be released from the sediments into the water

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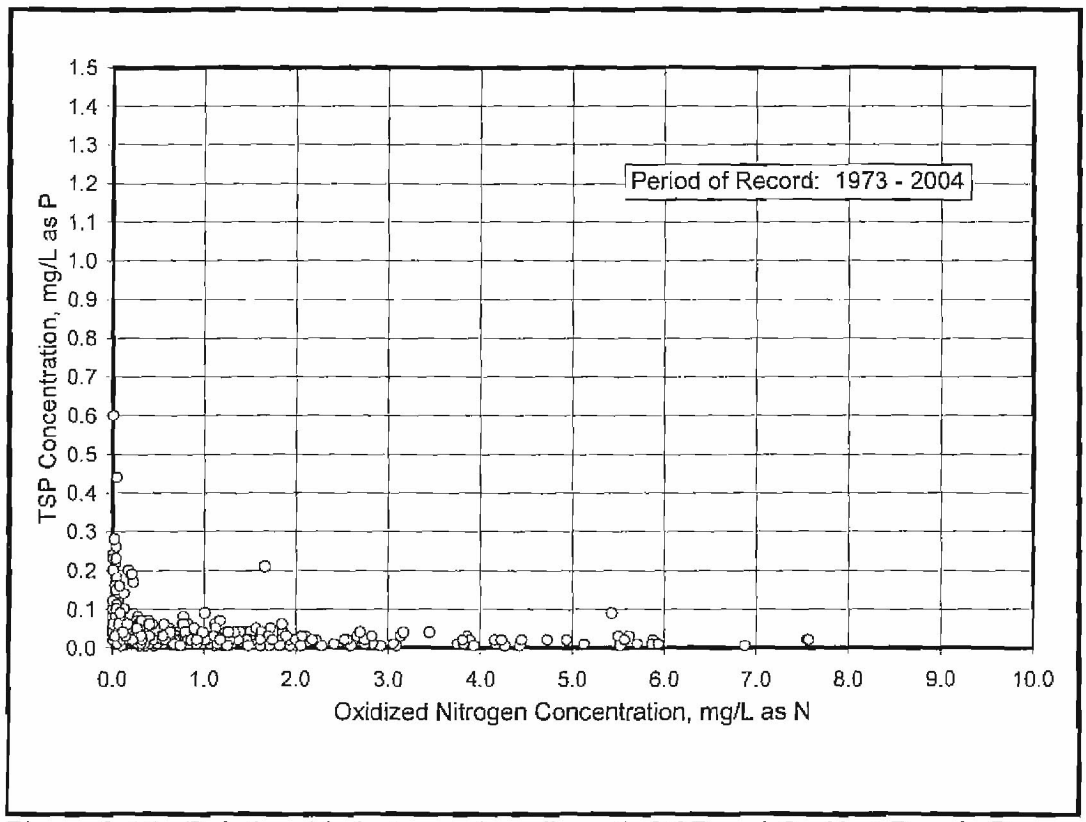

Figure 2-17. Relationship between hypolimnetic TSP and Ox-N at Ryan's Dam (RE15) for conditions of DO less than 0.5 mg/L, 1973 - 2004.

column, although concentrations initially rose to only about 1 mg/L as N. Following the total depletion of Ox-N, however, ammonium release from the sediments increased rapidly, ultimately reaching a peak value of over 4 mg/L as N. Also following the depletion of Ox-N below 1 mg/L, TSP began to be released from the sediments at a substantial rate, ultimately reaching a peak concentration of over 1 mg/L as P.

Another feature of the dissimilatory denitrification process at work is also clearly illustrated in Figure 2-19. As nitrate is depleted in the system, the production of alkalinity is an additional benefit. The soils of the Occoquan Watershed give rise to relatively low alkalinity waters, and the lack of buffering capacity can occasionally cause difficulty in water treatment operations. In Figure 2-19, the most active period of denitrification in July and August may be seen to have resulted in a substantial increase in alkalinity.

The implications of Figure 2-19 are significant. The data suggest that the removal of oxidized nitrogen from the hypolimnion has the potential to trigger substantial releases of both reduced nitrogen and phosphorus from the sediments. In the case illustrated, the peak concentration of NH_4^+-N released from the sediments was approximately eight

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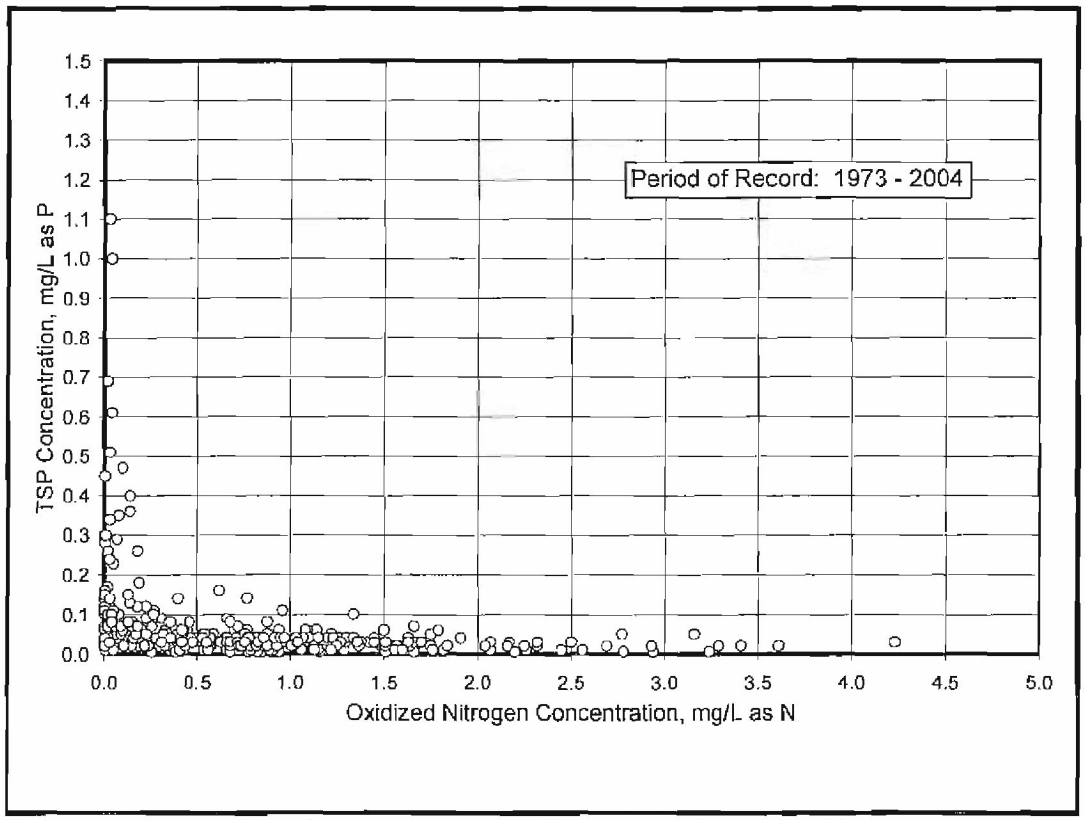

Figure 2-18. Relationship between hypolimnetic TSP and Ox-N at Occoquan Dam (RE02) for conditions of DO less than 0.5 , 1973 - 2004.

times higher than the concentration to which Ox-N had declined at the time ammonium release began. In similar manner, the release of TSP from the sediments created peak hypolimnetic concentrations that were approximately 25 times higher than those suggested by Metcalf and Eddy (1970) for successful control of algae in the Occoquan Reservoir.

Following the destabilization of the summer stratification in late September, and the reintroduction of dissolved oxygen and nitrate, NH_4^+-N and TSP concentrations rapidly declined to pre-stratification concentrations. However, it should be noted that, at the time of destratification, the high concentrations present at the time for both nutrient species in the hypolimnion served to dramatically increase the concentrations at the Reservoir surface.

The data shown in Figure 2-19 are not unique. The water quality database maintained by OWML is replete with similar observations clearly linking the presence of nitrate to reductions in the release of phosphorus and ammonium from the deposited sediments of the Reservoir. The data suggest that decisions to lower concentrations of nitrogen (in the oxidized form) from the UOSA WRF should be taken with great care, lest the

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resulting changes in chemistry and biochemistry actually increase the amount of phosphorus and nitrogen (as ammonium) released to the water column.

Localized releases of nitrogen and phosphorus in the Occoquan Reservoir have obvious consequences for water quality in the drinking water supply. However, it may also be argued that decisions to lower oxidized nitrogen concentrations in the Reservoir may have the unintended consequence of increasing the export of ammonium and phosphorus to the downstream waters of the Potomac Estuary, and ultimately, the Chesapeake Bay.

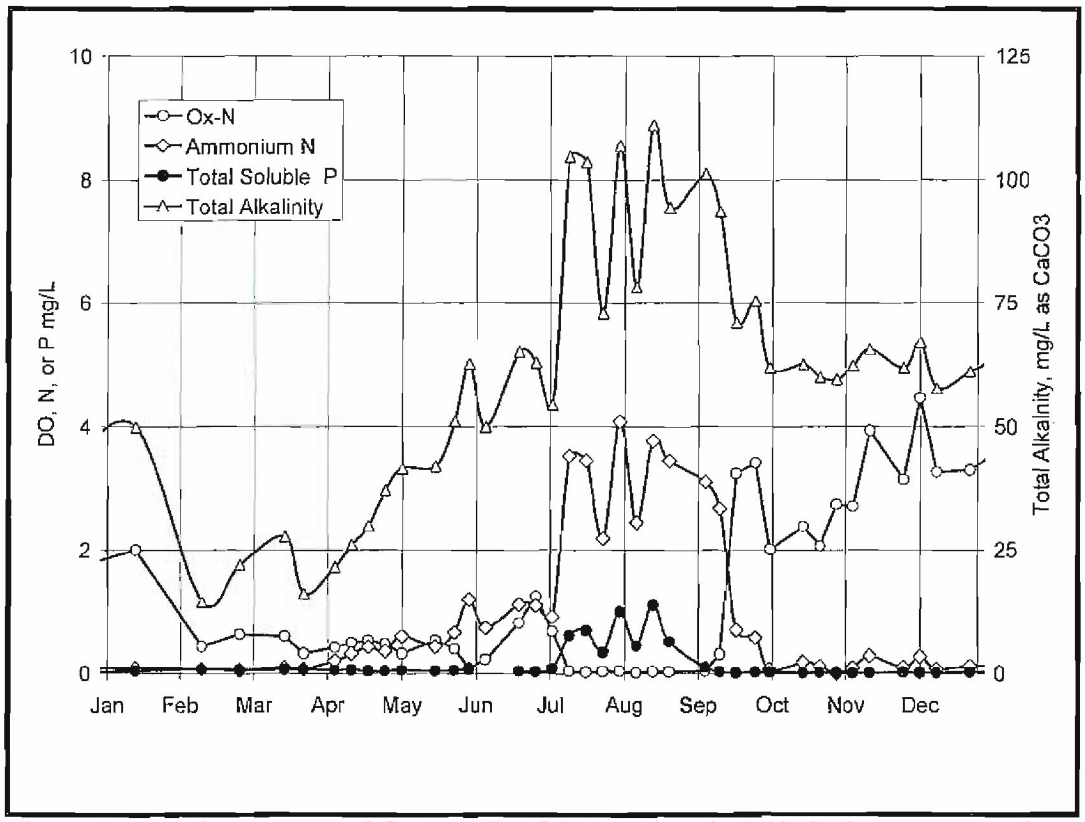

Figure 2-19. Time series of Ox-N, TSP, NH4+-N, and alkalinity in hypolimnetic waters at the Occoquan Dam (RE02) during summer 1998.

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MICROCOSM STUDIES

BACKGROUND

Microcosms are small scale representations of a discrete part of an environmental system. They may be deployed in the natural environment (*in situ*), or used in a laboratory setting. The advantage of studying a particular phenomenon with a microcosm is that it is generally possible to control the conditions of an experiment more completely than would be possible in a full-scale system. While this is a distinct advantage, care must be taken to insure that environmental changes are not introduced that have unanticipated consequences for experimental results.

Microcosms have long been used in the study of sediment-water systems in lakes and reservoirs. Mortimer (1941) conducted a series of classic microcosm studies on English lakes that are still cited today in the limnological literature. Mortimer was among the first investigators to report that the release of phosphorus from deposited lake sediments was very closely linked to the oxidation-reduction condition of the overlying water.

Microcosm studies in the Occoquan Reservoir have been used by investigators at the Occoquan Laboratory since the late 1970s to study sediment-water interactions. A particular focus of these studies has been the cycling of phosphorus to and from the water column under varying conditions, including the presence and/or absence of oxygen and other oxidized species, such as nitrate.

Results of several studies are summarized here, as is their explanatory power with respect to observed full scale sediment-water interactions in the Occoquan Reservoir.

INVESTIGATIONS OF SEDIMENT PHOSPHORUS RELEAS

Studies by To

The earliest known study of sediment-water interactions in the Occoquan Reservoir was conducted by To (To, 1974; To and Randall, 1976). To constructed very small scale batch microcosms, and subjected sediments from the Occoquan Reservoir to a variety of environmental changes. In summarizing his experimental work, he found that the release of phosphorus from Occoquan Reservoir sediments was strongly enhanced by:

- Anaerobic conditions (which he defined as the absence of dissolved oxygen;
- Increases in temperature;
- Increase in pH to values higher than generally found in the environment.

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To's findings, particularly those about anaerobic conditions, were generally in agreement with the understanding of sediment phosphorus cycling at the time. That is, upon the onset of reducing conditions, chemical and/or biochemical reduction of iron from the ferric (+3) to the ferrous (+2) oxidation state began, resulting in the liberation of phosphates associated with the less soluble (ferric) state. To also observed that the release was strongly related to the area of sediment in contact with the water column, leading to the conclusion that sediment phosphate release was largely a surface phenomenon, and not likely (at lease in the short-term) to be affected by phosphates stored deeper in the deposited sediments. To reported anaerobic release rates of 22.3 mg/m^2-d and 45.5 mg/m^2-d from sediments collected in the mainstem of the reservoir in the vicinity of Sandy Run and Bull Run Marina, respectively.

