# THE IMPACT OF ENVIRONMENTAL CHANGE ON THE TUALATIN RIVER CLEANUP – A CASE STUDY OF POLICY RESPONSES TO CLIMATE CHANGE

BY

JENNIFER MARIE NELSON

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Natural Resources and Environmental Sciences
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2011

Urbana, Illinois

Master's Committee:

Professor Wesley Jarrell, Chair
Professor Bruce Rhoads
Professor Murugesu Sivapalan
Professor Edwin Herricks

## Abstract

Since 1986, water quality in the Tualatin River basin outside of Portland, Oregon has been managed to prevent unsightly algal blooms, improve conditions for recreation and to improve salmonid habitat.  These efforts were shaped by EPA's 'watershed approach,' developed to improve non-point source water quality management.  The Clean Water Act itself does not provide the same rigorous regulatory structure for non-point source pollution as it does for point source pollution.  In the Tualatin Basin, point source controls for nutrient pollution both before and after the 1986 lawsuit focused on waste water treatment facilities, with substantial but clearly limited improvements in water quality resulting.  A 1986 lawsuit mandated the creation of a Total Maximum Daily Load (TMDL) standard which would allocate the upper limits for nutrients and other non-point source water quality parameters in the basin.  Enforcement involved many state and federal laws and regulations administered by a variety of agencies with the co-operation of several private parties.  One action taken to improve water quality was creation of a Flow Management Committee to govern release of water stored in Barney Reservoir during the summer months.  The practices of this Flow Management Committee directly influence water quality in the basin, particularly through summertime stream-flow augmentation to improve water quality and offset the waste water treatment facility's permit requirements.  These decisions are a sub-set of the overall TMDL policy and a microcosm of the 'watershed approach' that can be reviewed to determine their effectiveness.  While the 'watershed approach' could improve water quality protection in many ways, previous assessments of performance lack a strong framework to assess effects on ecosystem services and human well-being.  This research explores the how an assessment of these factors can improve

watershed management through a case study of twenty years of flow management decisions. The study considers whether use of a comprehensive ecological assessment tool as a soft model in policy analysis can help governments and agencies to identify potential problems and policy options, as well to predict outcomes and potential drawbacks in the face of such environmental change. One such tool that may be adapted for use in urban areas of developed nations may be the United Nation's Millennium Ecosystem Assessment tool (MEA), used in this research to assess both past flow management decisions and potential responses to climate change. This case study is modeled on the approach taken by EPA in its own review of state watershed management approaches in the 2002 Statewide Approaches Report. EPA's review characterized the programs based on existing data and first person interviews, then identified issues of concern and assessed which practices were effective. The SAR approach lacked a strong tool for evaluating impact of the programs on ecosystem services and human well-being, instead relying on assessing partnerships and quantitative water quality parameter improvements. Following the SAR model, this research applies the MEA to a similar case study. The case study, developed from existing data sources, provides a demonstration of how existing data within the public record can be used to forecast potential effects and guide decision making under this type of analysis. Weaknesses of the research methods utilized here are identified, recommendations for policy adaptations and further research are summarized, and a brief discussion of the potential value of comprehensive ecosystem assessments to regional decision making are presented. Ultimately, comprehensive ecological assessment would improve assessment and implementation of the 'watershed approach' in state programs by assessing the impacts of management decisions on both the ecological and the human communities as well as helping to identify areas where further research is needed in terms of establishing baseline conditions, monitoring change and predicting outcomes. Such a tool may also help to identify and address potential feedbacks from management decisions as these changes effect ecological services and human well-being, driving further changes in policy decisions.

Table of Contents:

## Executive Summary

Over the last two decades, water quality management in the Tualatin River basin outside of Portland, Oregon has been shaped by the U.S. Environmental Protection Agency's (EPA) 'watershed approach'. This concept in water quality management emerged in the 1980s as regulatory efforts to control point source pollution began to substantially outpace achievements in managing non-point source pollutants. While this new 'watershed approach' offered a potentially better perspective on water quality issues arising from across a basin, it is generally perceived as lacking a strong framework under which to produce results in terms of water quality improvements.

This research generally explores the question of how watershed science can be better incorporated into policies and decisions at the watershed management level to help deal with uncertainty about impending environmental changes, particularly in climate. More specifically, the research conducts a case study of twenty years of water quality management in the Tualatin River basin, targeted at limiting algal growth by reducing the load of bio-available phosphorus and by managing flow augmentation during summer month. The study considers whether use of a comprehensive ecological assessment tool as a soft model in policy analysis can help governments and agencies to identify potential problems and policy options, as well to predict outcomes and potential drawbacks in the face of such environmental change. One such tool that may be adapted for use in urban areas of developed nations may be the United Nation's Millennium Ecosystem Assessment tool (MEA), which we use here to analyze a sub-set of water quality management decisions (flow management during summer months to control algal growth with an eye to preventing undesirable algal blooms).

The research begins by considering the validity of using of the MEA as a domestic policy analysis tool, potential drawbacks to that use and potential modifications necessary since the tool was originally designed for other contexts. Next, a summary description of the history of water quality management as well as the physical and social setting of the Tualatin River provide proper context and background knowledge for application of the MEA assessment. The MEA framework is then used to describe and analyze flow management decisions from 1986 to 2006, with specific identification of areas available for further research. Looking forward, the research describes the expected impacts of climate change in the Pacific Northwest and attempts to predict possible consequences for ecosystem services and human well-being as well as to suggest areas for policy adaption and continued research. In conclusion, weaknesses of the research methods utilized here are identified, recommendations for policy adaptations and further research are summarized, and a brief discussion of the potential value of comprehensive ecosystem assessments to regional decision making are presented.

The historical context of water quality management on the Tualatin River is critical to understanding the 'watershed approach' as it occurred in that basin. Early Clean Water Act (CWA) enforcement focused on eliminating direct point source pollution to our nation's waterways, largely because these identifiable outfalls posed little difficulty in measuring concentrations of pollutants. Proving a violation of numeric criteria from such a localized source, then, was efficient and presented few legal difficulties in court. Little or no attention was paid to setting total maximum daily loads (TMDL) for watersheds – even after the spate of TMDL litigation in the mid-1980s, enforcement of TMDLs over non-point sources of pollution (NPS) such as urban runoff, storm sewer drainage and agriculture remained virtually non-existent in the face of difficulties proving that specific land users had caused these violations. Cases of non-point source pollution tend to occur due to the drainage of large, complex systems of land with many users, thus making it difficult to prove beyond a reasonable doubt (the criminal law standard of proof applicable in CWA violations) that just one of these many uses resulted in the specific violation.

In response to the realization that little had been accomplished under the CWA on non-point source pollution, EPA was faced with the challenge of retooling CWA implementation to address the more complex issue of NPS. They determined that the key to managing NPS was a broader perspective on water quality than the pursuit of individual violators allowed. Instead, management of land usage within the entire watershed was the only mechanism by which pollution from various land use activities across the source area could be effectively curtailed. This new watershed based perspective was simply called the 'watershed approach'.

Management of NPS and water quality generally in the Tualatin Basin under the Clean Water Act provides an early example of management at the watershed scale. While several surveys of the 'watershed approach' have been conducted, application of an ecosystem assessment tool such as the Millennium Ecosystem Assessment may provide new insights. The so-called 'watershed approach' represents an attempt by federal and state water quality managers to shift the focus of water quality management beyond simple point source regulation to address wider systemic issues stemming from non-point sources of pollutants through more collaborative work with local stakeholders rather than traditional top-down regulation. This watershed approach provides the additional benefits of reduced costs, localized management and greater attention to local priorities. These benefits are achieved by focusing on partnerships, defined management areas, coordinated management activities and strategically timed actions. Efforts to assess this 'watershed approach' have provided some insights into its benefits and drawbacks, but have fallen short of comprehensively assessing the environmental, social and economic impacts of watershed management efforts.

While succeeding in increasing local participant in watershed protection, quantitative assessment of the impacts of these programs is lacking. Current assessment focuses on how the methods employed in watershed management by local and federal agencies measure up to the EPA's prescriptions, rather than detailing the environmental impact or sustainability of those programs. A review of statewide water quality management programs reveals that while improvements have been made in collection of water quality data, in planning and assessment, and in permitting programs, the 'watershed approach' continued to inadequately resolve federal-state jurisdictional tensions as well as to incorporate fully its core principles. These assessments of watershed management programs in the U.S. focus on how well the execution of the 'watershed approach' measures up to expectations, and fall short in evaluation of the long term impacts of water quality management programs on both the ecological and human communities, overlooking important issues such as changes in ecological services, effects on human well-being, and economic consequences. Existing assessments by EPA do not consider the ability of watershed management programs to respond to environmental change over time or the impact such decisions may have on human and environmental well-being in conjunction with those changes.

These shortfalls in assessment of various watershed management programs may be addressed by employing an ecological assessment tool such as the Millennium Ecosystem

Assessment which inventories ecological services, monitors change, evaluates impact on human welfare, tracks feedback between change and future decisions, and identifies potential adaptations to future change. Application of the MEA to management decisions in a more developed nation such as the United States may require some adjustment but is certainly feasible and has been achieved in past studies.

This case study applies the MEA, with necessary adjustments in perspective, to flow management decisions on the Tualatin River. The primary purpose of this research is to assess those management decisions to determine their impacts on environmental and human well-being in terms of changes to ecosystem services, effects on human well-being and response to environmental change. Secondarily, this research will examine the benefit of utilizing an ecological assessment tool as part of a watershed management process. Budgetary and time constraints compel this research to focus on existing data and information, with the hopes that use of the ecosystem assessment tool may help to identify areas for further research, an approach that is consistent with other multi-disciplinary policy analyses within the field.

Although a long standing history of algal growth exists in the Tualatin basin, water quality problems grew beyond tolerable levels by the 1980s, presumably due to increased point source pollution of the river from waste water treatment plants (WWTPs) that were largely unregulated prior to a 1986 lawsuit compelling greater protection. During the early 1900s, Washington County was served by a number of small, less technologically sophisticated WWTPs which did little to remove nutrients from outgoing effluent despite the fact that in the 1970s, the Tualatin River had been identified under federal law as suffering from impaired water quality to such a great extent that establishment of a total maximum daily load (TMDL) for these nutrient pollutants would be required to guide water quality management efforts.