Studies by McLaughlin

McLaughlin (1981) conducted sediment phosphorus release studies on the Occoquan Reservoir using a much larger batch microcosm system. McLaughlin conducted his studies with bench-scale, closed vessels operated as continuously-mixed batch reactors (CMBRs). The reactor design was as previously reported by Grizzard (1982), and consisted of a plexiglass cylinder with a 19 cm inside diameter and a height of 38 cm, giving a volume of 10.8 liters. Each reactor had a removable cover, which was equipped with an annular groove in which an o-ring was seated in order to provide a gas-tight seal during experiments. Holes were situated around the circumference of the lid and aligned with similar holes in a flange at the top of the reactor cylinder. Carriage bolts and thumbscrews were passed through the holes, and tightened so that the o-ring was compressed in its groove, thereby providing a gas-tight seal. Seven other tapered holes were drilled in the reactor cover in order to provide access for the insertion of various electrodes, a low-rpm mixing paddle, gas sparging diffusers, and also to accommodate the insertion of sampling devices. The diameter and taper of the holes was selected to fit a number 7 neoprene stopper. Devices inserted into the holes were fitted through pre-drilled neoprene stoppers which allowed a gas-tight seal between both the device and the stopper, and the stopper and the reactor cover. Two ports were drilled into the side of the reactor in order to provide venting for any gases introduced above the water column, and to also permit sampling from below the water column. While in operation,

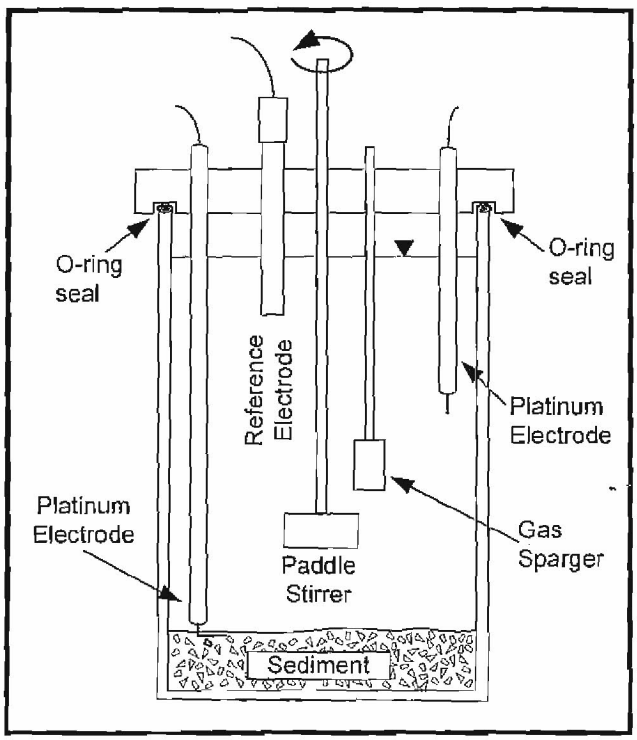

Figure 3-1. Schematic diagram of batch microcosm reactor, after Grizzard (1982).

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the reactors were maintained in darkness at a constant temperature of 20 °C. A schematic diagram of the reactor design (Grizzard, 1982) is shown in Figure 3-1.

As may be seen in the figure, platinum (Pt) electrodes were permanently inserted into the reactor to facilitate oxidation-reduction potential (ORP) measurements. One electrode was positioned at a mid-point in the water column, while the sensing element of the other was oriented horizontally and placed just beneath the sediment surface. The electrodes were connected to a common calomel reference electrode, which was also used as the reference for measurements of water column pH. Measurements of ORP were corrected to pH 7 and the zero potential defined for the hydrogen half-cell.

Because of documented problems in the literature with maintaining true anaerobic conditions in microcosms, McLaughlin employed a continuous, low-level purge of the headspace in the reactor(s) with nitrogen gas. Because the system was operated with a slightly positive headspace pressure of N_2 with respect to atmospheric pressure, it was possible to keep oxygen from penetrating into the reactor.

McLaughlin (1981) conducted batch experiments lasting up to 60 days, during which he cycled the microcosm systems between aerobic and anaerobic conditions, much as would be experienced during the natural stratification/destratification cycle in the Reservoir. Figure 3-2 shows a time series of observed total phosphorus (TP) concentrations in a microcosm containing water and sediment obtained from the vicinity of Bull Run Marina (RE30) in the Occoquan Reservoir. As may be seen from the figure, very high rates of release from the sediment were observed during the anaerobic period and high rates of sorption were observed during a subsequent aerobic period. The peak release rate reported by McLaughlin for Bull Run Marina sediments was approximately 23 mg/m^2-d. This value is about half of the peak release rate reported by To (1974) at the same location.

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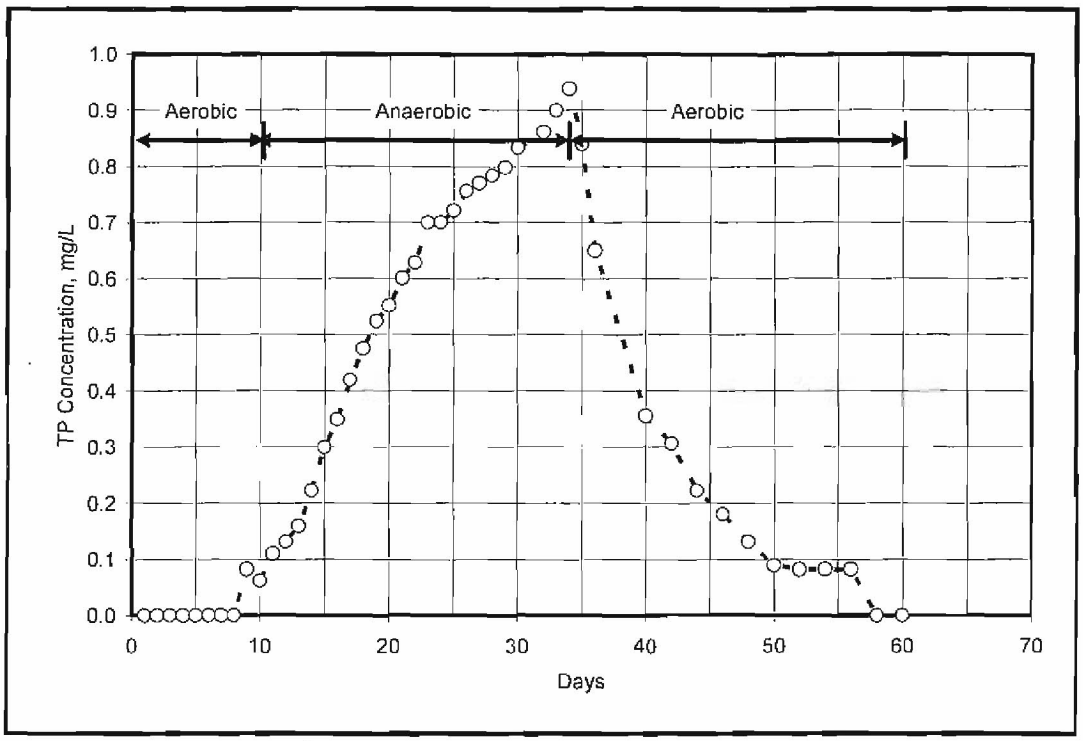

Figure 3-2. Release of Phosphorus from Bull Run Marina Sediments under aerobic and anaerobic conditions, after McLaughlin (1981).

INVESTIGATIONS OF NITRATE INTERACTIONS

Studies by Sherman

As noted previously, Ripl (1976) reported on the injection of nitrate fertilizers into the sediments of Scandinavian lakes for the purpose of retarding the release of sediment phosphorus under anaerobic conditions. Ripl postulated that the nitrate was serving as an alternate terminal electron acceptor that could be used in anoxic respiration by bacteria. By poising the system ORP at a value well above 400 mv, it was possible to prevent the reduction of ferric iron, which does not undergo reduction to the ferrous state until the ORP declines to approximately 200 mv. Because iron was being maintained in the oxidized state, it retained its ability (at least at the sediment surface) to immobilize phosphorus.

Early speculation by Sawyer (1970, 1971a, 1971b) had prompted the question of whether or not a highly nitrified effluent would have a beneficial effect on reservoir water quality. Sawyer, drawing on his knowledge of Lake Bloomington in Illinois, had postulated that, in addition to being more economical than nitrogen removal, the conversion of ammonia to nitrate in the reclaimed water discharge would assist in maintaining oxidizing conditions in the reservoir and would limit the growth of objectionable forms of algae.

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Because the UOSA WRF discharge to Bull Run was maintaining a continuous point source of nitrate to the Occoquan Reservoir, Sherman (1983) undertook a microcosm-based study to determine the potential effects of the nitrate supply on the release of phosphorus from reservoir sediments during periods of anoxia.

Sherman, as reported by Grizzard, et al. (1985), employed the same batch microcosm systems used by McLaughlin and designed by Grizzard (1978). Using an Ekman dredge, Sherman obtained wet sediment samples from the Occoquan Reservoir near Sandy Run. For the microcosm experiments, 1.5 L of wet sediment was placed in the reactor. Following placement of the sediment, 8.5 L of water was slowly added so as to avoid disturbing the sediments. When the water had been added, a head space of approximately 5 cm was present at the top of the reactor. The reactor cover was installed, but was left open to the atmosphere until the sediments had settled for three days. After 3 days, the cover was sealed, and a water sample taken to establish initial conditions. After sealing the reactor, sufficient quantities of stock solutions of KNO_3 and dextrose were introduced to bring the initial NO_3^-–N and COD concentrations to 10 mg/L in each case. The reactor was placed into a dark constant temperature chamber at 20 °C, and water quality conditions measured on a regular schedule for a period of 500 hours (nearly 21 days). A continuous low-rate purge of nitrogen gas was made in the reactor to both aid in slow mixing of the water column, and maintaining a slight positive pressure relative to the atmosphere so as to prevent infiltration of oxygen.

Aerobic heterotrophic activity immediately began to deplete the dissolved oxygen (DO) as the COD carbon source was metabolized. By hour 12, the DO had declined to approximately 0.1 mg/L. As may be seen in Figure 3-3, nitrate concentrations began to decline at about Hour 15. From that point, the rate of nitrate disappearance accelerated until it reached a maximum value at Hour 32, and by Hour 60 no nitrate remained in the water column.

Figure 3-4 shows the variation in water column and sediment ORP during the same experiment. As may be seen, the frequency of data display is much finer for ORP, because the electrode potentials were continuously recorded. At the onset of the experiment, the sediment and water column ORP values were at approximately 450-500 mv. When the reactor was sealed, the sediment ORP began to decrease rapidly until -250 mv was reached at approximately Hour 140. The rate of reduction in water column ORP did not increase dramatically until nitrate was depleted at Hour 60. At that point,

the water column ORP decreased at the highest rate observed in the experiment until a low value of -310 mv was reached. At that point, the water column ORP rose slightly until a value of approximately -230 mv was reached.

Referring back to Figure 3-3, It is interesting to note that approximately 65 hours after the depletion of nitrate, ammonium began to be released from the sediment. Ammonium release proceeded at a high rate until the termination of the experiment at Hour 500. The final ammonium concentration observed in the water column was over 5 mg/L as N. When viewed from the perspective of total nitrogen, it should be noted that

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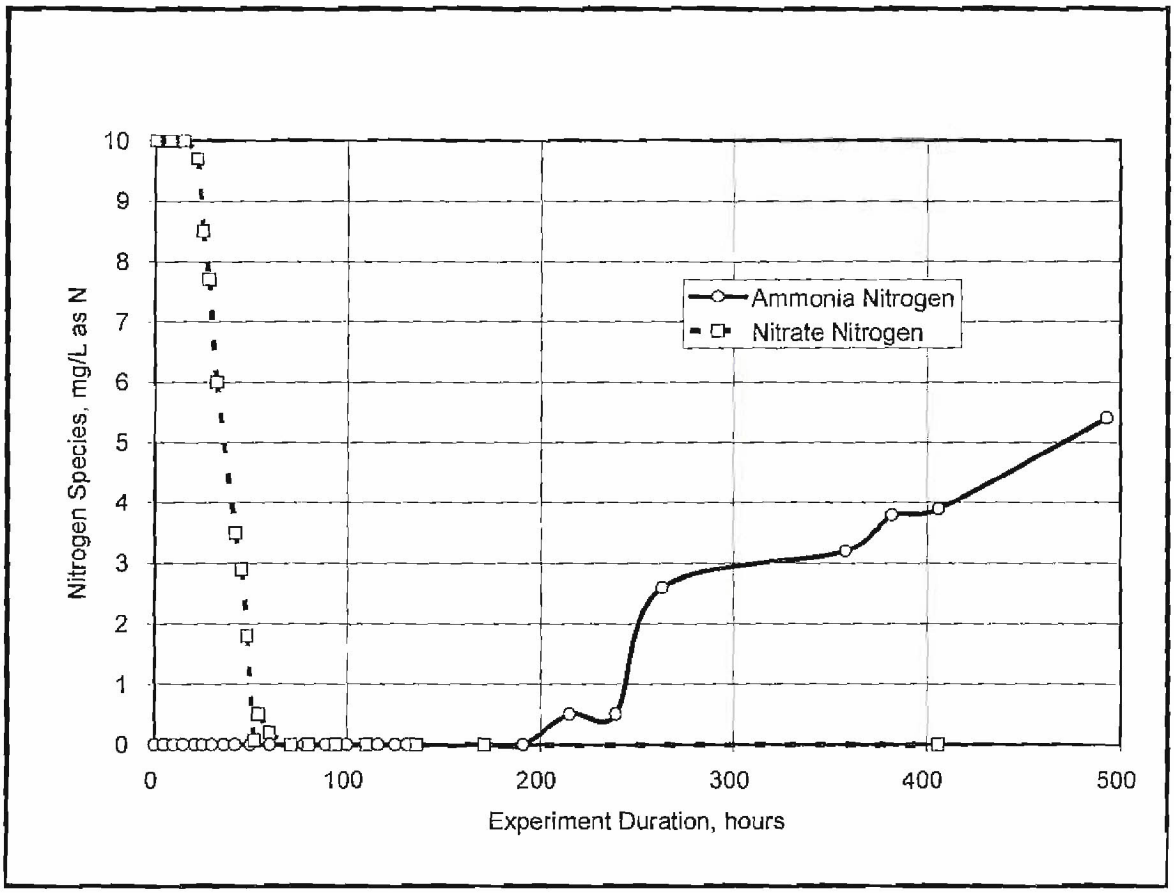

Figure 3-3. Time series of average nitrate and ammonium concentrations during sequenced aerobic and anoxic conditions in batch microcosm.

this was over 50 percent of the nitrate-nitrogen added to the system at the beginning of the experiment. This observation has particular relevance to any future attempts to control nitrogen fluxes from the Occoquan Watershed. Reduction of point source nitrate below levels that will maintain oxidizing conditions at the sediment interface may have the unintended consequence of dramatically increasing the release of ammonium from those same sediments.