That TMDL was not voluntarily implemented and the 1986 lawsuit set in motion a lengthy and contentious process to set a numeric criteria for total phosphorus in the main-stem river which triggered debates about the relative value of reducing nutrient inputs as the risk of further diverting return flow during the dry summer months. Social, economic and political factors became serious considerations along-side scientific data during this lengthy debate, as the cost to WWTPs of developing technology necessary to meet the criteria proposed by environmentalists were balanced against the value of this return flow. In addition, changing environmental factors such as shifts in precipitation and temperature patterns as well as rapid population growth were discussed. The numeric criteria ultimately decided upon represented a compromise between the scientifically recommended limitation and the economically efficient recommendation, and was based on the limited but best available data provided regarding sources and transport of phosphorus within the system.

Improvements to WWTPs aimed at meeting the new TMDL resulted in quantifiable improvements in ambient water quality and the reduction of phosphorus loads, although persistent problems remained that were difficult to explain based on existing information. More comprehensive studies of the sources and transport of phosphorus undertaken during the early management years indicated that point source control of phosphorus may not be adequate to reduce the occurrence of nuisance algal growth.

Washington County’s experience with creating a TMDL for total phosphorus reflects the need for a sound understanding of watershed level factors. A good description of the physical characteristics of the watershed is essential to generating sound policies for today and for the future.  Here, a summary of the extensive data and research available regarding the Tualatin basin provides a bird's eye view of the Tualatin Basin, both serving to familiarize the reader and to provide the foundations for our analysis.  Like previous work in the field, this description of the study area touches on the location of the basin, landforms, geology, soils, climate and water resources as a basis for later discussion of how these factors influence algal growth and how flow management affects that relationship during summer months.

Examination of the three critical reaches of the Tualatin River (located in northwest Oregon within a basin sharply defined by a mountainous ring containing the bowl of the basin) provides insight as to how these conditions shape water quality issues within the county.  The Upper course of the Tualatin River channels runoff from forested areas in a channel of cool water heavily shaded by a dense forest canopy moving at rapid velocity over a sheer basalt bed and is not heavily affected by algal growth.  During its Middle Course, the Tualatin River loses velocity as it erodes more of its sedimentary bed and banks, meandering across the landscape and picking up nutrients.  By its Lower course, the Tualatin River is broad and slow, laden in nutrients and exposed to significant sunlight due to the loss of riparian canopy; in these reaches, problems with algal growth begin to express themselves.

The geologic history of the Tualatin Valley also strongly influences water quality within the basin.  The layering of various basalt flows with deposits of organic material from the Bretts Floods and loess soils arriving from previously glaciated regions of Washington combined to create perfect anaerobic conditions for the mobilization of phosphorus into the groundwater table. This phosphorus laden groundwater is funneled along the basalt lines to areas beneath the riverbed where it then seeps into the river system, contributing to high nutrient levels.

Oregon's Mediterranean climate further contributes to the growth of nuisance algae within the basin, creating low flow conditions during summer months. During the winter, Oregon receives the substantial precipitation its climate is most well-known for, but summer months tend to be hot and dry due to the orographic effects of the Coast Mountains, which trap precipitation in Tillamook County. Unlike other areas of the state, Washington County does not form a substantial snowpack to meet human water needs or to contribute to summertime river flow. Increased sunshine due to reduced numbers of cloudy days during summer months also contributes to higher rates of evaporation and transpiration within the basin.

The hydrology and geomorphology of the Tualatin River system greatly affect both water management and algal growth. The types and distribution of water resources within the basin have been heavily modified by human activity within Washington County, dividing the land uses into three belts: forested uplands, agricultural lowlands and urban development. The transformation of Washington County land-uses has impaired the natural floodplain through drainage and the introduction of impervious surface, which have led to a reduction of surface water storage in the form of wetlands and marshes. As a result, the system has become flashier over time, requiring the creation man-made reservoirs to capture winter time precipitation to prevent flooding. These reservoirs have become a key part of both the 'natural' and the managed hydrology of the system. Additionally, tributary streams within the system have been straightened and engineered to export water from agricultural and urban areas more efficiently, reducing stored flow that would otherwise reach the river during warmer months. The morphology of the Tualatin River itself through its various courses combines with these changes in storage within the basin to create lower, slower flows in the Lower reaches of the river during the summertime months unless flow is artificially augmented from reservoir supplies.

An understanding of the life cycle and ecological role of algae is critical to designing successful flow management strategies for control of algal growth within the Tualatin basin, and thus these factors are explored within the context of the stream continuum. Algae require high inputs of sunlight and nutrients for their photosynthetic activities, which are facilitated by warm water temperatures and long residence times, making summertime low flow conditions ideal of algal growth. The morphology of the single-celled planktonic green algae and their limited motility can be exploited by using flow management techniques to increase disturbance of microhabitats, shorten residence times, decrease water temperature and dilute nutrient inputs. Because flow management captures winter precipitation and redistributes flow throughout the year, it can be utilized to further interrupt the connection of algae to the floodplain and thus further impair the development of large algal communities during summer months. However, algae provide a number of benefits to both in-channel and floodplain communities in terms of underpinning the food chain, cycling nutrients and positively conditioning water quality during their growth; thus, management activities to limit growth must be balanced with other ecological goals. Finally, flow management efforts must focus on the interaction of low regime and the factors discussed above in order to generate suitable results.

Understanding trends in water quality within the Tualatin basin since 1986 is another important factor in assessing the impact of water quality and flow management on ecosystem services and human well-being. Tualatin basin water quality reflects the impact of several human activities within the basin, and over time, has been improving in most areas. Research by the US Geological Survey in the Tualatin basin indicates that algal growth in the Lower section of the river as measured by chlorophyll-a can reach problematic levels when stream-flow declines below 300 cfs in conjunction with other summertime conditions favorable growth. By the late 1990s, it became clear that these poor water quality results were driven by additional phosphorus inputs beyond the point source discharges from WWTPs, including such disperse anthropogenic sources as urban and agricultural runoff as well as environmental inputs from tributaries and in-channel seeps of phosphorus-laden groundwater. WWTP return flows, valued by water quality managers for the volume of flow returned to the system within the critical Lower reach, continued to deliver a significant proportion of phosphates during the 1990s despite plant improvements, particularly where plant upgrades had not yet been completed. The relationship of the summertime algal bloom and dissolved oxygen levels presents complicated flow management concerns throughout the course of the summer as the Lower reach of the river has tended to display low dissolved oxygen levels over time.

Water resources, including the flow on the Tualatin River during summer months, are managed through partnerships between several agencies and authorities. After introducing the concept of flow management and describing the basic divisions in climactic patterns (wet versus dry years), this section analyzes flow management decisions. Focus is given to decisions made by the sewerage agency regarding the timing of releases of flow throughout the summer months to improve water quality. Such decisions balance available supply with predicted summer climate, and present two major challenges: spreading out releases of flow over the course of the dry season without running out, and creating sufficient storage space for the next rainy season.

A longer term consideration taken up by the entire consortium, planning for additional storage in the basin, is added to the analysis.

Oregon's system of water rights, combined with climatic factors, creates a distribution and timing of precipitation and flow that requires management to balance between multiple municipal, corporate and environmental uses. After creation of the phosphorus TMDL, the need to regulate releases of flow from the Scoggins Dam to meet water quality goals while fulfilling these competing uses while preventing flooding led to creation of target flows and the interagency Flow Management Committee, whose seasonal flow management decisions aimed at meeting those targets are contemplated in this report.

Both seasonal and decadal climate cycles, as well as climate change, converge to influence a pattern of wet and dry summer conditions – the Flow Management Committee is challenged to meet demands and flow targets during dry summers and wet summers, as well as to attempt to balance storage of precipitation between years as insurance against drought as well as maintain adequate storage potential to prevent winter and spring flooding.

This analysis focuses on the differences between management strategies in wet years and in dry years, and will examine the impact of each approach on ecological services and human well-being. Challenges arising within the inter-year flow budget will also be examined as they create potential feedback between current management strategies, the changes they drive and future management strategies. Baseline conditions within the Tualatin River basin prior to the start of water quality driven flow management included low summertime flows primarily augmented by return flow from WWTPs, high nutrient levels, low levels of dissolved oxygen, warm temperatures, abundant sunlight to the channel and little precipitation. The volume and velocity of flow within the river channel throughout the summer months, as well as the diurnal and daily variations in that flow, greatly impact supporting, regulating, provisioning and cultural services within the system.

Low summertime flows within the Tualatin River channel have several impacts on the timing and severity of algal growth by altering the conditions which most directly impact algal growth (available sunlight, nutrients, temperature, and residence time).  Over the course of a typical summer, algal growth alters the ecological balance of the river channel, with ancillary effects on the riparian community and human well-being.

Summertime flow management activities in the Tualatin Basin primarily act to curtail algal growth by increasing flow throughout the summer (both by diminishing variability in flow between weeks and by reducing the length of the low flow period), which in turn decreases water temperature, dilutes nutrients and effects several other conditions critical to algal growth.  Flow management also has direct impacts on water quality within the channel either unrelated to or indirectly related to algal growth such as dissolved oxygen and suspended sediment.  Flow augmentation during summer months creates direct benefits for human well-being such as increased access to recreation and indirect benefits to human well-being through the reduced impact on other ecological services.  Human well-being is also impacted by flow management decisions throughout the year and between years as a trade-off exists between storage of water for augmentation and sufficient storage space to prevent winter flooding.

During wet summers, flow managers face three primary challenges:  long duration of spring rains lead to excess storage in the spring, summer rains reduce need for flow augmentation, and the late onset of drier months.  While reducing the pressures associated with the normally dry summer months, all three of these scenarios reduce available storage during the next rainy season and reduce the ability to protect against flooding during the next season. Conversely, excess rain in the spring and summer months can provide insurance against longer-than-typical dry seasons in the fall (late onset of winter rains). Balancing these two concerns for human well-being has led in some years to flow experimentation and other activities designed to utilize excess flow in strategic ways; at other times, excess flow was less well managed, with serious impacts to human well-being and ecological services due to subsequent increased flooding. One strategy for balancing the need for storage of flow for flood protection and storage of flow for augmentation during both wet and dry years has been to increase use of inter-basin water storage and transfers.

While more common, dry summers can present specific flow management challenges, particularly when the length of the summer season is extended (spring rains end early or winter rains come late) or when drier than average conditions throughout the year (or in consecutive years) lead to flow deficits. Under these conditions, the primary concern is calibrating the timing and volume of flow throughout the summer season to meet either flow targets or water quality goals while fulfilling all other contracted uses without running short of stored water before the agricultural and flow augmentation seasons end. Effects on ecological services are compounded during dry summers which tend to be also sunnier and warmer than average summers, creating conditions favorable to rapid algal growth and thus increasing the need for preventative flow augmentation to reduce the effect of such growth on other ecological services and human well-being. Human well-being during dry summers is significantly impacted when stored flow fails to meet all uses throughout the dry season and when the rights of some water users are curtailed prior to the end of the year.

The challenges of individual or consecutive dry seasons can only be met through careful inter-agency planning and may also require increases in the efficiency of water delivery to agricultural and municipal uses, reduction in demand for water resources during summer months through voluntary or regulated conservation measures, and development of additional storage within this basin or neighboring basins. Increased storage may also reduce the risk of winter/spring flooding; however, increasing storage itself has significant implications for ecological services and human well-being, particularly where creating new dams and reservoirs is concerned.

Analysis of past trends in flow management provides one sort of useful insight into the effectiveness and appropriateness of such measures. However, proposals for new policy measures are short sighted if they fail to anticipate and adapt to impending changes in the most critical environmental factor involved in flow management, namely, precipitation. A review the current literature allows us to assess the effect of both short and long term climate patterns on flow management decisions, as well as the potential for climate change to affect precipitation in the region.

The climate of the Pacific Northwest is influenced by decadal cycles as well as long term climate change. Although this research is limited to the impact of changing climate on ecosystem services, human well-being and sound management decisions, the interactions of land use change with these factors should also be considered in future studies. Decadal long climate cycles, caused by shifts in the course of the global thermohaline current and its associated weather patterns such as the El Nino, produce variations in temperature and precipitation in the Willamette Valley (of which the Tualatin Valley is a sub-basin) which during the 1980s and 1990s pushed conditions towards a warmer and drier state than during the preceding two decades (without, however, creating record warm & dry conditions). The El Nino Southern Oscillation (ENSO) itself impacts climate cycles in the region on a less than decadal frequency (approximately every 3-7 years), disrupting the normal delivery of several wet weather events during a typical winter (via the so-called Pineapple Express), blocking delivery of precipitation during el Nino years and increasing it in la Nina years.

Global climate change has also had a measurable effect on local climate patterns over the past few decades, and climate models call for increased temperatures which may increase the frequency of severe weather precipitation events during the winter while increasing demand for water resources during summer months, thus increasing both the risk of flooding during the winter and the risk of drought during the summer. Models at the global and local scale accounting for different geographic and anthropogenic factors give a wide range of predicted outcomes for the Pacific Northwest; for several reasons, global models tend to under-predict regional changes in temperature and over-predict regional increases in winter precipitation. Thus, the impact of global climate change in this region may result in an even greater deficit in the annual water budget than predicted.

In managing flow augmentation and flood prevention, then, careful attention must be paid to the impacts of long term climate cycles and global climate change on the annual water budget for the Tualatin basin. One way to address the challenges caused by shifts in precipitation between years in the Tualatin basin would be to employ models which attempt to predict the interaction of these climate variables and the resulting patterns of precipitation they may yield in any given year or over a period of several years. Consideration of longer term shifts in climate would also allow water quality and quantity managers within the basin to plan for the likelihood of more severe winter precipitation events combined with more frequent and longer summer droughts by increasing long term storage within the basin. These considerations may also lead to indirect water quantity management strategies aimed at increasing return flow to the river (while continuing to decrease the load of various pollutants) and decreasing demand for consumption of water during critical summer months, as well as riparian restoration efforts that may make conditions less favorable for algal growth.

The research ends with tentative but favorable conclusions as to the value to comprehensive ecological assessment in the Tualatin basin and to other basins under the 'watershed approach'. This research ultimately indicates that use of a comprehensive ecological assessment tool might enhance water quality management in certain cases. In the case of the Tualatin River, use of a comprehensive ecological assessment tool would help to assess the impacts of management decisions on both the ecological and the human communities. Use of a comprehensive ecological assessment tool here would also help to identify areas where further research is needed in terms of establishing baseline conditions, monitoring change and predicting outcomes. Such a tool may also help to identify and address potential feedbacks from management decisions as these changes effect ecological services and human well-being, driving further changes in policy decisions.

The Millennium Ecosystem Assessment, although designed for use in different parts of the world, can provide the basis for developing such an assessment tool. The use of a comprehensive ecological assessment tool would also help promote the ‘watershed approach’ as it more comprehensively identifies stakeholders and the effects of various management decisions on them, as well as incorporates a perspective of overall watershed health. An ecological assessment tool may ultimately increase the efficiency and efficacy of watershed-wide water quality management by providing a framework under which to assess existing knowledge, identify needed knowledge, analyze and compare various management scenarios, and finally monitor and assess their success.

The absence of such a framework for processing the large amount of information involved in assessing basin-wide policies may lead to increased delay in decision making, unnecessary conflict over alternatives and implementation of mistaken policies not based in the best available science. Going forward in the Tualatin basin and in other watersheds, use of a comprehensive ecological assessment tool may help to assess the potential effects of climate change and land use change on ecological services and human well-being, as well as to identify and assess potential policies to adapt to or mitigate these effects. Predicting potential interactions between policy decisions, ecological services and human well-being may help to identify and avoid potentially undesirable feedbacks in policy making.

# Chapter 1 The Watershed Approach and the MEA

## A. Summary

Early CWA enforcement focused on eliminating direct point source pollution to our nation's waterways, largely because these identifiable outfalls posed little difficulty in measuring concentrations of pollutants. Proving a violation of numeric criteria from such a localized source, then, was efficient and presented few legal difficulties in court. Little or no attention was paid to setting TMDLs for watersheds – even after the spate of TMDL litigation in the mid-1980s, enforcement of TMDLs over non-point sources of pollution such as urban runoff, storm sewer drainage and agriculture remained virtually non-existent in the face of difficulties proving that specific land users had caused these violations. Cases of non-point source pollution tend to occur due to the drainage of large, complex systems of land with many users, thus making it difficult to prove beyond a reasonable doubt (the criminal law standard of proof applicable in CWA violations) that just one of these many uses resulted in the specific violation.

In response to the realization that little had been accomplished under the CWA on non-point source pollution, EPA was faced with the challenge of retooling CWA implementation to address the more complex issue of non-point source. They determined that the key to managing NPS was a broader perspective on water quality than the pursuit of individual violators allowed. Instead, management of land usage within the entire watershed was the only mechanism by which pollution from various land use activities across the source area could be effectively curtailed. This new watershed based perspective was simply called the 'watershed approach'. In this chapter, we review literature on the success of the watershed approach and introduce the

MEA as one potential form of ecosystem assessment that could enhance this approach. The methods for this research are then outlined.

Management of non-point source pollution in the Tualatin Basin under the Clean Water Act provides an early example of management at the watershed scale. While several surveys of the 'watershed approach' have been conducted, application of an ecosystem assessment tool such as the Millennium Ecosystem Assessment may provide new insights. The so-called 'watershed approach' represents an attempt by federal and state water quality managers to shift the focus of water quality management beyond simple point source regulation to address wider systemic issues stemming from non-point sources of pollutants through more collaborative work with local stakeholders rather than traditional top-down regulation. This watershed approach provides the additional benefits of reduced costs, localized management and greater attention to local priorities. These benefits are achieved by focusing on partnerships, defined management areas, coordinated management activities and strategically timed actions. Efforts to assess this 'watershed approach' have provided some insights into its benefits and drawbacks, but have fallen short of comprehensively assessing the environmental, social and economic impacts of watershed management efforts.

While succeeding in increasing local participant in watershed protection, quantitative assessment of the impacts of these programs is lacking. Current assessment focuses on how the methods employed in watershed management by local and federal agencies measure up to the EPA's prescriptions, rather than detailing the environmental impact or sustainability of those programs. A review of statewide water quality management programs reveals that while improvements have been made in collection of water quality data, in planning and assessment, and in permitting programs, the 'watershed approach' continued to inadequately resolve federal-state jurisdictional tensions as well as to incorporate fully its core principles. Current assessments of watershed management programs in the U.S. focus on how well the execution of the 'watershed approach' measures up to expectations, and fall short in evaluation of the long term impacts of water quality management programs on both the ecological and human communities, overlooking important issues such as changes in ecological services, effects on human well-being, and economic consequences. Existing assessments by EPA do not consider the ability of watershed management programs to respond to environmental change over time or the impact such decisions may have on human and environmental well-being in conjunction with those changes.

These shortfalls in assessment of various watershed management programs may be addressed by employing an ecological assessment tool such as the Millennium Ecosystem Assessment which inventories ecological services, monitors change, evaluates impact on human welfare, tracks feedback between change and future decisions, and identifies potential adaptations to future change. Application of the MEA to management decisions in a more developed nation such as the United States may require some adjustment but is certainly feasible and has been achieved in past studies.

This case study applies the MEA, with necessary adjustments in perspective, to flow management decisions on the Tualatin River. The primary purpose of this research is to assess those management decisions to determine their impacts on environmental and human well-being in terms of changes to ecosystem services, effects on human well-being and response to environmental change. Secondarily, this research will examine the benefit of utilizing an ecological assessment tool as part of a watershed management process. Budgetary and time constraints compel this research to focus on existing data and information, with the hopes that use of the ecosystem assessment tool may help to identify areas for further research, an approach that is consistent with other multi-disciplinary policy analyses within the field.

B. EPA's Watershed Approach

- **The 'watershed approach' represents an attempt by federal and state water quality managers to shift the focus of water quality management beyond simple point source regulation to address wider systemic issues stemming from non-point sources of pollutants through more collaborative work with local stakeholders rather than traditional top-down regulation.**

The watershed approach was designed to be a more inclusive process, both in terms of the scope of changes sought throughout the basin and in terms of the individuals creating those changes and criteria for measuring their implementation. EPA defines the watershed approach as a framework for management that uses public and private efforts to address both surface and ground water quality problems within a hydrologically-defined geographic area (EPA 1996). The watershed approach is guided by the principles of building partnerships between stakeholders within the basin (in contrast to the top-down regulatory approach of the NPDES permitting process), of creating a geographically based jurisdiction that is congruent with watershed boundaries, and of basing management decisions on valid science and data (often generated by participation of the stakeholders) (EPA 1996).