The phenomenon of ammonium release from deposited sediments under anoxic and/or anaerobic conditions has been described by a number of investigators (Kamiyama, *et al.*, 1977; Verdouw, *et al.*, 1985). During aerobic periods, when the ORP is high, ferric iron compounds precipitate at the sediment surface create an "oxidized microzone," which was first described by Mortimer (1941). This zone creates an effective seal between the oxidizing environment of the water column and the reducing environment of the sediments and interstitial water below the interface. Following the onset of truly anaerobic conditions ($E_7 < 200$ mv), the precipitated iron compounds forming the microzone are solubilized by the reduction of Fe^{3+} to Fe^{2+}, and the barrier to migration of reduced compounds from the lower sediment layers and interstitial waters is removed.

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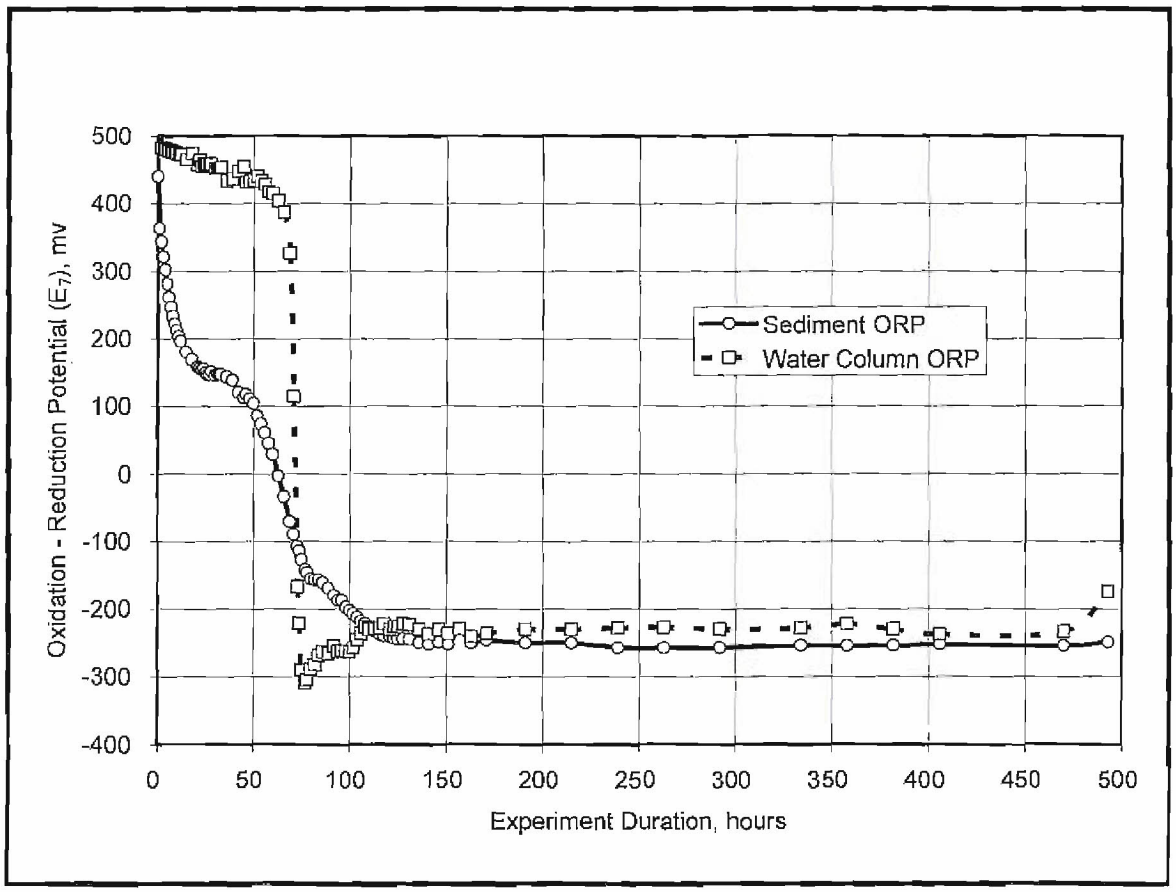

Figure 3-4. Time series of water column and sediment ORP during sequenced aerobic and anoxic conditions in batch microcosm.

Ammonium sorbed to the sediments, and ammonium derived from anaerobic decomposition in the interstitial waters is then free to diffuse to the upper layers and eventually into the water column.

Figure 3-5 shows a time series of the variation in soluble iron, soluble manganese, and soluble phosphorus during the same experiment. As may be seen, the increase in water column concentrations of all three constituents began at approximately the same time as the liberation of ammonium from the sediments. In all three cases, this followed the reduction of ORP to a value below -200 mv, and is consistent with the destruction of the oxidized microzone at the sediment surface. As may be seen in the figure, by the end of the experiment at Hour 500, the phosphorus, iron, and manganese concentration in the water column had reached values of 1 mg/L, 6.8 mg/L, and 3.4 mg/L, respectively.

The liberation of these three species from the sediments at the concentrations observed following the depletion of nitrate and the onset of anaerobic conditions prompt some concern from both the perspectives of water quality management and drinking water treatment. It should first be reiterated that, in the full scale system, there is no

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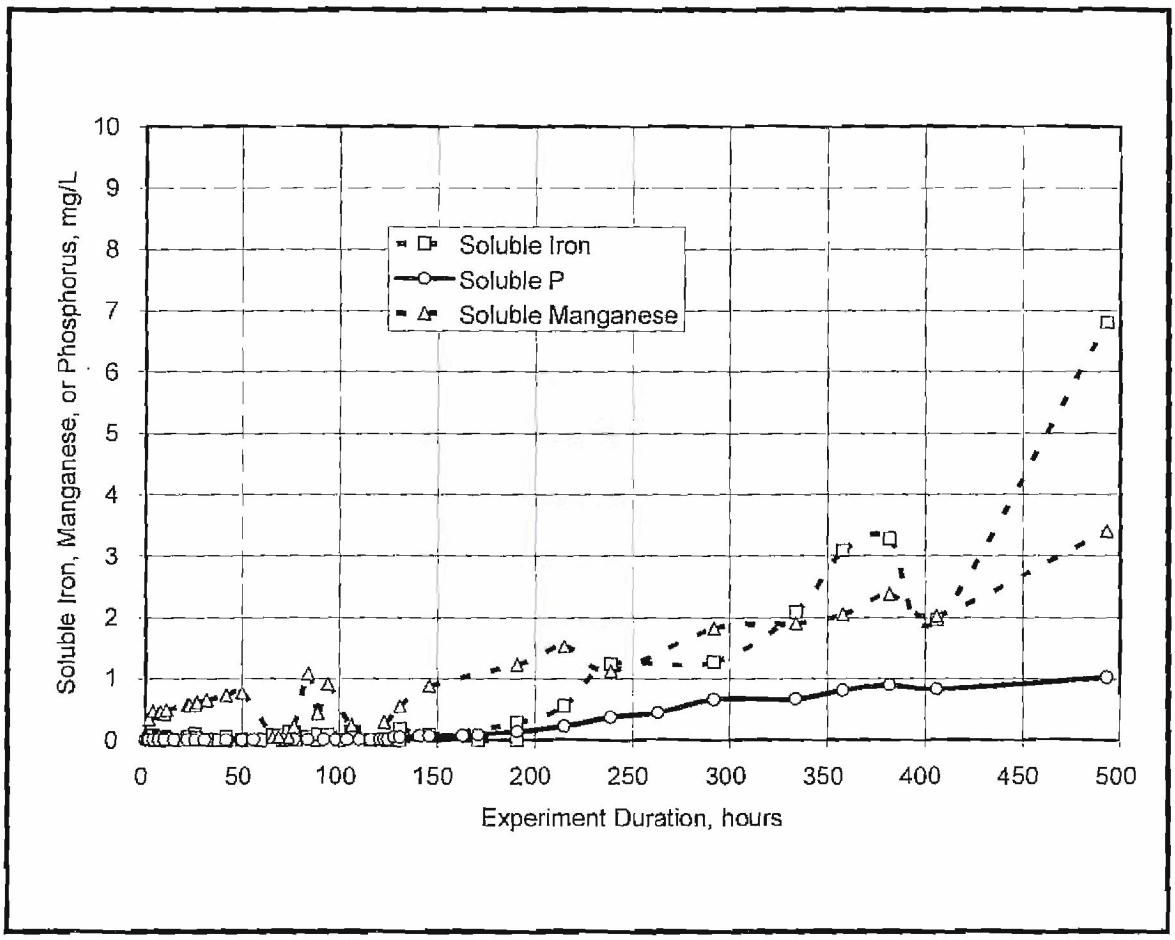

Figure 3-5. Time series of soluble iron, manganese, and phosphorus during sequenced aerobic and anoxic conditions in batch microcosm.

assurance that these ions will be confined to the hypolimnetic waters during the summer stratification. Because of its long, narrow shape, the Occoquan Reservoir is subject to short term stratification disruptions caused by hydrodynamic mixing during storm events. As a result, hypolimnetic species are often mixed towards the surface on several occasions during the summer. Although some dilution of the hypolimnetic concentrations would occur when mixed with surface water, the values observed in this experiment are nevertheless of sufficient magnitude to be of concern.

Phosphorus concentrations in the 1 mg/L range are over 1.5 orders of magnitude above those thought to be necessary to limit algal production in phosphorus limited systems. The iron and manganese concentrations of 6.8 mg/L and 3.4 mg/L, respectively, reached by the end of the experiment were also far above the Secondary Maximum Contaminant Levels (SMCLs) of 0.3 mg/L and 0.05 mg/L, respectively, for both species.

In summary, it may be said that Sherman's work represented a clear demonstration of the role of nitrate in controlling the liberation of reduced species from deposited

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sediments in batch systems. Her results demonstrated that the presence of nitrate in oxygen-depleted sediment-water systems can retard the release of a number of constituents of concern (at concentrations of concern), including:

- Phosphorus
- Iron
- Ammonium Nitrogen
- Manganese

Studies by Banchuen

Sherman (1983) clearly described some of the water quality risks associated with allowing true anaerobic conditions to develop in the bottom waters of the Occoquan Reservoir. She was able to observe the ORP effects of depletion of nitrate in an anoxic environment, and the subsequent liberation from the sediments of several chemical species of water quality concern. Her studies, however, were conducted in batch reactors, and while successful as a "proof of concept" in the use of microcosms to investigate sediment-water interactions, they were unable to integrate the effects of water renewal in a continuous flow system.

Banchuen (2002), in a continuation of the use of microcosms to investigate rates of denitrification in sediment-water systems, designed a novel continuous flow experimental system. In order to deal with some of the limitations of batch microcosm systems, he constructed a multi-reactor flow through system that could be configured to operate with realistic detention times for segments of the Reservoir to be studied. In addition, the system was designed to provide for realistic ratios of reactor volume to exposed sediment surface area (V:A). This was done, along with the detention time controls, in order to maintain conditions of sediment-water exposure that approximated those in the Reservoir. Yung (1990), in a study of the exertion of sediment oxygen demand (SOD), had described the volume:sediment area ratio as effective depth. She found that the exertion of SOD was closely related to effective depth, because of the role of the exposed sediment area in controlling the rate of diffusion of soluble organic matter into the water column. volumes (large effective depth) as on shallow water bodies.

Because the presence of an oxidized microzone (Mortimer, 1941) at the sediment surface appears to play a key role in regulating the passage of reduced species from the sediments and pore water into the water column, it follows that flux rates should be affected by the exposed area of the sediment. Further, the volume of the bulk water in contact with the exposed sediment area should also affect the rate of flux. In fact, a gradient flux law statement of the rate of mass transfer across a sediment-water boundary should have an A/V term included. The term A/V may also be taken as the inverse of the effective depth described by Yung (1990).

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Banchuen (2002) concluded that microcosms constructed to represent a given water body ought to have effective depths comparable to those of the actual aquatic system being simulated. In addition, while many successful microcosm studies have been performed with batch CMBR systems, the long, narrow physical nature of the Occoquan Reservoir makes it more likely to be successfully simulated as a plug-flow system. Banchuen (2002) concluded that a microcosm system for the Occoquan Reservoir should, therefore, be composed of a set of continuously stirred tank reactors (CSTRs) in series. An additional advantage of such an arrangement is that individual reactors could be manipulated to provide detention times and effective depths that would effectively represent changes in the physical system representation as a function of distance downstream. Several investigators have successfully used this type of microcosms in studies, including Cooke and White (1987) and Montuelle *et al.* (1997).

A two-CSTR cascade system, a schematic of which is shown in Figure 3-6, was selected for the study of denitrification rates in the upper reaches of the Occoquan Reservoir. As with the system previously described by Grizzard (1978), the reactors were constructed of plexiglass, but had an inside diameter of 43 cm. The reactor was 50 cm high, and could accommodate a water column depth of approximately 40 cm. The reactors were constructed with a cover having an O-ring seal to ensure an airtight seal. Four vertical baffles were mounted on the inside circumference to improve mixing by preventing vortexing. To prevent algal growth within the reactor, the reactor body was covered with a thin black sheet of neoprene rubber attached to the reactor with Velcro strips. The reactor cover had eight bored holes, one of which was enlarged to accommodate a 32-mm ID glass tube. The tube was inserted into the reactor, and extended below the liquid surface. This arrangement made it possible to insert instruments sensors into the reactor, while exposing only a small area of liquid surface to the atmosphere. Another bore hole was used to house a similar, but smaller glass tube to reduce the exposed water surface area even further for thinner electrodes. Other holes were used for ORP electrodes and the liquid inlet and outlet. Unused holes were closed and sealed with neoprene stoppers.

A variable-speed DC motor was selected so that mixing energy could be varied by changing the impeller speed. At the impeller shaft entry point into the reactor, the shaft was sealed against the reactor lid with a rotary-shaft seal, preventing air leaks around the motor shaft. The seal was lubricated with a Sil-Glyde® compound.