Stakeholder involvement is considered by EPA to be a key element of the new watershed approach, particularly because many of the policies implemented under the CWA take place by voluntary agreement with these stakeholders rather than command & control regulatory authority. Stakeholder involvement increases the total knowledge base, improves understanding of issues and roles, brings to the forefront environmental justice concerns and encourages iterative decision making and review of policies (EPA 1996). Because watersheds often cross political boundaries, various governmental jurisdictions can be involved in water policy planning. EPA expects that enhancing stakeholder involvement across federal, state, tribal and local jurisdictions will increase the validity of policies by including the concerns of each effected group, building a sense of community around the resource, increasing commitment to action and reducing conflict – all of these effects are viewed as improving the likelihood of successful water quality improvement (EPA 1996). Although stakeholder involvement is a defining element of the watershed approach, EPA recognizes the need for a lead agency to spearhead management and coordination efforts.

- **This watershed approach provides the additional benefits of reduced costs, localized management and greater attention to local priorities.**

The EPA cites additional benefits to the watershed approach as well. The watershed approach is perceived to be economically more viable than the federal command & control approach, in large part by removing the need for federal oversight of the management of local issues. EPA notes that by focusing on data specific to the watershed, managers can make critical budget decisions with limited resources in a more effective manner. Interagency partnerships at a local level also allow better leveraging of funding from local partners (EPA 1996). EPA expects that local management will improve communication between managers, allow for the coordination of various restoration and pollution reduction efforts between stakeholders, reduce duplicated efforts, eliminate conflicting actions and improve efficiency of the permitting process (EPA 1996). Thus, the cost savings of the more localized watershed approach are anticipated not only to improve EPA's budget, but to translate to better tailored policies that enhance the economies of states and local communities as well.

The removal of such federal oversight is also perceived as allowing greater tailoring of local policy to local needs by bringing new groups to the table – "for example, by jointly reviewing the results of assessment efforts for drinking water protection, pollution control, fish and wildlife habitat protection and other aquatic resource protection programs, managers from all levels of government can better understand the cumulative effects of various human activities and determine the most critical problems within each watershed (EPA 1996)." Thus, the watershed approach allows a local team of managers to understand and address watershed scale issues and priorities in a way that uniform national policy simply cannot. This local understanding of the ecological functioning within the watershed allows for more specialized environmental monitoring as well, helping to solve problems prioritized at the local level and record success rather than focusing on national program mandates (EPA 1996).

- **These benefits are achieved by focusing on partnerships, defined management areas, coordinated management activities and strategically timed actions.**

In order to ensure that these values become a reality in localized watershed planning, EPA instructs management groups to address four key areas of concern in their planning process. First, to foster better partnerships, watershed managers are directed to increase stakeholder involvement to improve local understanding of problems and increase local participation in setting goals, then identifying and implementing solutions (EPA 1996). Second, watershed managers are encouraged by EPA to define their management area on the basis of geographic management units. These GMUs are areas defined by the geography of the land surrounding a river which defines the area of land that contributes surface and ground water to that river.

When considering water quality throughout the river's course, the GMUs are obviously contiguous with the watershed boundaries. However, water quality can and sometimes must be managed on smaller scales such as reaches or segments – in these cases, the GMU is defined in a manner similar to that by which the entire watershed is delineated, but on a scaled down level (EPA 1996).

Thirdly, management teams are directed to coordinate the management activities within their basins in order to avoid duplicate effort, eliminate conflict between activities and save funds. EPA intends for various agencies with various mandate to work with each other and local groups in their identified high priority areas to leverage limited resources in pursuit of common goals (EPA 1996). Lead state and tribal agencies, then, can coordinate existing management activities across stakeholders to reduce or eliminate this duplication and conflict. Vital activities to be coordinated include assessment and characterization of ecosystems and environmental problems, monitoring of environmental quality and ecosystem degradation, identification of causes and sources of such problems, coordination of goals between agencies and activities, prioritization of problems, allocation of resources, resource targeting, development of management options and watershed planning, plan implementation, and ongoing monitoring and evaluation. Finally, it is essential that this broad array of management activities be coordinated not only in terms of resources but in terms of timing – establishment of a management schedule as part of the watershed plan assists all stakeholders in prioritizing projects, seeing projects in light of a larger scheme, and accomplishing goals in a timely manner (EPA 1996).

- **Efforts to assess this 'watershed approach' have provided some insights into its benefits and drawbacks, but have fallen short of comprehensively assessing the environmental, social and economic impacts of watershed management efforts.**

Since its conception in 1996, the watershed approach has gained some popularity amongst local jurisdictions as framework for managing water quality. Water quality management in the Tualatin basin contained elements of a watershed approach from its inception. -Management under the Healthy Streams plan was an early expression of the approach's potential even as early as the mid-1990s. In 2001, EPA released Protecting and Restoring America's Watersheds: Status, Trends and Initiatives in Watershed Management (hereafter America's Watersheds Report or AWR), and in 2002, EPA published a formal review of the watershed management programs, A Review of Statewide Watershed Management Approaches (hereafter Statewide Approaches Report or SAR). These documents offer insight both into the criteria by which EPA has assessed the validity of the watershed approach over the past fifteen years, as well as the results of their self-assessment. A brief consideration of each report illuminates the need for a more comprehensive ecosystem assessment tool in addition to these review procedures.

*America's Watersheds Report*

- **While succeeding in increasing local participant in watershed protection, quantitative assessment of the impacts of these programs is lacking. Current assessment focuses on how the methods employed in watershed management by local and federal agencies measure up to the EPA's prescriptions, rather than detailing the environmental impact or sustainability of those programs.**

The America's Watersheds Report was generated from a series of regional watershed round table discussions involving stakeholders and from the Watershed Re-invention workgroup, which was tasked with identifying ways to improve federal involvement in and support of watershed management. The report noted that in practice, watershed management programs tend to focus on seven themes: public education and awareness, partnership building, monitoring and research, setting plans and priorities, implementing solutions and evaluating results. Most of these seven objectives were outlined specifically in the original guidance documentation for the watershed approach, with the notable exception of public education and awareness. The AWR noted from the outset that assessing performance under the watershed approach can be difficult and is often more qualitative than quantitative (EPA 2001). Thus, the AWR provides a description of common successes and failures in each of these seven areas based on reports from the roundtable discussions and work by the re-invention workgroup.

This method of assessing the watershed approach is useful for understanding how well individual watershed management programs stack up against EPA's vision of the watershed approach, as well as highlighting individual practices in each of the seven theme areas that helped to further EPA's stated goals. For example, at the round tables, managers expressed the belief that local practices were best changed through peer education as opposed to other educational programs (EPA 2001). The AWR recognized the growing number of partnerships between agencies and other stakeholders throughout the nation, including the increasing role of citizen participation as state and federal governments receded from a leadership to a supporting role (EPA 2001). However, the resulting effects of the work of such partnerships both on the well-being of the stakeholders and on the impact of watershed management on ecosystem health were not assessed in either qualitative or quantitative way (EPA 2001).

According to the report, although watershed monitoring and research has improved with increased training, government partnerships and funding, a lack of data on habitat quality and biological indicators of water quality continues to impair the work of most watershed councils (EPA 2001). Because many water quality programs cover entire watersheds, the geographic areas involved imply huge amounts of data to be stored, processed and interpreted. According to the AWR report (2001), a lack of local data and co-ordination of data severally dampens local action. This type of understanding calls both for better scientific research and for a greater context in which to understand that research in terms of effects on human well-being and ecosystem services. The AWR report (2001) concludes that both a wider base of background data and a stronger context for interpreting that data in terms of both ecosystems services and human well-being would help planners understand the ramifications of different projects in the long and short term, as well as determine what causes success or failure of water quality programs (EPA 2001).

In terms of setting priorities, several national efforts have been undertaken during the last decade to determine which watersheds were in the direst of need in order to guide national funding decisions. At the local level, decision making must also be guided by priorities, which often include the needs of local and regional residents, as well as the ties of the local community to the nation at large and the greater world. According to EPA's AWR report (2001), watershed wide programs continue to pose problems in planning and coordination due to the diversity of government agencies and stakeholders involved with a variety of sub-issues. The AWR report notes examples of well-intentioned planning and the paths it has paved brought forth from the southeastern round table, where even though a super majority of state delegations agreed land use planning and zoning was a top priority, their individual in-state programs failed to adequately address these issues and in fact may have promoted furtherance of policies that result in water quality degradation (EPA 2001). Use of an assessment tool that allowed planners and stakeholders to explore the potential impacts of various choices both on environmental health and on human well-being at multiple scales would help to establish local priorities. Clearly identifying the connections between local policy and effects on national and international systems may also open the doors to further research funding.

The AWR notes that the selection and implementation of projects has been notoriously biased toward watershed protection rather than restoration because watershed protection seems inexpensive and effective by comparison to restoration projects which are risky and have effects that are difficult to measure. This creates a paradox, however, since the currently degraded quality of many of our nation’s watersheds requires a greater emphasis on restoration work to improve water quality (EPA 2001). This research proposes that by identifying the trade-offs in ecosystem services of both protection and restoration programs, a solid ecological assessment could better support the long term efficacy of restoration programs. This is particularly true where the assessment can categorize the ecological services preserved versus those restored, and can connect them directly to improvements or losses of human well-being. By considering how these changes in well-being might affect individual choices and thereby feedback into new changes in ecosystem services and well-being, the long term tradeoffs between protection and restoration might be clearly understood. Applying such an analysis after the project is complete can help to assess the value of the work – sadly, the AWR itself concluded that such evaluations are rare in part because "many existing measurement tools and environmental indicators are complex and have only indirect linkages to on-the-ground changes (EPA 2001)." A clearer qualitative tool such as the MEA might assist in providing the snapshot of impact with the needed level of sophistication and yet greater accessibility to multi-disciplinary management teams.

This research further proposes that use of such an ecosystem assessment tool could help capture the effect of the watershed approach on the overall health of the ecosystem or help track effects on human well-being generated by the management activities. The failure of previous evaluations of the watershed approach such as the AWR may underlie many of the inadequacies indicated by the report, and thus a comprehensive ecosystem assessment tool could provide a breakthrough in the future management of watersheds. While the broad brush recommendations are useful advice for future planning methods, they provide no detailed guidance on how to evaluate possible outcomes of various watershed management decisions and no tool by which to evaluate actual outcomes later. A tool such as the MEA provides opportunities for public and peer education as well by allowing managers to illustrate the pathways connecting non-point source pollution, ecosystem change and human well-being, as well as feedbacks within the system.

C. A Review of Statewide Management Approaches

- **A review of statewide water quality management programs reveals that while improvements have been made in collection of water quality data, in planning and assessment, and in permitting programs, the 'watershed approach' continued to inadequately resolve federal-state jurisdictional tensions as well as to incorporate fully its core principles.**

In 2002, EPA conducted a more formal review of selected states that had implemented the watershed approach to assess existing watershed management programs and draw recommendations for future programs from them (EPA 2002). The five step study began with an analysis of existing documents and interviews with lead managers in several offices to identify issues of concern. Based on this preliminary investigation, eight states (Kentucky, Massachusetts, New Jersey, North Carolina, Ohio, Oregon, Texas and Washington) were selected for the study. Interviews with water resource managers and staff were conducted by phone, mail and in person in order to detail each state's approach to watershed management. The evaluators then reviewed these summaries to develop their findings and recommendations, which were published in the Statewide Approaches Report (SAR). The research presented in this thesis is modeled largely on the SAR approach.

The findings of the SAR were largely positive, with a strong majority of participants expressing positive feelings about the watershed approach in their state. The SAR focused on programmatic functioning and found many improvements in management. These included growth of monitoring, planning and assessment capabilities as well as improved permitting programs (EPA 2002). The report also identified continuing weaknesses in the watershed approach, including continuing conflict between agencies and other partners as well as between levels of government and ineffective federal oversight of state programs. Most importantly, the SAR indicated that water quality management programs attempting to utilize the watershed approach continued to omit “core water quality program elements,” indicating a fundamental failure of these programs to achieve the driving goals of the new approach (EPA 2002). Twelve recommendations for improving the state programs were made based on these concerns, including a call for expanded partnerships and increased technical and financial support from the federal level to remedy these issues (EPA 2002).

- **Both the AWR and the SAR focus on how well the execution of the ‘watershed approach’ measures up to expectations, and fall short in evaluation of the long term impacts of water quality management programs on both the ecological and human communities, overlooking important issues such as changes in ecological services, effects on human well-being, and economic consequences. Neither the AWR nor the SAR considers the ability of watershed management programs to respond to**

**environmental change over time or the impact such decisions may have on human and environmental well-being in conjunction with those changes.**

The SAR provided a more objective qualitative evaluation of these state programs than the AWR. Like the AWR, it provided a good account of what managers perceive to be the strengths and weaknesses of the watershed approach. However, both assessments fail to provide an objective, external measure of the impact of the watershed approach on ecosystem services and human well-being. It also fails to identify ways in which management choices may unintentionally create benefits or costs through a series of feedbacks between human behavior and ecological functioning. Both the SAR and the AWR fundamentally assume the validity of the watershed approach, and thus focus on measuring implementation of that approach against expectations, rather than attempting to describe qualitatively or quantitatively the benefits of the approach. While the recommendations of both the SAR and the AWR will certainly strengthen programs if adopted, the use of an evaluative tool that ties ecosystem services to human well-being may support requests for funding of these changes by providing substantive predictions as to their effects.

Unlike the AWR, the SAR does provide specific detail about watershed management in selected states. Only 8 of 20 states employing a watershed approach were considered in depth – conveniently for this research, Oregon was one of those states. Thus, the SAR provides a snapshot of watershed management in Oregon in 2002. The SAR begins by noting that Oregon's water quality management program is complex and hierarchical, with agency actions and goals driven by the Oregon Plan for Salmon (The Oregon Plan), a policy document intended to guide recovery efforts for these endangered fish populations across the multiple agencies, non-governmental groups and programs involved in water quality and quantity regulation (EPA

2002). State agencies then act with local watershed councils to implement the Oregon Plan at the watershed level.

According to the SAR, while the state plan in general encourages a watershed based approach, not every listed waterbody is managed under the same approach and internal policies often interpret the “watershed approach” differently (EPA 2002). For example, ODA does not delineate its programs along watershed boundaries, but they rely heavily on the themes of the ‘watershed approach’ in working directly with landowners. The call for a more comprehensive watershed based approach to salmon protection has led to better information sharing and consensus building among stakeholders in Oregon as it has in other states, but conflicts remain over physical and program jurisdictions, roles and responsibilities, which are exacerbated by the varying interpretations of the approach and definitions of watershed boundaries (EPA 2002). For example, the SAR notes that DEQ sets TMDLs at the sub-basin (8 digit HUC) level but watershed councils operate on still smaller sub-basin scales (11 to 14 digit HUC), while federal and regional plans operate at still larger scales encompassing multiple watersheds (EPA 2002). Each of these groups defines its mission, goals and activities by the scope within which it operates – territorial disputes can arise when organizations have different goals for the same nested watersheds and areas can be overlooked when they fall outside anyone’s defined jurisdiction (EPA 2002).

The SAR lays out the benefits and complications of the state hierarchical system in Oregon, but fails to address any particular watershed's performance in terms of effects on ecosystem services or human well-being. Many questions remain unanswered regarding the functioning of these relationships within the Tualatin basin, and some of these questions may be well address through use of the MEA to identify and trace the actions and interactions of various stakeholders and managers through their effects on ecosystem services and human well-being.

D. Comprehensive Ecosystem Assessment and the MEA

- **These shortfalls in assessment of various watershed management programs may be addressed by employing an ecological assessment tool such as the Millennium Ecosystem Assessment which inventories ecological services, monitors change, evaluates impact on human welfare, tracks feedback between change and future decisions, and identifies potential adaptations to future change.**

Ultimately, watershed management focuses on the dual goals of improving water quality and improving human well-being. One of the defining features of the watershed approach is its focus on partnerships and stakeholder involvement – this focus implies a concern with the effect of management decisions on human well-being in the area. Addressing the effect of a management decision on local, regional, national and global human well-being in addition to its impacts directly on the ecosystem itself is in fact critical to effective management. History has demonstrated that point source pollution control via regulation may be efficient in the sense that little concern as to the effect of the regulation on the community needs to be considered. However, such gains are limited in a setting where pollution issues stem more from non-point source pollution. In cases of non-point source pollution, the individual decisions of land users and stakeholders play an essential role in water quality management. Individual choices are greatly affected by changes in individual well-being - because every management decision has the potential to effect human well-being as well as the environment, the feedback between changes in management decisions, human well-being and consequent behavior changes which may further modify the environment must be considered.

The United Nation's Millennium Ecosystem Assessment tool provides a framework for multi-disciplinary teams of experts from various levels of government as well as the private sector to consider such interactions between management, ecosystem services and human well-being and decision making at various scales, producing " an integrated assessment of the consequences of ecosystem change for human well-being” and analyzing policy alternatives to improve both ecosystem services and human well-being in response to various drivers of change (Hassan, Scholes and Ash 2005). The assessment framework consists of three components: change drivers, ecosystem services and human well-being. In this context, change drivers are those events or decisions which immediately impact the environment in some way (that is, direct change drivers which alter the physical environment) or in some way influence more direct effects (that is, indirect drivers of change). The MEA attempts to identify these events and decisions, and then to trace their effect on the services provided by the ecosystem as a way of assessing environmental change. These effects may be beneficial by enhancing some ecosystem services or may be harmful by degrading others (Hassan, Scholes and Ash 2005).

Ecosystem services can include the mechanisms by which the ecosystem provides food, shelter and clothing for human beings (provisioning services); by which the ecosystem ensures a stable climate, clean water and air, and fertile soil (regulating services); by which the ecosystem fulfills the spiritual, recreational or cultural needs of a people (cultural services); and by which an ecosystem creates the ongoing conditions necessary for its functioning and for the production of these services (supporting services). By identifying which services are currently being provided by an ecosystem before a change driver comes into effect, the effect of that change on the system can be evaluated (Hassan, Scholes and Ash 2005).

The MEA differs from other ecological assessments primarily in the structure by which it forces a methodical consideration of how environmental health, human well-being and human actions interact. These interactions are identified by the MEA as a three part cycle consisting of change drivers, ecosystem services and human well-being. Before considering the effect of human activity on an ecosystem and the community of persons that relies on it, one must somehow quantify or describe qualitatively the traits and characteristics of the existing ecosystem. The MEA compels organization of these traits into four categories – this allows like characteristics to be grouped with each other, and allows for easier identification of the effects of change on the system (Hassan, Scholes and Ash 2005).

In order to be comprehensive in assessing the characteristics of an ecosystem and not overlook values that are easily under-rated by economic or scientific models, the MEA identifies four categories of ecosystem services: regulating, provisioning, cultural and supporting services. Provisioning services include products for human use that are gained from the ecosystem. They embody the ability of the ecosystem to provide the materials necessary for the welfare of other organisms, and are the most obvious and paid the greatest amount of attention in most policy analyses. In particular, the ability of the ecosystem to provide drinking water, food or materials for manufacturing is often identified (Hassan, Scholes and Ash 2005).

Regulating services are those characteristics of the ecosystem that underpin functioning of the ecosystem itself but do not directly provide other services. These services function behind the scenes to keep the system running. These can include macro-scale functions that operate throughout the world such as climate regulation. They are often included as background assumptions about the functioning of provisioning services rather than expressly address as a separate set of functions (Hassan, Scholes and Ash 2005).

Also often overlooked are the supporting services, which are necessary for the existence of all other ecosystem services. These are the characteristics of ecosystem functioning that facilitate the life cycle needs of other members of the biological community. These may include activities such as seed dispersal or nutrient cycling. For example, the purification of water within the water cycle supports the provision of clean drinking water or the irrigation of crops but does not provide a direct service to human beings. Like supporting services, regulating services underpin ecosystem functions that we measure more directly through the assessment of provisioning services. Finally, cultural services such as recreation, education and spirituality can be overlooked by all but the most diligent of social scientists (Hassan, Scholes and Ash 2005).