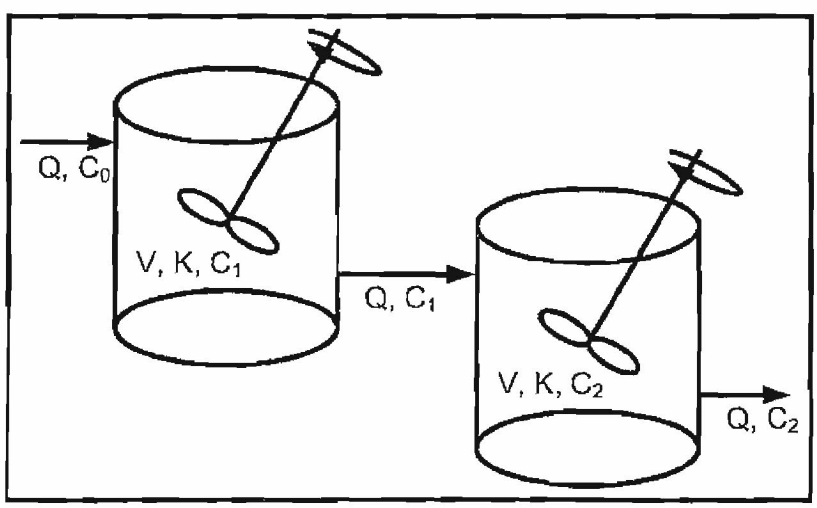

Figure 3-6. Schematic representation of the CSTR cascade used in the continuous flow experiments.

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The experiment was set up to simulate summer conditions un the upper reaches of the Occoquan Reservoir at depths greater than 10 feet, which was taken to approximate the anoxic zone during the period of stratification. The reaches simulated extended from the tail waters of the Bull Run arm (near RE30) to Ryan's Dam (RE15) below the confluence with Occoquan Creek. For 56 days, feed water was prepared from a mixture of Bull Run Water and UOSA WRF discharge to give a mixed Ox-N concentration of about 7 mg/L. The feed water reservoir was stored in a 20-gallon tank stored at 4°C and continuously stirred with a magnetic stirrer. In order to insure no negative effects from air leaks, the headspace of both reactors was kept filled with nitrogen gas at a slightly positive pressure.

Sediments for the experiment were collected with an Ekman Dredge from the following locations in the Occoquan Reservoir:

- Midpoint between the tailwaters of the Bull Run arm and Station RE30
- Midpoint between RE30 and the Bull Run-Occoquan Creek confluence
- Midpoint between the Bull Run-Occoquan Creek confluence and RE20
- Midpoint between RE20 and RE15

Collected sediments from each location were placed in 50-mL beakers, and allowed to consolidate. Sediment was added until the depth was approximately 3 cm. The cross-sectional area of the beakers was determined to be 11.7 cm^2, and was used in the computation of effective depth (V/A) for each of the two reactors. It was determined that nine beakers containing sediments from the three upstream sites would be placed in the first reactor, and three beakers containing sediment from the most downstream site would be placed in the second reactor. The reactors were then slowly filled with the feed water and sealed. The effective depths in Reactors 1 and 2 were 4.18 ft and 8.52 ft, respectively, which was a reasonable representation of the effective depth in the Reservoir reaches being simulated. The assembled reactors were placed in a 20 °C incubator, and connected to a peristaltic pump and a nitrogen gas tank.

The pump flow rate was adjusted to give reactor detention times typical of non-storm flow conditions in the upper Reservoir during the summer months. A flow rate of 0.6 mL/min was used, resulting in detention times of 11.09 days and 11.33 days in Reactor One and Two, respectively.

Figure 3-7 shows a time series of dissolved oxygen and nitrate for the duration of the experiment. As may be seen from the figure, at steady state, Ox-N removal in the first reactor, which was configured to simulate the Bull Run reach above the confluence with Occoquan Creek, was approximately 3 mg/L. Similar overall removals were observed in Reactor 2, which was configured to simulate the reservoir reach from the Bull Run - Occoquan Creek confluence to Ryan's Dam.

Computation of the first order denitrification rate constant in each of the microcosms was performed by constructing a materials balance on each reactor assuming the existence of completely a completely mixed condition existed. Using the inflow and outflow

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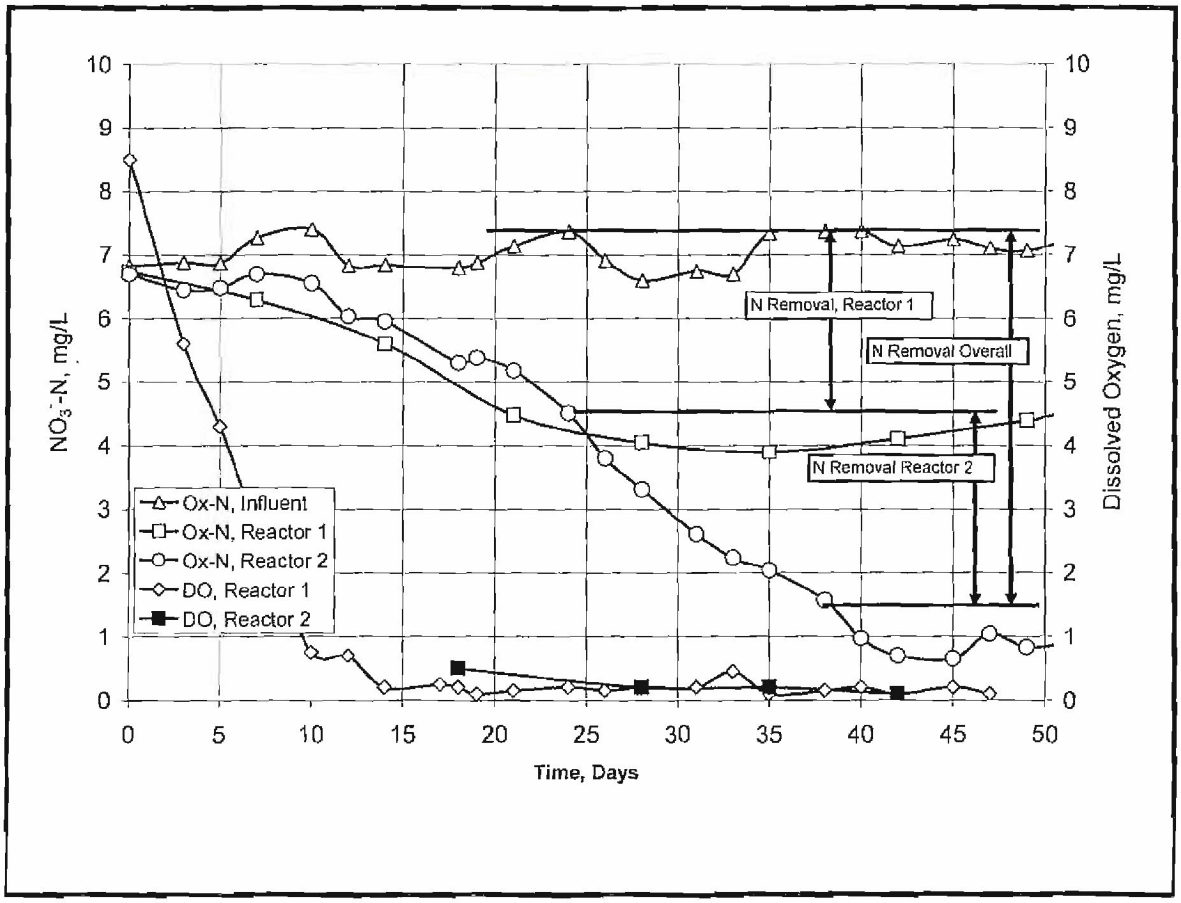

Figure 3-7. Time series of dissolved oxygen (DO) and oxidized nitrogen (Ox-N) in 2-CSTR cascade simulating the Occoquan Reservoir from the tailwaters to Ryan's Dam.

concentrations of Ox-N for each reactor, along with the detention times cited above, at steady state, the following materials balance was constructed:

$$\frac{dC}{dt}V = Q_{in}C_{in} - Q_{out}C_{out} - k_{dn}C_{out}V$$

where,

V = Reactor Volume, L^3

$Q_{in} = Q_{out}$ = Flow rate, L^3/t

C, C_{in}, C_{out} = Concentrations of constituent of interest, mass/L^3

k_{dn} = first-order denitrification rate constant, t^{-1}

at steady state:

$$k_{dn} = \frac{Q_{in}C_{in} - Q_{out}C_{out}}{C_{out}V} \quad \text{and rearranging....} \quad k_{dn} = \frac{Q(C_{in} - C_{out})}{C_{out}V}$$

Since $Q/V = 1/t_d$ the equation may be expressed as: $k_{dn} = \frac{(C_{in} - C_{out})}{t_d C_{out}}$

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The computed values of k_{dn} were found to be:

- Bull Run tailwaters to Confluence with Occoquan Creek: $k_{dn} = 0.07\ d^{-1}$
- Bull Run-Occoquan Creek Confluence to Ryan's Dam: $k_{dn} = 0.36\ d^{-1}$

It should be noted that the value of k_{dn} computed from the microcosm study for the reach from the Occoquan Creek-Bull Run confluence to Ryan's Dam was found to be more than two times higher than the highest recommended value (0.15 day^{-1}) for the CE-QUAL-W2 model (USACE WES, 2000). In fact, recent experience at OWML with the development of a CE-QUAL-W2 model for the Occoquan Reservoir revealed that the microcosm-determined value of k_{dn} was required in order to obtain a satisfactory calibration. It should be noted, however, that the 0.36 d^{-1} value is within the range of (0.0 – 1.0 day^{-1}) recommended in *Rates, Constants and Kinetic Formulations in Surface Water Quality Modeling* (ERLORD, 1985). The difference between the rate microcosm-observed rate in this work and the values cited from other sources may be attributed, as suggested by Messer and Brezonik (1984), to the site-specificity of the denitrification phenomenon in reservoirs.

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PHYTOPLANKTON ISSUES

INTRODUCTION

This chapter addresses the effects of the absolute and relative concentrations of the nutrients nitrogen and phosphorus in the Occoquan Reservoir, and effects on the distribution and growth of the various algal taxa found therein. In addition, pertinent literature citations are included to address the risk of undesirable species shifts if nitrate is removed from the system or if N:P ratios drop to lower values, such as those experienced in the pre-1978 period. Data used in this assessment were drawn from reports by Rashash (1991), the Occoquan Watershed Monitoring Laboratory (OWML, 1998), current OWML Reservoir physicochemical data (through December, 2004), and phytoplankton count data received from Fairfax Water by OWML (through October, 2001).

Dr. Bruce C. Parker, an internationally known phycologist, who is also Professor Emeritus of the Virginia Tech Department of Biology (Parker, 2005), was a key contributor, along with OWML staff, to the data analysis in this chapter.

HISTORICAL CHANGES IN NITROGEN, PHOSPHORUS, AND PHYTOPLANKTON

Figures 4-1, 4-2, 4-3, and 4-4 are time series plots of seasonal average values of total phosphorus (TP), total Kjeldahl nitrogen (TKN), Oxidized Nitrogen (Ox-N), and ratios of total inorganic nitrogen to total soluble phosphorus (TIN:TSP) at four monitoring stations in the Occoquan Reservoir for the period from 1973 - 2004.

Pre-1978

Before start-up of the UOSA WRF in 1978, average concentrations of nutrients in the Bull Run arm of the Reservoir were consistently high, with TP and TKN concentrations generally in excess of 0.2 mg/L as P and 1.5 mg/L as N, respectively. Similar trends were observed in the lower Reservoir, although concentrations declined somewhat in the downstream direction, eventually reaching approximately 0.1 mg/L as P, and 1 mg/L as N, respectively, just upstream of the Occoquan Dam (RE02). In the Occoquan Creek arm of the Reservoir (RE35), above the confluence with Bull Run, pre-1978

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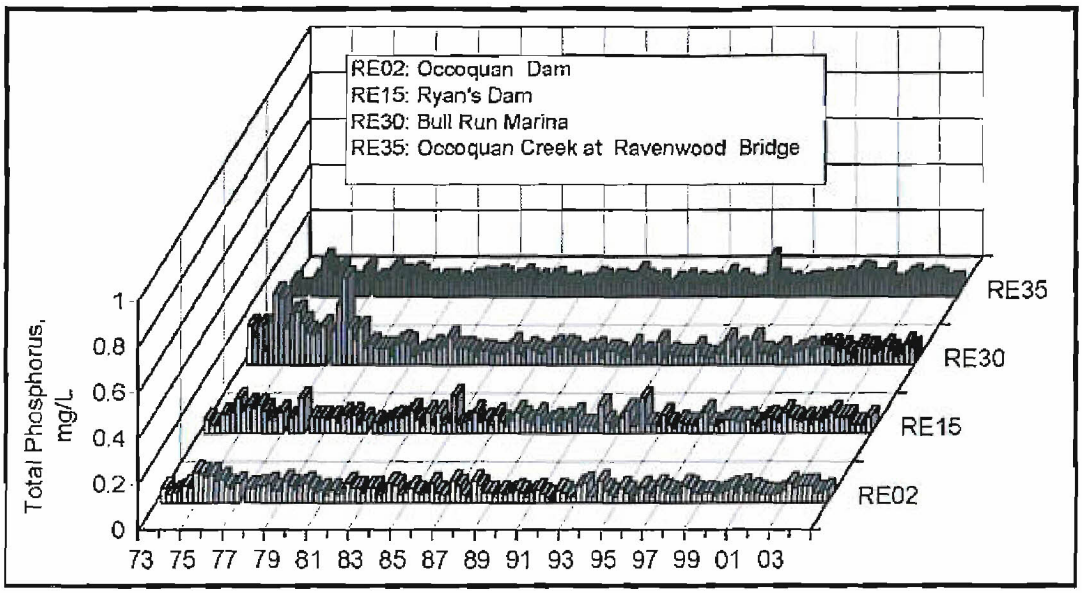

Figure 4-1. Seasonal average concentrations of total phosphorus (TP) at Occoquan Reservoir monitoring stations, 1973 - 2004.