These categories intentionally connect to the effects of environmental change on human well-being as well. Those effects are difficult to assess. According to Butler (2003) "how well-being and ill-being, or poverty, are expressed and experienced is context- and situation-dependent, reflecting local social and personal factors such as geography, ecology, age, gender, and culture. These concepts are complex and value-laden." Butler asserts that by categorizing the elements of ecosystem health in terms of their association to human well-being, it becomes easier to track and predict the effects of change on human well-being over time (Butler 2003). Butler further concludes that such assessments can also track or predict how changes in well-being will affect changes in behavior, which themselves become change drivers to be evaluated. (Butler 2003)

- **Application of the MEA to management decisions in a more developed nation such as the United States may require some adjustment but is certainly feasible and has been achieved in past studies.**

Although the tool was originally designed for use assessing global ecosystem health and evaluating the effects of management decisions in less developed areas of the world, it can certainly be utilized to consider the impacts of these decisions in more developed nations. While water quality management decisions in western Oregon may have less dire consequences for residents than management decisions in Pakistan, even these more subtle effects change individual behavior in ways which, collectively, may create greater enhancement or degradation of the environment. Indeed, the MEA has been applied in more developed areas both in approved U.N. assessments and in associated assessments in British Columbia, Norway, Australia, and within the United States, in Alaska and Wisconsin. Researchers in Alaska have used the MEA to investigate how fire affects the boreal ecosystem and human well-being in the surrounding area, as well as how this relationship is being altered by human action. That study considers how various alternative actions could further change the system in the future and what policy options may mitigate negative effects (Peterson 2003). In Wisconsin, the MEA has been applied to identify the ecosystem services provided by the Northern Highlands Lake District, consider the effects of human action in the District and determine whether those policies are sustainable, particularly in the face of external change drivers than cannot be altered by local policy, especially those related to land use changes and population pressure (Ullsten 2004).

This thesis posits that an ecological assessment tool that incorporates human well-being like the MEA can be used to address several of the shortcomings of the watershed approach cited by the AWR as well as provide a more robust evaluation of the effects of the approach. The

MEA can assist with understanding the public health and environmental impacts of emerging pollution threats. In 2005, Chopra concluded that the MEA can help identify policy alternatives with positive effects for ecosystem services and human well-being that are better aligned with development and sustainability goals because the MEA helps to identify the trade-offs created for stakeholders by an particular set of decisions at multiple scales (Chopra 2005). Additionally, this research posits that a good ecological assessment tool like the MEA may help to adapt current management strategies to predicted environmental change in climate and land use by considering future environmental change drivers and the feedback between changes in human well-being, collective/individual choices ecosystem services.

E. Research Methods

- **This case study will apply the MEA, with necessary adjustments in perspective, to flow management decisions on the Tualatin River.**

- **The primary purpose of this research is to assess those management decisions to determine their impacts on environmental and human well-being in terms of changes to ecosystem services, effects on human well-being and response to environmental change. Secondarily, this research will examine the benefit of utilizing an ecological assessment tool as part of a watershed management process.**

- **Budgetary and time constraints compel this research to focus on existing data and information, with the hopes that use of the ecosystem assessment tool may help to identify areas for further research, an approach that is consistent with other multi-disciplinary policy analyses within the field.**

This case study applies a conceptual framework to information obtained through a literature review to generate a working analysis of water management policy in the Tualatin River watershed. The project considers whether application of a comprehensive ecological assessment tool such as the MEA might enhance watershed management under the CWA. This research began with a comprehensive review of the academic literature related to the Tualatin

River basin as well as the numerous government agency reports generated in the process of management. To enhance understanding of factors related to human well-being and social context as well as to help formulate a timeline for management decisions, newspaper articles from the time period were summarized as well. These articles spanned a period from 1988 through 2009 and were reviewed to create a separate, free standing history utilized as a basis for this analysis. Where articles were cited directly in this writing, they are cited accordingly.

A description of the basin before and during management was derived from the materials as well as a description of the expected effects of environmental change (particularly climate change). The MEA framework was then applied as a guide to assess the costs and benefits of past flow management decisions and used as a framework to predict the challenges of climate change. This application also identified potential adaptations in management and assessed potential drawbacks to those options. This investigation further identified potential areas to strengthen research and knowledge about the ecosystem services and effects of various management decisions on human well-being. Finally, a review of this case study method was undertaken to assess effectiveness.

At heart, the Millennium Ecosystem Assessment focuses on the interaction between human activities and the environment as reflected by changes in ecosystem service and human well-being over time. Identification of the factors which drive change, the effect of those change drivers on ecosystems and the effect of these interactions on human well-being, as well as an identification of potential feedbacks is not unusual to the analysis of many policy decisions. It is certainly very common in the analysis of management decisions related to water quality and quantity, as demonstrated by a few examples here.

In 2010, the Committee on Sustainable Water and Environmental Management in the California Bay Delta (convened by the National Research Council) published its report analyzing alternative management strategies for their potential effect on threatened and endangered species in that watershed(Huggett 2010).  Like Oregon, the hydrologic functioning of California's watersheds has been altered on a massive scale to accommodate human activity.  The Committee sought specifically to review two Biological Opinions issued by federal agencies regarding the management of this engineered water distribution system.  Huggett (2010)  reported that although the alteration have met user demand for many years, the impacts of human re-engineering and of population pressure drove change in the ecosystem that have led to declining health and abundance of fish populations in the river delta as well as the introduction of non-native species (Huggett 2010).

Comparison of Hugget's report and the research compiled here reveals that California and Oregon share many similarities in terms of their water management challenges.  Both states share a need to manage water resources under the prior appropriate scheme of water rights in the face of population pressure and environmental change (Huggett 2010).  Finally, both states operate their environmental protection programs under the dual pressures of environmental values (embodied in each primarily by the needs of a sensitive fish species) and economic needs (Huggett 2010).   Although the California Bay Delta faces greater overall aridity throughout the year than does the Tualatin Basin, the methods chosen to analyze various water quantity and quality options in California (as embodied in the Biological Opinions reviewed) are instructive for the Oregon case.  Perhaps the most compelling similarity between the two cases is the complexity of the management decisions to be made (Huggett 2010).  As related by Huggett

(2010), the California situation must protect several species listed as endangered under the ESA, meet existing and future water regional water demand, and respond to complications introduced through human action and environmental change, all of which take the form of immutable external change drivers from the perspective of the managing authorities (Huggett 2010). Indeed, even some of the same potential management decisions were considered in the California analysis. Both agencies had proposed and evaluated the management options of purchasing additional water to enhance in-stream-flow and restoring habitat for native fishes. In both cases, the management decisions being made ultimately are made to benefit an indicator species of particular concern within the basin, and these management options reflect those goals.

As does our research, the analysis by the NRC committee relied primarily on the testimony of experts to provide the background of the problem and evaluation of the effects of the various solutions. In both the case of this research and the case of the NRC, the multi-disciplinary nature of the problems combined with the large amount of information to be considered makes primary research of all aspects of the problem impractical – to undertake novel research into each topic necessary to understanding the whole would overwhelm the analyst's resources without producing a comparison of the options. It was the very complexity of the problem in the California case that persuaded the Department of the Interior to seek the assistance of the NRC to analyze the two options provided by U.S. Fish and Wildlife and National Marine Fisheries Services (Huggett 2010). While the NRC was presented with an existing set of options for analysis, the approach they applied to analyzing those options could be applied to any set of management choices (such as those contemplated here). In addition to analyzing the proposed options, the committee was specifically asked to make recommendations as to other reasonably prudent alternatives not identified by either Biological Opinion. The committee was not asked to review policy on a decision-by-decision basis, but rather to consider the overarching themes and categories of action to whether the RPAs drew from the best available science, whether alternative RPAs existed that would have lower environmental side effects, and whether there was any way to resolve incompatibilities between FWS and NMFS actions (Huggett 2010).

The analysis embodied in the Committee's report reflects many elements similar to those embodied in the Millennium Ecosystem Assessment. The context of the water management problem is identified and summarized, with particular focus on those activities and events which created changes to the Bay Delta and its upstream watershed. The Committee then took a more in-depth look at the critical factors that affect the life cycle of the indicator species, including the life histories of the three species in question and other stressors. While there was not an explicit inclusion of detailed reporting on the physical setting, climate or social history of the area, such is implied to be known throughout the report. The report then goes on to identify 'Other Stressors,' including in these what we would identify under the MEA as Change Drivers, including the introduction of contaminants and altered nutrient loads, changes in the habitat available to these species, introduction of competitor species, changes in channel structure that impede fish activities, disease and climate change (Huggett 2010).

The occurrence of each of these change drivers is explained, and the effects upon the fish species (and thereby ecosystem functioning) are identified. By evaluating the economic impact of these changes, the report even begins to assess some of the impacts on human well-being caused by these changes. For each of the proposed actions to be analyzed, the committee then identified the policy in question, considered the disagreements about the impact of the action, assessed the validity of the argument in favor of the policy, identified other reasonable alternatives, and finally assessed the interactions of the various recommended policies.  In each case, the effect of the policy on ecosystem health and functioning was considered along with its economic impact.  These considerations are currently required by U.S. environmental law and they conveniently mirror in an unstructured way the MEA framework which requires explicit consideration of the effect of change drivers on supporting, regulating, cultural and provisioning services as well as on human well-being (Huggett 2010).

# Chapter 2 Description of the Tualatin River Watershed and the History of Water Quality Management in the Basin

## A. Summary

This foundational Chapter explores the history and background of the Tualatin River basin which underlies the following case study of water management decisions.

Although a long standing history of algal growth exists in the area, water quality problems in the Tualatin basin grew beyond tolerable levels by the 1980s, presumably due to increased point source pollution of the river from waste water treatment plants (WWTPs) that were largely unregulated prior to a 1986 lawsuit compelling greater protection. During the early 1900s, Washington County was served by a number of small, less technologically sophisticated WWTPs which did little to remove nutrients from outgoing effluent despite the fact that in the 1970s, the Tualatin River had been identified under federal law as suffering from impaired water quality to such a great extent that establishment of a total maximum daily load (TMDL) for these nutrient pollutants would be required to guide water quality management efforts.

That TMDL was not voluntarily implemented and the 1986 lawsuit set in motion a lengthy and contentious process to set a numeric criteria for total phosphorus in the main-stem river which triggered debates about the relative value of reducing nutrient inputs as the risk of further diverting return flow during the dry summer months. Social, economic and political factors became serious considerations alongside scientific data during this lengthy debate, as the cost to WWTPs of developing technology necessary to meet the criteria proposed by environmentalists were balanced against the value of this return flow. In addition, changing environmental factors such as shifts in precipitation and temperature patterns as well as rapid population growth were discussed. The numeric criteria ultimately decided upon represented a compromise between the scientifically recommended limitation and the economically efficient recommendation, and was based on the limited but best available data provided regarding sources and transport of phosphorus within the system.

Improvements to WWTPs aimed at meeting the new TMDL resulted in quantifiable improvements in ambient water quality and the reduction of phosphorus loads, although persistent problems remained that were difficult to explain based on existing information. More comprehensive studies of the sources and transport of phosphorus undertaken during the early management years indicated that point source control of phosphorus may not be adequate to reduce the occurrence of nuisance algal growth.

Washington County's experience with creating a TMDL for total phosphorus reflects the need for a sound understanding of watershed level factors. A good description of the physical characteristics of the watershed is essential to generating sound policies for today and for the future. Here, a summary of the extensive data and research available regarding the Tualatin basin provides a bird's eye view of the Tualatin Basin, both serving to familiarize the reader and to provide the foundations for our analysis. Like previous work in the field, this description of the study area touches on the location of the basin, landforms, geology, soils, climate and water resources as a basis for later discussion of how these factors influence algal growth and how flow management affects that relationship during summer months.

Examination of the three critical reaches of the Tualatin River (located in northwest Oregon within a basin sharply defined by a mountainous ring containing the bowl of the basin) provides insight as to how these conditions shape water quality issues within the county. The Upper course of the Tualatin River channels runoff from forested areas in a channel of cool water heavily shaded by a dense forest canopy moving at rapid velocity over a sheer basalt bed and is not heavily affected by algal growth. During its Middle Course, the Tualatin River loses velocity as it erodes more of its sedimentary bed and banks, meandering across the landscape and picking up nutrients. By its Lower course, the Tualatin River is broad and slow, laden in nutrients and exposed to significant sunlight due to the loss of riparian canopy; in these reaches, problems with algal growth begin to express themselves.

The geologic history of the Tualatin Valley also strongly influences water quality within the basin. The layering of various basalt flows with deposits of organic material from the Bretts Floods and loess soils arriving from previously glaciated regions of Washington State combined to create perfect anaerobic conditions for the mobilization of phosphorus into the groundwater table. This phosphorus laden groundwater is funneled along the basalt lines to areas beneath the riverbed where it then seeps into the river system, contributing to high nutrient levels.

Oregon's Mediterranean climate further contributes to the growth of nuisance algae within the basin, creating low flow conditions during summer months. During the winter, Oregon receives the substantial precipitation its climate is most well-known for, but summer months tend to be hot and dry due to the orographic effects of the Coast Mountains, which trap precipitation in Tillamook County. Unlike other areas of the state, Washington County does not form a substantial snowpack to meet human water needs or to contribute to summertime river flow. Increased sunshine due to reduced numbers of cloudy days during summer months also contributes to higher rates of evaporation and transpiration within the basin.

The hydrology and geomorphology of the Tualatin River system greatly affect both water management and algal growth. The types and distribution of water resources within the basin have been heavily modified by human activity within Washington County, dividing the land uses into three belts:  forested uplands, agricultural lowlands and urban development. The transformation of Washington County land-uses has impaired the natural floodplain through drainage and the introduction of impervious surface, which have led to a reduction of surface water storage in the form of wetlands and marshes. As a result, the system has become flashier over time, requiring the creation man-made reservoirs to capture winter time precipitation to prevent flooding.  These reservoirs have become a key part of both the 'natural' and the managed hydrology of the system.  Additionally, tributary streams within the system have been straightened and engineered to export water from agricultural and urban areas more efficiently, reducing stored flow that would otherwise reach the river during warmer months. The morphology of the Tualatin River itself through its various courses combines with these changes in storage within the basin to create lower, slower flows in the Lower reaches of the river during the summertime months unless flow is artificially augmented from reservoir supplies.

An understanding of the life cycle and ecological role of algae is critical to designing successful flow management strategies for control of algal growth within the Tualatin basin, and thus these factors are explored within the context of the stream continuum. Algae require high inputs of sunlight and nutrients for their photosynthetic activities, which are facilitated by warm water temperatures and long residence times, making summertime low flow conditions ideal of algal growth.  The morphology of the single-celled planktonic green algae and their limited motility can be exploited by using flow management techniques to increase disturbance of microhabitats, shorten residence times, decrease water temperature and dilute nutrient inputs. Because flow management captures winter precipitation and redistributes flow throughout the year, it can be utilized to further interrupt the connection of algae to the floodplain and thus further impair the development of large algal communities during summer months. However, algae provide a number of benefits to both in-channel and floodplain communities in terms of underpinning the food chain, cycling nutrients and positively conditioning water quality during their growth; thus, management activities to limit growth must be balanced with other ecological goals. Finally, flow management efforts must focus on the interaction of low regime and the factors discussed above in order to generate suitable results.

Understanding trends in water quality within the Tualatin basin since 1986 is another important factor in assessing the impact of water quality and flow management on ecosystem services and human well-being. Tualatin basin water quality reflects the impact of several human activities within the basin, and over time, has been improving in most areas. Research by the US Geological Survey in the Tualatin basin indicates that algal growth in the Lower section of the river as measured by chlorophyll-a can reach problematic levels when stream-flow declines below 300 cfs in conjunction with other summertime conditions favorable growth. By the late 1990s, it became clear that these poor water quality results were driven by additional phosphorus inputs beyond the point source discharges from WWTPs, including such disperse anthropogenic sources as urban and agricultural runoff as well as environmental inputs from tributaries and in-channel seeps of phosphorus-laden groundwater. WWTP return flows, valued by water quality managers for the volume of flow returned to the system within the critical Lower reach, continued to deliver a significant proportion of phosphates during the 1990s despite plant improvements, particularly where plant upgrades had not yet been completed. The relationship of the summertime algal bloom and dissolved oxygen levels presents complicated flow management concerns throughout the course of the summer as the Lower reach of the river has tended to display low dissolved oxygen levels over time.

B. Brief History of Water Quality Management

- **Although a long standing history of algal growth exists in the area, water quality problems in the Tualatin basin grew beyond tolerable levels by the 1980s, presumably due to increased point source pollution of the river from waste water treatment plants (WWTPs) that were largely unregulated prior to a 1986 lawsuit compelling greater protection.**

In 1986, John Churchill was fed up with algae. Every summer, the former EPA employee and resident of the Tualatin River Valley had seen the river choked with the prolific autotrophs from June through September, interfering with the aesthetic beauty of the river, recreational use and drinking water quality. The river had most likely been that way for most of the years he lived west of Portland. One can imagine that he may have wondered – 'has it always been this way?' This is a question with no short answer, just as there has been no simple solution to modern water quality issues in the basin.

One might summarize the history of water quality before 1986 in the Tualatin by noting that algae has always played a role in the system, with that role becoming increasingly problematic during modern times. Early European and Canadian settlers to the region noted the river's greenish hue, and its slow, sluggish course is in fact the source of its Native American name. However, low summertime flows and high levels of algal growth apparently were not so sever as to interfere with the uses of the early settlers, who relied on the river primarily for irrigation and navigation. During the early 20th century, the river was in fact a tourist attraction, despite its greenish cast. However, as urban development and population pressure increased after the World Wars, the river's water quality became the focus of some scrutiny, with emphasis on waste water management.

- **During the early 1900s, Washington County was served by a number of small, less technologically sophisticated WWTPs which did little to remove nutrients from outgoing effluent despite the fact that in the 1970s, the Tualatin River had been identified under federal law as suffering from impaired water quality to such a great extent that establishment of a total maximum daily load (TMDL) for these nutrient pollutants would be required to guide water quality management efforts.**

Prior to the 1970s, Washington County was served by several small wastewater treatment facilities – located on tributaries to the main-stem river near the communities they served, these facilities were not very technologically advanced and released substantial amounts of nutrient waste to the system through their effluent. Consolidation of these facilities and release of managed flow from Hagg Lake offered some early relief from water quality impairment, but the continued strain of population growth outpaced improvements (Bonn 2008). Responding to the 1972 amendments to the CWA, DEQ listed the Tualatin River as water quality limited, that is, as a stream that was failing to meet the legally fixed standards despite use of standard technology to control effluent from point sources. Once the river had been placed on what is commonly referred to as the 303(d) list, the CWA called for identification of the designated uses of the river as well as impaired water quality parameters in preparation for assessing the total maximum daily load (TMDL) of various pollutants that could be allowed consistent with achieving the designated use. After the overarching TMDL for the river for any pollutant was determined, sources of that pollutant were to be identified and the total permissible load divided amongst them. This task fell to state environmental agencies, but during the 1970s and early 1980s, most states did not proceed beyond listing streams as impaired – this trend included Oregon. In the early 1980s prior to the lawsuit, Oregon DEQ twice more listed the Tualatin River on the 303(d) list due to low dissolved oxygen concentrations and nuisance levels of algae. By this time, designated uses had been identified for the river, including its aesthetic quality and use for swimming, both impaired by the conditions created when algal growth developed into unsightly algal blooms (Bonn 2008). That TMDL was not voluntarily implemented and the 1986 lawsuit set in motion a lengthy and contentious process to set a numeric criteria for total phosphorus in the main-stem river which triggered debates about the relative value of reducing nutrient inputs as the risk of further diverting return flow during the dry summer months.

After investigating the causes of these undesirable conditions, Churchill decided something had to be done. Assuming that the phosphorus laden effluent from the waste water treatment plant (whose operations were barely regulated at the time) must surely be the driving factor, Churchill along with the Northeast Environmental Defense Center successfully sued the Oregon Department of Environmental Quality and the U.S. EPA for creation of a total maximum daily load for phosphorus on the Tualatin River. Their aim – to manage algal growth during low summer flows to prevent blooming by essentially starving the algae, restricting the phosphorus necessary for growth – met with heavy political resistance from the beginning, requiring a twenty year process to set both a basin maximum daily load and permit limitations on the waste water treatment plant that had any hope of success. Along the way, participants in the process came to discover the natural relationship between water quality and water quantity – that is, the role that the physical characteristics of the river and its basin play in providing the habitat in which algae grow.

NEDC filed suit against U.S. EPA under the CWA in December of 1986 over the lack of TMDLs for the Tualatin River. Although it is the responsibility of state agencies to set TMDLs, where they fail to do so, the CWA requires U.S. EPA to step in and set them for all impaired waters. In this case, Oregon DEQ was joined as a co-defendant. Ultimately, the litigation was settled by the parties with the understanding that Oregon DEQ would establish appropriate TMDLs for all impaired water quality conditions by the end of the decade (Bonn 2008).