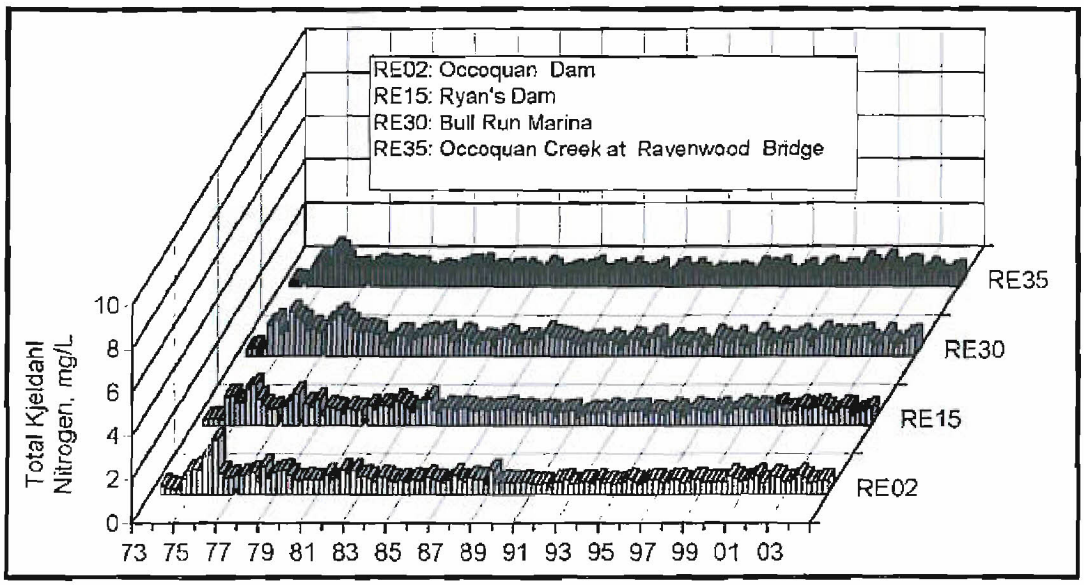

Figure 4-2. Seasonal average concentrations of total Kjeldahl nitrogen (TKN) at Occoquan Reservoir monitoring stations, 1973 - 2004.

concentrations of TP and TKN were much lower than those observed in Bull Run, averaging approximately 0.1 mg/L as P and 1 mg/L as TKN, respectively. The substantial differences in nutrient concentrations between the Bull Run and Occoquan

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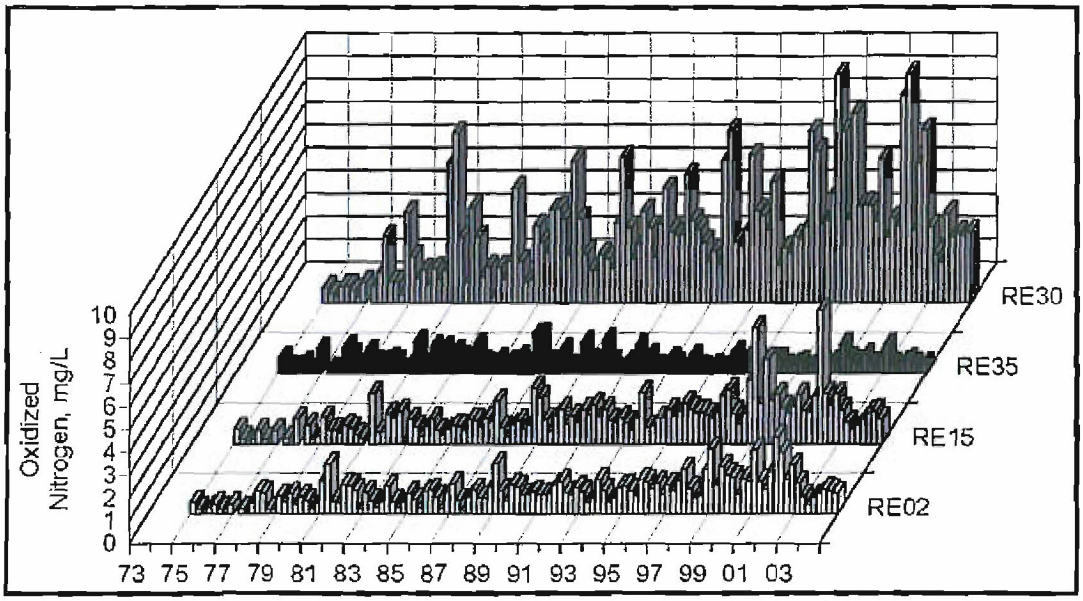

Figure 4-3. Time series of seasonal average Ox-N concentrations at Occoquan Reservoir monitoring stations, 1975 - 2004.

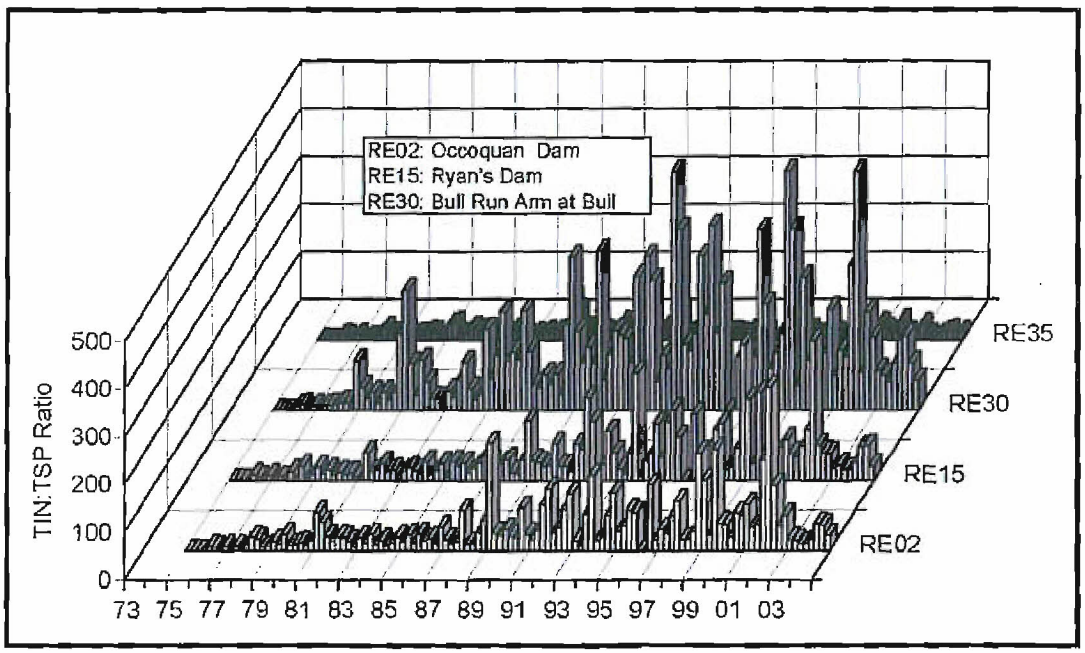

Figure 4-4. Time series of seasonal average TIN:TSP ratios at Occoquan Reservoir monitoring stations, 1975 - 2004.

Creek arms of the reservoir were principally due to the discharge of up to 2.9 MGD of secondary treated wastewater with no nutrient removal into Bull Run and its tributaries.

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The high nutrient concentrations prior to the start-up of the UOSA WRF, coupled with low TIN:TSP ratios had some clear consequences in terms of algal speciation in the pre-1978 period.

Nutrient Limitation. The familiar Redfield Ratio (Redfield, 1958), which is often used to interpret nutrient limitation data, was developed from the observation that the molar ratio of carbon:nitrogen:phosphorus in marine plankton is usually found to be about 106:16:1. On a mass basis, this same ratio may be expressed as 41:7.2:1. Numerous studies from Redfield (1958) to Hillebrand and Sommer (1999) show that N:P ratios of 16:1 to 17:1 generally represent a balance for these two essential nutrient elements. Ratios lower than 16:1 where there is less N available relative to P tend to favor N-fixing blue-green algae, while ratios higher than 17:1 tend to discourage them.

Work by Schindler (1977) performed at the full-scale on experimental Ontario lakes indicated that there may be distinct water quality risks associated with removing too much nitrogen from freshwater aquatic systems. Schindler found that even at moderate N:P ratios no lower than 22:1, algal successions tended to shift from diatoms and greens towards the blue-greens.

Other investigators have reported wider ranges of N:P ratios in freshwater algae, ranging up to a 27:1 mole ratio (Rast and Lee, 1978), which is a 12.7:1 mass ratio. Other investigators have reported freshwater algae mass-based nutrient ratios ranging from 10:1 to 17:1 (Sakamoto, 1966; Dillon and Rigler, 1974; Forsberg, *et al.*, 1978). Lee and Jones (1980) reported a 7.2:1 mass ratio on the basis of *available* N and P.

Overall, the higher N:P ratios reported for freshwater systems are consistent with the generally held view that freshwater lakes and reservoirs are more likely to be P-limited, and marine systems more likely to be N-limited.

In interpreting the N:P ratio data for the Occoquan Reservoir, the computation has been performed using readily available forms: total inorganic N (NH_4^+-N + NO_2^--N + NO_3^--N) and total soluble phosphorus (TSP). For the purposes of this report, the ratio of concern for nitrogen limitation has been taken to be a TIN:TSP mass (or concentration) ratio below 15:1.

In-Reservoir Observations. In the pre-1978 period, TIN:TSP values of less than 15:1 were frequently observed in all locations in the Occoquan Reservoir, as shown in the

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seasonal time series in Figure 4-4. In fact, the observed ratios were more often less than 10:1, leading to strongly nitrogen-limited conditions for phytoplankton growth. Coupled with the high overall nutrient concentrations observed during the same period (Figures 4-1 and 4-2), conditions favored the frequently-experienced summer and early fall blooms of nuisance blue-green algae or cyanobacteria, such as *Microcystis, Anabaena, Aphanizomenon* (Rashash, 1991). Photographs of typical bloom conditions were shown earlier in this report in Figures 1-3 through 1-5.

The species most often observed, among other blue-green algae, have been implicated in numerous treatment problems in public water supplies, including the occurrence of taste and odor episodes and impacts on filtration performance due to the formation of floating mats of algae. Some of the blue-green species have also been discovered to excrete extracellular metabolites that have been found to serve as efficient pre-cursor compounds in the formation of regulated disinfection by-products in drinking water treatment (Hoehn, *et al.*, 1980). During the pre-1978 period, the excessive nutrient concentrations also supported the growth of high cell numbers of green algae. It is interesting to note that considerably lower numbers of diatoms were found prior to 1978, during intervals between copper sulfate treatment of the Reservoir (Rashash, 1991; OWML, 1998).

Post-1978

In the period following the mid-1978 start-up of the UOSA WRF, as may be seen in Figure 4-1 and 4-2, TP and TKN concentrations were substantially reduced in Bull Run (RE30) and at the lower Reservoir stations (RE15 and RE02). As may be seen in Figure 4-3, oxidized N concentrations were observed to increase dramatically in the Bull Run arm (RE30) in the same period because of the operation of the UOSA WRF in a nitrification mode. As the figure also shows, increasing flows from UOSA in subsequent years have resulted in much higher TIN:TSP ratios in the Bull Run arm of the Reservoir (RE02), and also at the lower Reservoir monitoring stations (RE15, RE02).

Overall, the enhanced Oxidized nitrogen supply (NO_2^--N + NO_3^--N) has led to in-Reservoir conditions where the TIN:TSP ratio is rarely below 20:1, and often is much higher in the summer and fall seasons (OWML, 1998). The exception may be found in the Occoquan Creek arm (RE35), which does not receive the highly nitrified discharge from the WRF. It should also be noted that the increase in Ox-N in the post-1978 period has been accompanied by dramatic declines in phosphorus (Figure 4-1) in the Bull Run arm (RE30), and as a result, in the lower Reservoir as well (RE15, RE02).

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The phosphorus concentration decline experienced is an illustration of the success of three successful water quality restoration strategies in the watershed: (1) the high performance removal of phosphorus at the UOSA WRF to concentrations less than 0.1 mg/L as P, (2) the use of WRF-supplied nitrate to reduce summer and fall cycling of sediment phosphorus, and (3) aggressive implementation of watershed-wide stormwater quality management programs beginning in the late 1970s. It should be noted that the local governments of northern Virginia were involved in BMP development and implementation programs for the Occoquan Watershed well in advance of state-mandated efforts directed towards the Chesapeake Bay restoration.

Algal count data obtained from Fairfax Water (2005) have also revealed a biological indicator of lowered PO_4^{-3} concentrations, namely, the presence of *Dinobryon spp.* (Hutchinson, 1967). The organism has made appearances at Hooes Run, other locations upstream, and in the main body of the Occoquan Reservoir. The higher N:P ratio after 1978, coupled with the reduced phosphorus supply, have led to somewhat reduced phytoplankton cell numbers, but more importantly, it has been accompanied by a shift to dominance of green algae and diatoms over the blue-green algal component of the phytoplankton community. Rashash (1991) noted that the influx of NO_3^- and the resulting increase in N:P ratios was the likely cause of the observed shift to diatom and green algae dominance. Figure 4-5 is a plot of the species dominance reported by Rashash in the years prior to and following start-up of the UOSA WRF. As may be seen in the figure, the UOSA start-up was accompanied by increased frequency of dominance by the *Bacilariophycota* (diatoms) followed by the *Chlorophycota* (green algae). In the post-UOSA WRF years, the dominance of blue-green algae has subsided to the point of non-occurrence.

The shift in dominance is most probably related to the documented preference for NO_3^- utilization by a number of green algae (Hutchinson, 1967) and diatoms (Hutchinson, 1967; Patrick, 1977). Coupled with the deterrence of blue-Green algae at High N:P ratios in freshwater environments, the maintenance of high NO_3^- concentrations in the Occoquan Reservoir may be directly responsible for the more preferable dominance of diatoms. In addition, the much-lowered concentrations of phosphorus in the Reservoir during the post-1978 period has reduced the overall production capability of the system, regardless of species.

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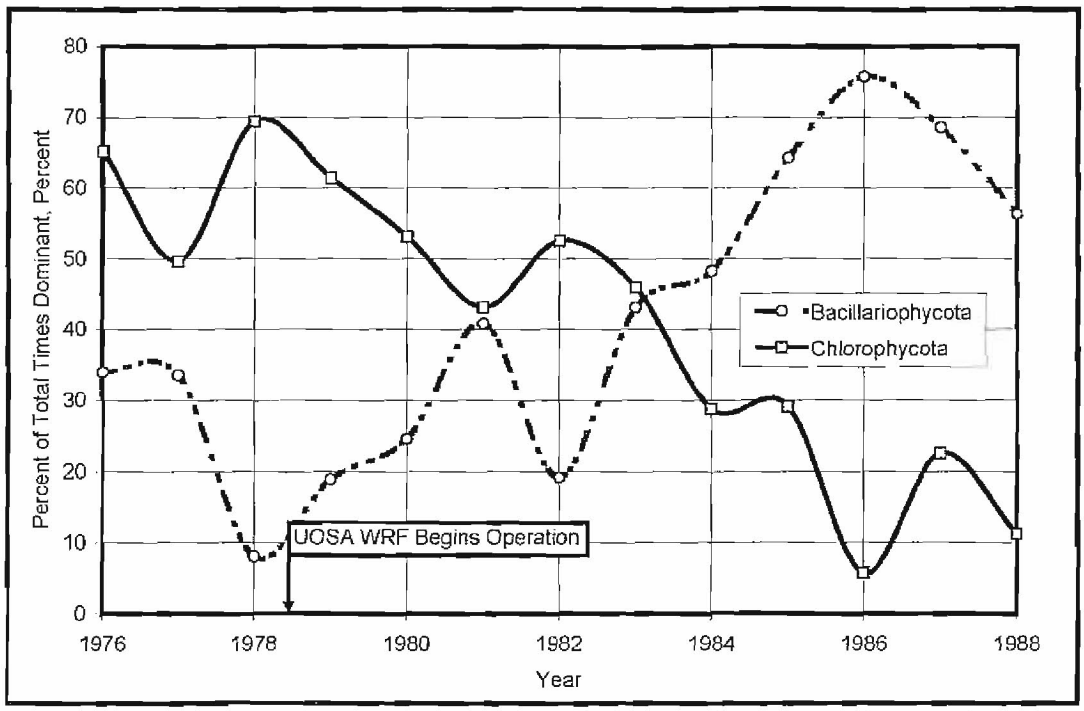

Figure 4-5. Algal species dominance changes in the Occoquan Reservoir before and after start-up of the UOSA Water Reclamation Facilty, 1976 - 1988 (after Rashash, 1991).

Recent Trends

Figure 4-6 shows box and whisker diagrams of the distribution of TIN:TSP ratios at four Occoquan Reservoir monitoring stations over the past 10 years (1994 - 2004). As may be seen, median values of TIN:TSP ratios at the Bull Run arm monitoring station (RE30), and the lower Reservoir stations (RE15 and RE02) have remained very high, largely due to the continuous oxidized nitrogen supply from UOSA and, as noted previously, the limitation of phosphorus entering the Reservoir from both point and nonpoint sources. At RE30, the median TIN:TSP ratio was well over 100:1, and the minimum was over 50:1. In the mid- to lower reservoir (RE15 and RE02), the median values declined to between 50:1 and 60:1, respectively, and the 25th percentile value at RE02 dropped to 30:1. In the Occoquan Creek arm of the Reservoir (RE35), however, the median value over the same period was 14:1, and the 25th percentile was 10:1, indicating some period of nitrogen limitation in the arm of the Reservoir receiving no WRF flow.

The data from the last 10 years also show continued dominance of diatoms and green algae over blue-green species. In fact, only a few non-nitrogen-fixing blue-green algae

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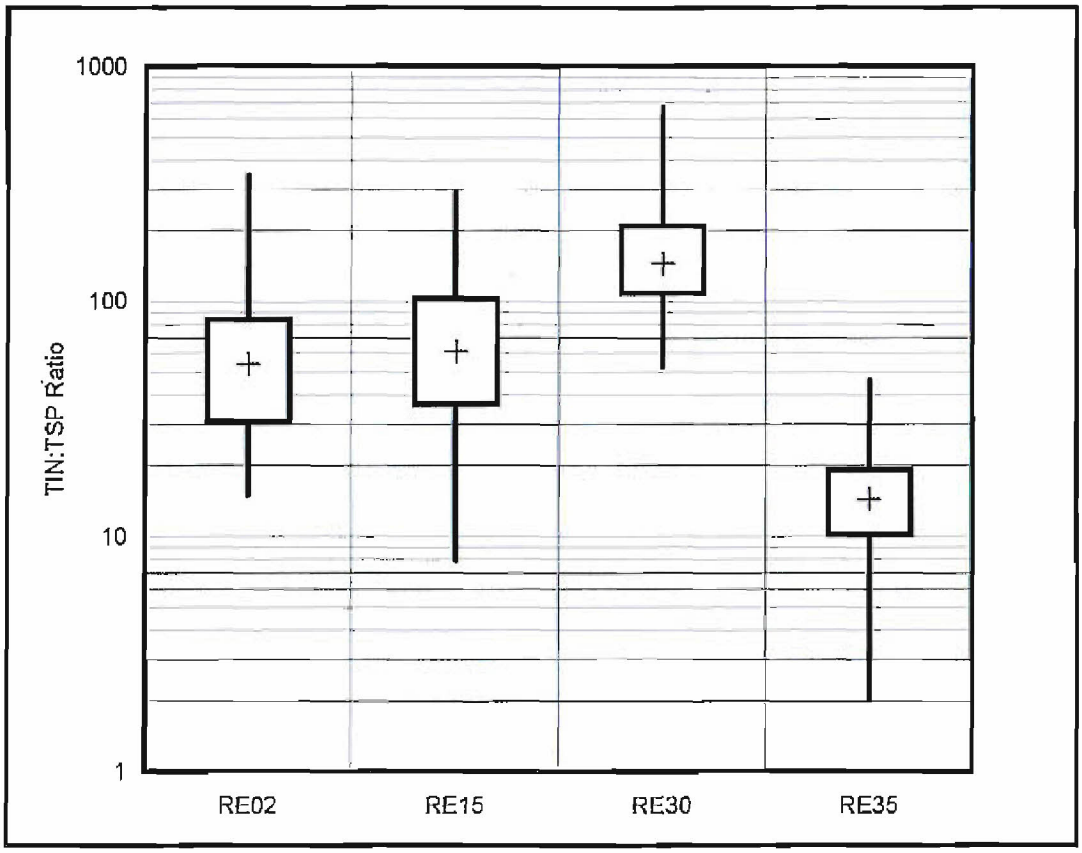

Figure 4-6. Box and Whisker diagrams illustrating TIN:TSP variation at Occoquan Reservoir monitoring stations, 1994 - 2004.

(*Oscillatoria, Microcystis*) have been observed in low cell numbers during summer and early fall.

The N-fixing heterocystous blue-green algae (*Anabaena, Aphanizomenon*) which was often present in the Occoquan Reservoir before 1978 occur only rarely and then in only very small numbers in recent years. This is consistent with the observations of (Sprent, 1987) that N-fixation only occurs only when concentrations of combined nitrogen are low.

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IMPACT ASSESSMENT OF FUTURE NITROGEN REMOVAL

A key question for future management of the Occoquan Reservoir and setting treatment requirements for the UOSA WRF is how to determine the risk of provoking undesirable algal species shifts if the NO_3^- supply is reduced in the system. Other variables beyond N and P supply should be addressed in such an analysis, including issues that (1) affect community structure, (2) affect organisms metabolizing nitrate, and (3) impact N:P ratios in the Occoquan Reservoir.

Other Variables

Nuisance blue-green algae often favor higher temperatures (30°C), higher pH (>7.5), and higher alkalinities (>100 mg/L as $CaCO_3$) than occur normally in the Occoquan Reservoir. Blue-green algae are more often physiologically capable than other algae at adjusting their photosynthetic pigments to bring about more efficient light absorption (*i.e.*, chromatic adaptation). This capability enables them to compete more effectively for photosynthetically available light to, for example, survive at greater depths where nutrients may be more abundant. Such chromatic adaptation to low light may be important in a reservoir of relatively low transparency as may be judged by historical Secchi disk readings in the Occoquan Reservoir (OWML, 1998).

Whereas essentially all algae are capable of luxury uptake and storage of N and P when the nutrients are abundant in the environment, the blue-green algae again have an advantage in that they are especially capable of doing so. Many blue-green algae can take up surpluses of combined nitrogen and phosphate, and store them in cyanophycin granules as polypeptides of aspartic acid and arginine and polyphosphate bodies (Lee, 1999). Both stored nutrients may then be made available to support additional cell divisions when these essential elements become limiting in the extracellular environment.

Of all the major groups of phytoplankton routinely identified in the Occoquan Reservoir, the blue-green algae are the least important in food chains; thus, a blue-green algal population would be more resistant to feeding reduction by consumer organisms.

Blue-green algae can also produce natural chelating substances or siderophores which help scavenge essential trace elements (Fe, Mn, Cu) that may be deficient in their local aquatic environment.

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All the above variables come into play in the total matrix of factors that determine the resulting phytoplankton community. Given the conditions routinely experienced in the Occoquan Reservoir, however, it is likely that the low-light efficiency and the aversion of consumers to utilizing blue-greens as a food source, would be of most concern for future management.

Organisms Metabolizing Nitrate

Nitrate is the most abundant form of combined N in most aquatic systems and can be utilized by many plants, algae, and other microorganisms (but not animals) (Sprent, 1987). Given the establishment of anoxic conditions, at least 73 bacterial genera and some plants can perform dissimilatory NO_3^- reduction to NO_2^-. About 25 bacterial denitrifying genera can perform NO_2^- reduction, and some photosynthetic green algae are capable of dissimilatory NO_2^- reduction (Sprent, 1987). It is also likely that other phytoplankton groups may have this capability. Any organism can have more than one NO_3^- reductase (*e.g.*, induced and constitutive enzymes), all requiring molybdenum (Sprent, 1987). Essentially all algae, plants, and many bacteria can perform assimilatory denitrification starting with NO_3^-.

Impact of N:P Ratio

It has been noted that N:P ratios have generally increased in the mainstem of the Reservoir over the years since the UOSA WRF was put into service. Considering the N:P balance ratio of 16:1 to 17:1, the ratios for Occoquan Reservoir clearly make P limiting and, as a result, insure that combined N is not limiting, and is, in fact, present in excess. No doubt, this high N:P ratio, especially with much of the available N present as NO_3^-, explains the dominance of diatoms, green algae, and other eukaryote algae (*e.g., Cryptomonas*) over the prokaryotic blue-green algae. This assertion is supported by the algal count data, which show that a shift from significant blue-green algae presence and fewer diatoms to fewer blue-green algae and many more diatoms closely coincided with the WRF start-up in 1978 and its continuous operation as a nitrifying facility in subsequent years.

It seems reasonable to conclude that, if other variables remain unchanged, as long as a high N:P ratio is maintained, the nuisance blue-green algal populations will not return to dominate the phytoplankton of the Reservoir. However, if the N:P ratio were to be reduced towards the balance ratio, and persist for as little as one growing season, then the seed blue-green algae in the Occoquan Watershed could regain dominance in the Reservoir, along with the water quality problems historically experienced.

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From a microbiological point of view, One of the other problems resulting from the removal of NO_3^- would be a much reduced occurrence of both dissimilatory and assimilatory denitrification. In the instance of the former, more prolonged and severe conditions of bottom water and sediment ORP depression could be expected to occur, as has been proposed earlier in this report. The accompanying reduction of ferric iron could be expected to cause increased releases of sediment-bound phosphorus, which could, in turn, increase water column concentrations sufficiently to move the system to a higher eutrophic state. Increased water column phosphorus would also be expected to decrease the N:P ratio, thereby increasing the risk of algal blooms including more blue-green species. While non-N-fixing blue-green algae (*Microcystis, Oscillatoria*) might well occur as nuisance algae, almost certainly with lower N:P ratios and combined N limitation, the N-fixing heterocystous blue-green algae (*Anabaena, Aphanizomenon*) would return to dominance, as occurred before 1978.

With a reduced NO_3^- supply, assimilatory denitrification would also be expected to be curtailed, which would also be likely to move the system away from the desirable diatom dominance now experienced.

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SUMMARY AND RECOMMENDATIONS

SUMMARY

UOSA Water Reclamation Facility

Since 1978, the UOSA WRF has discharged reclaimed water of very high quality to Bull Run and the Occoquan Reservoir. The facility routinely produces reclaimed water that greatly exceeds treatment requirements that are already the most stringent in the Commonwealth, if not the nation.

From the time of UOSA start-up, wastewater has ceased to be a significant source of phosphorus loads to the Occoquan Reservoir. This is an impressive achievement, particularly given the fact that wastewater flow rates of less than 3 MGD were identified by Metcalf and Eddy (1970) as the greatest contributors of phosphorus to the Occoquan Reservoir in 1969. Today, even though UOSA reclaimed water flows are over 10 times higher, the phosphorus loads to the Reservoir are approximately one-tenth of those experienced in 1969. Degradable organic matter removal at UOSA has been equally impressive. In fact, the traditional measure of wastewater organic strength, biochemical oxygen demand, is no longer included in the UOSA permit for the simple reason that the values are too low to analytically quantify.

Because the UOSA WRF has been operated to convert ammonium to nitrate throughout its service history, the plant has provided a continuous load of nitrate to Bull Run for over 25 years. During that time, there has been a clear recognition of the beneficial effects of the nitrate discharge on water quality in the Occoquan Reservoir. As a result, the VSWCB adopted a revision to the *Occoquan Policy* in 1980 to require nitrogen removal at the UOSA WRF only when concentrations of nitrate reach 50% of the drinking water Maximum Contaminant Level (MCL) at the Fairfax Water (FW) raw water intake. UOSA, FW, and OWML have a monitoring and reporting agreement so that adequate lead time is available when nitrogen removal is required.

Since 1978, flows from the UOSA WRF have served as a significant supplement to the safe drinking water supply yield of the Occoquan Reservoir. At the current design flow of 54 MGD, reclaimed water has increased the natural safe yield of the Reservoir by over 50 percent. Fairfax Water (FW) is currently constructing the Fred W. Griffiths Water Treatment Plant, a state-of-the-art 120 MGD facility, which has been designed to take advantage of the increased yield of the system.

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Occoquan Reservoir Water Quality

For nearly 27 years, the UOSA WRF has achieved high performance removal of phosphorus, degradable organics, trace organics, and microbial pathogens from the reclaimed water discharged to the Occoquan Watershed. During that time, the poor water quality conditions that threatened the water supply in the 1960s and 1970s have been largely eliminated, and in fact, Reservoir water quality has been quite stable in spite of the growth of watershed population to over 350,000. The improvements in water quality may be attributed to the combined effects of the high quality reclaimed water discharge and well-developed local government programs to manage nonpoint source pollution.

Thermal Stratification Effects on Water Quality. During the summer months, solar heating begins a process that results in the creation of a layer of warm (and less dense) water on the surface of the Occoquan Reservoir. Because of the density difference from the cooler waters below, this layer acts as a barrier to mixing throughout the summer and, typically, into the early fall. The warm surface layer (also called the epilimnion) also acts as a barrier to the diffusion of oxygen from the atmosphere into the lower depths of the Reservoir. For that reason, biological activity in the deeper waters (the hypolimnion) rapidly deplete the available dissolved oxygen, which cannot be replenished until the density stratification disappears in the fall when the surface waters begin to cool. This is a wholly natural process, and occurs in a similar way in many deep reservoirs throughout the southeastern United States. The consequences for water quality, however, can be significant.

Even though oxygen cannot be replenished during thermal stratification, bacteria in the deep waters and at the sediment interface continue to degrade organic matter, of which there is a nearly 50-year accumulation in the Reservoir. When the supply of oxygen is depleted, and no other inorganic electron acceptors are present, oxidized iron in the deposited sediments becomes chemically reduced, and releases of phosphorus and ammonium, as well as manganese and sulfide to the water column soon follow. Iron and manganese of particular importance to the water supply industry, and can have significant economic consequences to treatment facility operations. Of particular water quality significance, however, is the release of sediment-stored phosphorus and ammonium under anaerobic conditions. This phenomenon has been observed in the Reservoir and in controlled laboratory scale microcosm systems (To, 1974; McLaughlin, 1981; Sherman, 1983). When the bottom waters reach the true anaerobic conditions that facilitate iron reduction, it has not been uncommon for total phosphorus (TP) and total Kjeldahl nitrogen (TKN) concentrations to reach 0.1 mg/L and 3.0 mg/L,

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respectively. From the standpoint of nitrogen delivery to the tidal Potomac, and ultimately to the Chesapeake Bay, the nitrogen concentration is of some particular significance.

Fate of Nitrate and Effects on Water Quality. During the summer months, the temperatures of tributary inflows are lower than the surface water temperatures of the Reservoir. As a result, streams tend to mix downward until they find water of equal density at a greater depth in the Reservoir. In the case of Bull Run, the stream also carries the highly nitrified WRF discharge from UOSA. As the nitrate is carried into the oxygen deficient bottom waters of the Reservoir, it serves as the next-preferred alternate electron acceptor (to dissolved oxygen) in bacterial respiration.

Simply put, as long as nitrate is available to support bacterial respiration in the absence of oxygen, a less-oxidizing, or anaerobic, condition is not experienced in the hypolimnion. The maintenance of more oxidizing conditions at the sediment interface than would have otherwise been possible has been a key effect of the nitrate supply from the UOSA WRF over the last 27 years.

In addition to providing a mechanism to maintain oxidizing conditions in the Reservoir, the nitrate itself is removed in the process. The same biochemical process that allows the bacteria to use nitrate as an electron acceptor in respiration results in the reduction of the nitrate (NO_3^-) to nitrogen gas (N_2). In this way, any nitrate used in delaying the onset of anaerobic conditions in the Reservoir is also permanently removed from the inorganic nutrient pool available to algae and other organisms. Because the end-product, nitrogen gas, is approximately 80% of the atmosphere, any excess above the normal solubility simply diffuses out of the water column.

That the Occoquan system has become, in a sense, optimized for nitrate removal is reinforced by the results of Banchuen (2002), who reported denitrification rates approximately two times higher than those commonly assumed for mainstream lake and reservoir water quality models.

Nitrate addition to oxygen-depleted waters to produce an oxidized environment over deposited sediments is a well known lake restoration and/or management technique, and the earliest results were reported in the literature (Lawrence, 1959; Ripl, 1976; Andersen, 1982) over 45 years ago. Lawrence (1959) found that addition of nitrates could be effective in poising the oxidation-reduction potential (ORP) of an aquatic system above the point at which sulfate could be reduced to sulfide. Ripl (1976)

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showed that nitrate addition to the sediments of a Swedish lake resulted in the oxidation of the upper layer of sediment, and in a decrease in the soluble phosphorus concentration in the overlying water due to a retardation of sediment release. Andersen (1982), in an investigation of eutrophic Danish lakes, found that no sediment phosphorus release occurred if the oxidized nitrogen concentration in the hypolimnetic waters was at least 1.0 mg/L.

As noted previously, the phenomenon takes place because nitrate, in the absence of molecular oxygen, acts as an alternate terminal electron acceptor for certain bacteria. In that role, it delays the onset of truly anaerobic conditions, and poises the system at an oxidation state sufficiently high to maintain iron in the oxidized (ferric) form and thereby insure the integrity of the *oxidized microzone* (Mortimer, 1941) at the sediment-water interface. As long as iron is not reduced, releases of soluble phosphorus, ammonium, and manganese from the sediments are retarded. In addition, as noted above, the maintenance of iron and manganese in the oxidized state has the beneficial effect of reducing the impacts of some commonly-occurring water treatment problems in the summer months. Previous microcosm studies (Grizzard, *et al.*, 1985) have demonstrated the link between the loss of bottom water nitrate and the release of iron and manganese at concentrations in excess of the Safe Drinking Water Act Secondary Maximum Contaminant Levels (SMCLs).

Finally, the biochemistry of the denitrification process produces alkalinity as a by-product. Because the streams of the Occoquan Watershed are normally of relatively low alkalinity, this has been an additional benefit of *in-situ* denitrification in the Reservoir. Improved raw water buffering capacity generally results in more predictable treatment with hydrolyzing metal salts because of the greater resistance to pH reduction below the optimum coagulation range.

Nitrate Effects on Algal Populations. An analysis of the available algae and nutrient data, as well as the current literature, clearly supports the conclusion that the current dominance of green algae and diatoms (and the concurrent decline of blue-green algae) in the Occoquan Reservoir has resulted from the presence of nitrate as the principal nitrogen form, and the maintenance of high N:P ratios in the impoundment.

Maintenance of high N:P ratios, largely due to the nitrate discharge from the UOSA WRF, has insured phosphorus-limited growth conditions. Such conditions, with N:P ratios in excess of 20:1, favor green algae, which tend to utilize the available phosphorus early in the growing season. Lowering of the N:P ratio by removing too

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much nitrogen from the Reservoir could result in a return to the dominance of blue-green species as was experienced prior to 1978. There is also some risk that low N:P ratios could serve as a trigger mechanism for the dominance of blue-green algal species that can fix atmospheric nitrogen to satisfy their nutritional requirements. Should this occur, not only would more problematic algal species regain dominance, but they would also enhance the import of nitrogen into the system.

The preference of some species of green algae and diatoms for nitrate as their nitrogen source also reinforces the dominance of these species over the blue-green algae. If nitrogen removals are proposed that will result in the decrease of N:P ratios to values that were experienced historically, there is a risk that this will also impact the ability of the more desirable algal species to maintain dominance in the Reservoir.

Initial Modeling Results. Over the past few years, OWML has been involved in the updating and calibration of a new version of the Occoquan Watershed Modeling System. The new system is based on a similar suite of software to that used in the EPA Chesapeake Bay model. The Occoquan Model consists of an implementation of the EPA-supported watershed model HSPF, and the US Army Corps of Engineers hydrodynamic reservoir water quality model CE-QUAL-W2. The two models are operated in a linked system, which has been fully calibrated for the 1988-1992 period. A model update is currently underway that will bring the calibrated period up to the present time.

Although model calibration has not yet been completed for current UOSA flows, it was possible to execute some scenarios that were useful for examining potential effects of reduction of nitrate loads to the Occoquan Reservoir. By scaling the concentrations of nitrate in the UOSA discharge to also account for increases in flow since the 1988-1992 calibration period, it was possible to examine three scenarios at current UOSA WRF flows:

1. UOSA at 20 mg/L NO_3^--N
2. UOSA at 8 mg/L NO_3^--N
3. UOSA at 3 mg/L NO_3^--N

Over the four year calibration period, the model clearly predicted periodic conditions of nitrate deficiency in the Reservoir even under the current operating condition of a fully-nitrified discharge. Given that result, it is no surprise that the simulations with the UOSA WRF operating to remove nitrogen to 8 and 3 mg/L, respectively, showed more frequent, and longer-lasting periods of nitrate depletion.

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RECOMMENDATIONS

This report has examined a variety of existing data, including:

- OWML Stream and Reservoir water quality data from 1973 - 2004;
- Operations data from the UOSA WRF from 1978 - 2004;
- Microcosm studies conducted by:
    - To (1974)
    - McLaughlin (1981)
    - Sherman (1983)
    - Banchuen (2002);
- Algal species and count data from Fairfax Water from 1976 - 2002

The available data and the analysis presented in this report contribute to a compelling picture of the importance of the nitrified discharge from the UOSA WRF in the maintenance of existing water quality conditions in the Occoquan Reservoir.

The data also suggest that there are risks associated with the removal of nitrogen from the UOSA WRF discharge without fully understanding the local water quality impacts. To that end, OWML staff have developed several observations and recommendations:

- Given the long history of improved Occoquan Reservoir water quality related to the nitrate supply from the UOSA WRF, it would be prudent to defer changes in nitrogen permit limits until the scale of consequences to local water quality and the regional water supply are fully understood;

- A broad review of existing OWML databases should be conducted to extract additional information on the rates of nitrate loss from the Reservoir under varying conditions of seasons, UOSA flow, hydrologic conditions, and impoundment pool elevations;

- Additional water quality data collection should be conducted to provide more detailed knowledge of the vertical and longitudinal movement and reaction of key water quality constituents in the Occoquan Reservoir during all seasons of the year, including: ammonium, organic nitrogen, nitrate, phosphorus, iron, manganese, sulfate, and alkalinity;

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- Continuous flow microcosm studies should also be conducted in order to better understand the chemical and biochemical interactions of the aforementioned key water quality constituents across the sediment-water interface under varying conditions of oxygen and nitrate supply.

- Laboratory scale studies of algal growth potential should be conducted to examine the impacts on species dominance of altering the forms of nitrogen present and lowering the N:P ratios experienced in the Occoquan Reservoir;

- The Occoquan Model System should be updated to include denitrification and sediment release algorithms to improve prediction of the movement of dissolved species across the sediment-water interface as a function of oxidation-reduction potential.

The above list of recommendations should not, at this point, be considered comprehensive, but simply a starting point for designing a series of integrated studies to be conducted in order to provide required management information. It is also clear that the study needs are of a scale that several years will be required to design and execute the work. In order to establish a well-organized approach to the scope and schedule for required work, a technical committee with representation from, at least, the following governments, organizations, and agencies should be convened as soon as possible with a charge to identify information needs for decisionmaking, detailed scope of the required studies, and development of funding sources to support the effort:

- Counties of Fairfax and Prince William
- Cities of Manassas and Manassas Park
- Upper Occoquan Sewage Authority
- Fairfax Water
- Occoquan Watershed Monitoring Subcommittee
- Occoquan Watershed Monitoring Laboratory
- Virginia Department of Environmental Quality
- Virginia Department of Health
- Virginia Department of Conservation and Recreation

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EXHIBIT 2

Recent Water Quality Effects Due to TN Loads Reduction - September 14, 2009 Letter from Dr. Thomas J. Grizzard, OWML's Director

Exhibit 2

VirginiaTech
College of Engineering

Occoquan Watershed Monitoring Laboratory
The Via Department of Civil & Environmental Engineering
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14 September, 2009

Mr. Charles P. Boepple, P.E.
Executive Director
Upper Occoquan Service Authority
14631 Compton Road
Centreville, VA 20121-2506

Dear Mr. Boepple:

At your request, I am writing to provide an assessment of the water quality impacts in the Occoquan Reservoir resulting from changes in nitrogen management strategies at the Upper Occoquan Service Authority (UOSA) in the period from 2007-2008.

I understand that the near-term need for this analysis was precipitated by a 12 August, 2009 letter from the Virginia Department of Environmental Quality (VDEQ) requesting that you provide information on the impact of the reduced UOSA nitrogen loads on water quality in the Occoquan Reservoir during that period.

2005 Assessment and Recommendations

As you know, within the constraints of our funding, we have been actively studying this issue for some time. The most recent detailed analysis was contained in a document that I authored and conveyed to the Occoquan Watershed Monitoring Subcommittee (OWMS), UOSA, and VDEQ in the spring of 2005. *An Assessment of the Water Quality Impacts of Nitrate in Reclaimed Water Delivered to the Occoquan Reservoir* contained a detailed review of the historical *in situ* data on nitrate sources, transformations, and removals in the Occoquan Reservoir, as well as summaries of laboratory microcosm experiments that have been conducted at the Occoquan Watershed Monitoring Laboratory (OWML) over many years. The report contained a range of observations and recommendations, among which were the following statements:

> "The available data and the analysis presented in this report contribute to a compelling picture of the importance of the nitrified discharge from the UOSA WRF in the maintenance of existing water quality conditions in the Occoquan Reservoir.
>
> The data also suggest that there are risks associated with the removal of nitrogen from the UOSA WRF discharge without fully understanding the local water quality impacts."

2005 Occoquan Watershed Monitoring Subcommittee Recommendations
The report and all its recommendations were unanimously adopted by the OWMS at its meeting of 09 June, 2005. Further, the OWMS directed the Chairman, Dr. Clifford W. Randall, to communicate the endorsement and a summary of the technical rationale on which it was based to the chairman of the VSWCB. That letter, dated 15 June, 2005, contained the following recommendation:

> "...it is the conclusion of the OWMS that implementation of the proposed [technology-based] nitrogen reductions for UOSA would be detrimental to water quality in the Occoquan Reservoir, and would needlessly threaten the public health of the more than 1.2 million FW [Fairfax Water] customers who rely on the Reservoir for drinking water. Therefore, the OWMS, by unanimous vote, recommends that the new nitrogen reduction requirements not be imposed on the UOSA WRF at this time, and that the current nitrogen management strategy of the *Occoquan Policy* remain in force pending the completion of needed research by OWML."

I should point out that the recommendations of the OWMS were based on an implicit understanding that ***no*** reductions in nitrate in the UOSA discharge would be undertaken unless necessitated by the requirement to maintain a raw water intake concentration of 5 mg/L as N.

2007 Nitrogen Cap
In spite of the OWML assessment and the OWMS recommendation, VDEQ nevertheless imposed an annual total N load cap of approximately 1.3 million pounds in 2007. I must say that this decision has always concerned me. I do not make this statement lightly, and it is in no way meant to minimize the importance of the continuing effort to reduce nitrogen loads to the Chesapeake Bay. In two terms of service as an at-large member of the Scientific and Technical Advisory Committee (STAC) to the Bay Program, I have developed a clear understanding and appreciation of the nitrogen management challenges faced by the states and the District of Columbia. However, as I have stated to you many times, regulatory approaches that rely on an end-of-pipe accounting of nitrogen loads may ignore significant transformations in the environment, and may, therefore, be vulnerable to unintended and undesirable consequences. The case of the Occoquan Watershed is, in my judgment, an object lesson on this point.

Recent Reservoir Conditions
In the last 2+ years, UOSA has been gaining operational experience with its nitrogen removal capabilities, and has dramatically decreased the nitrate load delivered to the Occoquan Reservoir. During that period, we have had an opportunity to observe the water quality effects of the load reduction. The 2005 Assessment made the point that undesirable water quality conditions occur in the deep Reservoir waters during periods of nitrate deficiency. At this point, we are developing an internal consensus that nitrate deficiency results when the concentration declines below 2 – 3 mg/L as N. We have

studies underway to refine this value, but for the purposes of this discussion, the stated range should serve to illustrate the point.

The attached figure is a time series of rainfall, ammonium, oxidized nitrogen, and total phosphorus in the deep waters of the Occoquan Reservoir upstream of the Occoquan Dam. This sampling station (RE02) is generally visited by OWML staff on a weekly basis, except during the winter months, when the sampling frequency is reduced to bi-weekly. Also shown on the plot are the annual total nitrogen loads from UOSA from 2004 – 2008.

An examination of the plotted time series data from the same period clearly illustrates the water quality consequences stemming from nitrate deficiency during the mid- to late-summer periods for both years. Periods when nitrate discharges from UOSA were inadequate to maintain a protective concentration in the deep waters were consistently accompanied by dramatic increases in the release of ammonium nitrogen and phosphorus from the sediments.

The summer of 2007 is perhaps the most representative period in that there were no very large rain events that resulted in flushing of the Reservoir and lowering of the nitrate concentrations by dilution. During that year, the highest deep water concentration of nitrate observed was approximately 3.5 mg/L as N, and occurred early in the year. By early March, the concentration had declined below 1 mg/L, and the concentration was effectively zero for most of the summer. The peak ammonium concentration reached after the depletion of nitrate was, by contrast, nearly 5 mg/L as N. In the same period, a peak total phosphorus concentration of over 1 mg/L was observed (much of it soluble). The concentrations of both these nutrients remained high in the deep water until the fall circulation, which did not occur until early November.

These conditions are well-known consequences of the establishment of anaerobic conditions in deep eutrophic reservoirs during the period of stratification. What is of note in this system, however, is that the releases may be seen to be tempered in large part by the presence of nitrate. In its role as an alternate terminal electron acceptor (TEA) in anoxic respiration, nitrate has the effect of poising the oxidation-reduction potential at a level that significantly reduces the release of phosphorus and ammonium from the sediments. Of course, in its role as an alternate TEA, nitrate is largely converted (reduced) to nitrogen gas and removed from the system. This too has been observed in the Occoquan Reservoir for many years.

It should be noted that the increased N and P releases from the sediments may also be observed during periods when the nitrate concentrations were artificially decreased by large storm events entering the system. In fact, a peak ammonium concentration of over 5.5 mg/L as N was observed in September, 2006 following such an event prior to the fall circulation.

Summary and Continuing Work

I think there is an essentially unambiguous interpretation of the water quality data presented for 2007 – 2008: the decreased UOSA nitrate supply had clear and undesirable consequences for local Reservoir water quality. The increased release of stored nitrogen from the Reservoir sediments very likely had additional consequences for loads delivered downstream. We have not yet completed our analysis of the overall nitrogen mass balance for the period, but reference to the attachment shows that peak concentrations of ammonium nitrogen (released from the sediments) exceeded peak nitrate concentrations (largely originating from UOSA) by 42 percent.

As you know, we are continuing to conduct intensive studies of the behavior of nitrate in the reservoir system. During the summer of 2009, with your cooperation, we have been able to study the system response during an extended period of operation of the UOSA WRF in full nitrification mode. The data collection during this period has been substantially enhanced by the purchase of an instrument (funded by UOSA) to measure continuous nitrate concentrations *in situ*. This has made is possible for us to develop detailed longitudinal and vertical profiles of nitrate in the Reservoir for most of 2009. The study is not yet complete, and our detailed analysis has only just begun. However, it is clear that our understanding of denitrification in the Reservoir has been enhanced by the *in situ* measurements. We have, for example, seen that nitrate carried in the flows of Bull Run is preferentially mixed into the deep waters of the Reservoir even during periods of very weak thermal stratification. This is encouraging news from the standpoint of nitrogen removal in the overall system, because the nitrate is consistently directed into the reservoir zones where denitrification is favored.

There are significant questions still to be answered. Some obvious ones are:

- What is the minimum *in situ* nitrate concentration required to maintain optimal water quality conditions in the reservoir deep waters?
- How much additional nitrogen and phosphorus may be exported to the Potomac Estuary as a consequence of Reservoir nitrate deficiency?
- What is the denitrification capacity of the Reservoir under varying flow conditions from UOSA and the Occoquan Watershed, and what is the longitudinal variability of Reservoir denitrification rates?
- How should the timing of nitrate loads be managed to insure an adequate supply is available at the early onset of thermal stratification?
- What are the risks of returning to *cyanobacter*-dominated algal populations if the N:P ratios are reduced from current values?

These are only a few of the important questions to be addressed, and there is much work still to be done. For example, there is a critical need for the development of a robust simulation capacity to help UOSA and FW develop best practices for start-up and shut-down of nitrogen removal. The basic model framework is in place, but extending the system to provide this predictive capability requires substantial enhancements.

I am also grateful for the continuing funding from UOSA that has supported our laboratory microcosm studies, which are making it possible to develop refined estimates of the longitudinal variability of denitrification rates in the Reservoir. These studies are also proving useful in quantifying the effects of nitrate in reducing the release of iron and manganese from the deposited sediments, which is an area of critical interest for the drinking water supply. Our capacity to simulate the entire length of the Reservoir as a cascade of completely mixed reactors is now well-established, and I hope that this capability will continue to reveal new insights into the behavior of the full-scale system.

In summary, I would say that I would strongly caution against the application of new nitrogen load reductions to the UOSA WRF, particularly at this point in time. The risks of undesirable outcomes with respect to local water quality are simply too great. A more rational approach would be to build on the base of the water quality studies and modeling work currently underway. Such a program, developed jointly by UOSA, FW, OWML, and DEQ, and adequately funded, should make it possible to answer the necessary questions in an objective manner. It should then be possible to engage in rational regulatory decision-making based on the scientific evidence.

I hope that these comments have provided some additional insights into the issues. If you would like to discuss the data further, please let me know at your convenience. Also, if you would like to arrange a meeting with DEQ representatives, I would be happy to participate.

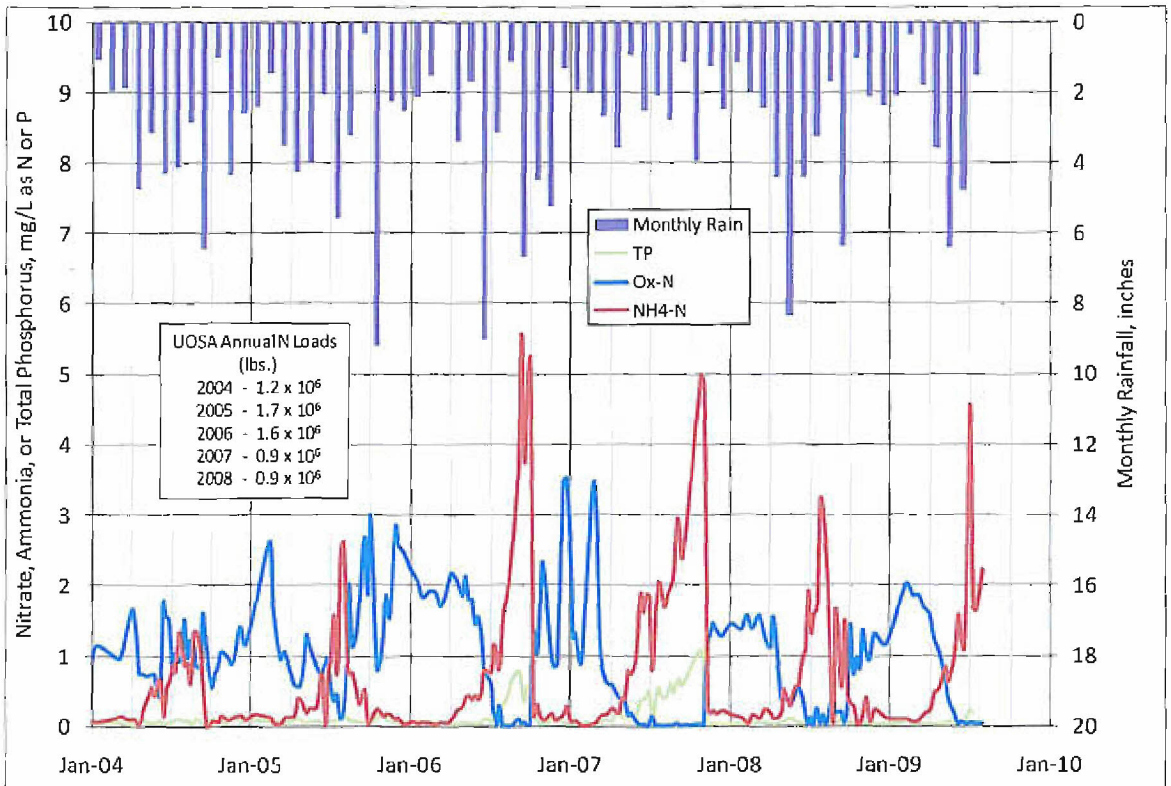
Sincerely,

Thomas J. Grizzard, P.E, Ph.D
Professor and Laboratory Director

TJG:mw

Attachment

cc: C.W. Randall



Time series of nitrogen and phosphorus species in deep water at Occoquan Dam (RE02)

EXHIBIT 3

Mr. Charles M. Murray, Fairfax Water's General Manager Letter dated October 20, 2010

Exhibit 3

FAIRFAX COUNTY WATER AUTHORITY
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Fairfax, Virginia 22031-2218
www.fairfaxwater.org

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TELEPHONE (703) 289-6012

FAX (703) 698-1759

October 20, 2010

Mr. Charles P. Boepple
Executive Director
Upper Occoquan Service Authority
14631 Compton Road
Centreville, VA 20121

Re: Occoquan Reservoir - Nitrate

Dear Mr. Boepple:

This is in response to your letter dated October 12, 2010, regarding the U.S. Environmental Protection Agency (EPA)'s draft Total Maximum Daily Load (TMDL) proposed nutrient regulations and their potential water-quality impacts on the Occoquan Reservoir.

Fairfax Water strongly supports further study of the relationship between nitrate and water quality in the Occoquan Reservoir. Since expressing our initial concerns about the potential threat to water quality, as discussed in our letter of July 29, 2005 (a copy of which is attached), we have had several years to experience the impact of reduced nitrate loading on the water quality of the Occoquan Reservoir. The data collected by the Occoquan Watershed Monitoring Laboratory (OWML), as referenced in your letter, clearly demonstrate the strong relationship between reduced nitrate levels and increased ammonia and phosphorus in the lower levels of the reservoir near Fairfax Water's intake. Such conditions expose Fairfax Water to increasing water-quality challenges. These conditions could be significantly exacerbated by the changes to UOSA's nutrient allocation proposed in the Draft Chesapeake Bay TMDL.

Fairfax Water continues to be concerned about any threat to the Occoquan Reservoir as an effective drinking-water supply and would like to maintain the best water quality possible in the reservoir. As such, we respectfully endorse further study of the relationship between nitrate and water quality in the Occoquan Reservoir to answer the questions raised by the OWML (and summarized in its September 14, 2009 letter), specifically,

determining what in-situ nitrate concentrations are needed to maintain optimal water-quality conditions in the reservoir's deep waters. We continue to support the Occoquan Watershed Monitoring Subcommittee's recommendation that changes in UOSA's nitrogen limits be deferred until additional study can be completed.

I appreciate your continuing efforts to evaluate this issue and the impact on the water quality of the Occoquan Reservoir. Please contact me at 703-289-6011 if you have questions.

Sincerely,

Charles M. Murray
General Manager

Encl: 2005 Fairfax Water Letter to UOSA

cc: Mr. Philip W. Allin, Chairman, Fairfax Water
Dr. Thomas Grizzard, Director, Occoquan Watershed Monitoring Laboratory

Fairfax Water

FAIRFAX COUNTY WATER AUTHORITY
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FAX: (703) 698-1758

July 29, 2005

Frederick G. Tate
Chairman, Board of Directors
Upper Occoquan Sewage Authority
14631 Compton Road
Centreville, VA 20121

Re: Occoquan Reservoir - Nitrate

Dear Mr. Tate:

This is in response to your letter dated July 25, 2005, regarding the Virginia Department of Environmental Quality's proposed nutrient regulations and their potential water quality impacts on the Occoquan Reservoir.

The Occoquan Reservoir, which supplies approximately 40 percent of our raw water, is a valuable resource to Northern Virginia and the surrounding community. Combined, our Potomac River and Occoquan Reservoir supplies provide water for over 1.3 million people. Water quality in the Occoquan Reservoir has been stable despite significant growth in the watershed, mainly due to the high level of wastewater treatment provided by UOSA's Millard H. Robbins, Jr. Regional Water Reclamation Plant. As you are well aware, prior to the Occoquan Policy becoming effective and the establishment of UOSA, the Occoquan Reservoir suffered from major algae blooms, low dissolved oxygen levels, and other water quality problems.

I understand the Policy for Nutrient Enriched Waters (9 VAC 25-40) and the Water Quality Management Planning Regulation (9 VAC 25-720), proposed by the Virginia Department of Environmental Quality, would require UOSA to significantly reduce the level of nitrate (oxidized nitrogen) in the discharge from the water reclamation plant.

The report, "An Assessment of the Water Quality Effects of Nitrate in Reclaimed Water Delivered to the Occoquan Reservoir," by the Occoquan Watershed Monitoring Laboratory, provides an assessment of the relationship between nitrate and water quality in the reservoir based on available data. The report presents information supporting the concept that nitrate in the UOSA discharge protects water quality when the reservoir

is stratified and the bottom waters are oxygen-depleted, by keeping metals and phosphorus bound to the bottom sediments. The report recommends deferring changes in UOSA's nitrogen limits until additional study can be completed. This study outlines future work and recommends a broad review of existing data, additional data collection, microcosm studies, laboratory scale studies, and modeling.

Fairfax Water is concerned about any threat to the Occoquan Reservoir as an effective drinking water supply and would like to maintain the best water quality possible in the reservoir. As such, Fairfax Water endorses further study of the relationship between nitrate and water quality in the Occoquan Reservoir, as outlined in the above-mentioned report.

I appreciate your continuing to update our staff on this issue, and look forward to maintaining an ongoing working relationship between UOSA and Fairfax Water.

Sincerely,

Harry F. Day

Harry F. Day
Chairman

cc: John Kennedy, Virginia Department of Environmental Quality