The process to set the TMDL for the Tualatin River was led by Oregon's Department of Environmental Quality (DEQ), rather than by EPA, and was conducted in conjunction with the regional stakeholders (whose role was later formalized by the appointment of Designated Management Areas for agriculture, forestry and urban uses). Debate over the numeric criteria occurred in many arenas, from public town hall meetings to newspaper articles and editorials to internal DEQ decisions. While the process of setting the TMDL was too involved to recount in detail here, some of the options considered along the way illuminate water quality management decisions made later. From the earliest stages, the focus was on reduction of nutrient loads (particularly phosphorus) to reduce algal growth and prevent algal blooms in the basin.
As the initial TMDL was debated over the course of 1987 and 1988, stakeholders proposed various methods for reducing phosphorus in the Tualatin River (The Oregonian August 15, 1987).

In January of 1988, DEQ's studies indicated that an overall limit of 0.05 mg (TP)/L to 0.15 mg (TP)/L of phosphates in the river would be sufficient to control algal growth in the river, suggesting that perhaps limitations on discharge of waste water to the river by the sewerage agency was the solution. At that time, studies showed that levels of phosphorus in the river ranged anywhere from 0.2 to 0.6 mg (TP)/L. According to John Churchill, plaintiff in the original lawsuit and generally considered the voice of the varied environmental groups, algae would grow steadily at 0.15 mg (TP)/L and significant reductions in growth would occur under 0.10 mg (TP)/L during the warm summer months. By contrast, the sewerage agency advocated for a much higher limitation of 0.15mg (TP)/L for phosphorus loading on the river, noting that the burden of such reductions would fall primarily upon it as the sole identified point source. Such an expectation could prove impossible to meet, and even if technology were available for such stringent reductions in phosphorus effluent, upgrades would be costly (The Oregonian August 15, 1987).

The sewerage agency suggested that if strict limits were applied, it would be more cost effective to divert return flow of effluent to the neighboring Willamette and Columbia Rivers, which due to their size, were not subject to such regulations. Although initial investment would be high (between $48-82 million for various proposals), existing treatment requirements for the summer months already cost the agency $2100/day – removing more phosphorus over longer periods of time would be even more costly. Other early options for decreasing phosphorus and increasing water quality along river included use of treated wastewater for irrigation, increasing flow augmentation during the summer with water stored in reservoirs, further limiting emissions from waste water treatment facilities, reducing impoundment in Lake Oswego and controlling non-point source pollution (The Oregonian August 15, 1987).

- **Social, economic and political factors became serious considerations alongside scientific data during this lengthy debate, as the cost to WWTPs of developing technology necessary to meet the criteria proposed by environmentalists were balanced against the value of this return flow. In addition, changing environmental factors such as shifts in precipitation and temperature patterns as well as rapid population growth were discussed.**

The debate over the phosphorus standard and necessary WWTP upgrades occurred during an economic downturn as well. This created political tensions between development, the sewerage agency, DEQ and environmentalists, among others. Land use planning emerged at the beginning of the development planning process as a major bridge between development and the health of the river: citizens worried about development issues such as drainage and runoff simultaneously with concerns about the recession and other social issues. During 1987 and 1988, voters expressed concerns unrelated to water quality and management, including economic recovery, road maintenance, sheriff's enhancement districts, county communication including public access to board meetings, solid waste disposal, criminal justice, budget issues for the public library, probation officer labor disputes, and mental health services.

Still, the mandated Tualatin River cleanup was both a top priority for city mayors and a source of major uncertainty, and the reasons for undertaking the cleanup weren't apparent to everyone. Uncertainty about the economy and the benefits of a cleanup was coupled with uncertainty on how to proceed since the Tualatin basin was one of the first to face such a lawsuit for implementation of TMDLs. Conflict between upstream and downstream users became apparent early on in the process, with residents of the relatively wealthy Lake Oswego area of Clackamas County seen as demanding improvements in water quality provided by the tax payers and water users of Washington County upstream. In addition to conflicts between local users and local economic pressure, the state of Oregon was feeling the fiscal pinch as well.

The role of climate and rainfall was highlighted during the TMDL process as well, with a severe drought experienced in 1987 that raised questions about water quality and quantity management during the river's poorest conditions. Decreased summertime precipitation impacted both the natural flow of the river and decisions regarding flow augmentation, with more water used to augment flow during that summer, resulting in the lowest water level ever seen on Hagg Lake, raising public concerns regarding management of the reservoir for multiple uses including recreation and irrigation.

As a result of litigation and after vigorous public debate, DEQ eventually set the first summertime TMDLs for ammonia and phosphorus for the river, resulting in new NPDES permits for the wastewater treatment plants as the sole identified point source - even though inputs from non-point sources were considered significant, they were only informally addressed. (Jarrell 2003) In-river concentration of phosphorus exceeded 1mg (TP)/L on average – while there was consensus that 1mg (TP)/L was far too high, parties were divided on the appropriate limit. Environmentalists sought a level 0.03mg (TP)/L. USA proposed several versions of the rule, arguing most consistently for a 0.10mg (TP)/L standard that was considered technologically achievable.

Ultimately a compromise was reached – based on summertime flow rates of tributaries and the main stem, a limitation of 70 micrograms (0.07 milligrams) total phosphorus (TP) per liter was set for the warm, low flow season from May through the end of October when algal growth exceeded acceptable levels (Jarrell 2003). Total phosphorus allocations were made for non-point sources including urban development, agriculture and forestry, but enforcement mechanisms were lacking (Bonn 2008). DEQ set loads for streams in forested areas at 0.02mg (TP)/L, for agricultural areas at 0.05mg (TP)/L and for the urban streams at 0.07 mg (TP)/L, all designed to limit algal growth, restore beneficial uses and reduce violations of related criteria such as dissolved oxygen and pH. One of the first TMDLs in the nation, the Tualatin River instantly became a test case for the formation and enforcement of future TMDLs, and potentially a model (Jarrell 2003).

Even at a limit of 0.10 mg/L, the sewerage agency had determined it would be more cost efficient to pump water from the Durham treatment plant to the Willamette River and from the Rock Creek treatment plant to the Columbia River. A more expensive option involved pumping water from the Durham plant to Rock Creek, and then both flows combined to the Columbia. The sewerage agency acknowledged that it could alternatively begin treatment with lime at both plants for approximately $54 million, but that scaling up the operation would take time, would leave less water for return flow via effluent and would result in sludge which was costly to dispose of. Finally, the sewerage agency did propose as an alternative that all of the effluent from both plants could be used for irrigation of crops not used for human consumption, provided sufficient demand could be found (The Oregonian, January 20, 1988).

Each of these options, of course, resulted in decreased flow back to the Tualatin River during the summertime months. On all sides of the debate, flow was acknowledged to be a critical component of the problem. The larger rivers in the region could accommodate flow transfers bearing nutrient concentrations leaving Durham and Rock Creek treatment plants after tertiary treatment because of their ability to better dilute these pollutants. During summer months, the low flow of the Tualatin River could not provide such dilution and thus the nutrient concentrations contributed to the algal growth problems. However, summertime flow rates in the Tualatin River were already being augmented by these return flows from the waste water treatment plants – this additional flow helped to maintain the uses of the river during months when natural river flow might be too low to support them. Exporting the nutrient laden flow, therefore, would substitute one water quality problem for another – in either case, algal growth rates could be high, and in the case of export of return flow away from the Tualatin, other uses could be impaired (The Oregonian May 5, 1988). However, the relative importance of flow as opposed to phosphorus loading was disputed. While environmentalists took a hard line on concentration limits, the sewerage agency noted that increased flow could protect the river's health, and that some of their options protected flow better than others. Lime treatment would cause the least disruption of return flow, and obviously diversion to other rivers would cause the most. Use as irrigation water would cause a reduction in flow greater than immediately obvious as little flow returns from agricultural fields during the summer due to a number of factors (high losses to evapo-transpiration, conservative irrigation practices to protect field against erosion, etc.).

Aware of the effect that reduced flows to the Tualatin would have during the summer when natural flow is already low, the sewerage agency proposed a standard of 0.15 mg/L of phosphate. At that limitation, the Rock Creek facility would meet NPDES standards for release of effluent to the Tualatin. The existing treatment level at the Durham plant, however, would result in effluent that could not meet the standard and would have to be exported to the larger river systems via a pipe. The sewerage agency proposed that this plan would be the only cost affordable way to meet the new water quality standards if they were made more rigorous than existing standards while at the same time minimize reductions of return flow to the Tualatin (The Oregonian January 20, 1988). By April, sewerage agency officials were citing Clean Water Act provisions that allow avoidance of cleanup if the cost is economically unfeasible in their arguments against the more stringent standard (The Oregonian April 22, 1988).

To further complicate matters, some argued that the standard for phosphorus shouldn't be a numerical criterion at all, but rather should be merely descriptive, allowing different levels of phosphorus for different flow conditions. The sewerage agency joined this position, seeking a standard that regulated nutrients based on both the physical appearance of algae (descriptive) and a numerical criterion on a sliding scale dependent on flow levels. The sewerage agency also called for strict control of other non-point sources of nutrients, particularly agriculture and forestry (The Oregonian April 22, 1988).

Should DEQ's recommended stringent numerical criteria be adopted, the sewerage agency was already looking to alternatives to nutrient reduction that may help bring them into compliance with regulations. One option for meeting a permit requirement of 0.05 mg/L or 0.1 mg/L would be to increase flow augmentation during the summer months. This option would not only employ the old ‘pollution dilution' strategy, but would also decrease flow temperature and residence time, as well as increase the force of the flow. Such increased flow augmentation would go hand-in-hand with a unified sewerage district under which the sewerage agency took responsibility for all phosphorus loading from urban sources. Such a plan would cost about the same as flow diversion but would be implemented over several years, spreading the costs (The Oregonian April 22, 1988).

Officials from other levels of government also weighed in on the debate. For example, the city of West Linn, located near the mouth of the river and within the area troubled annually by algal growth, supported the more stringent 0.05 mg/L level (The Oregonian May 5, 1988). The federal EPA also expressed some concern over the establishment of the phosphorus criteria, although their concerns focused primarily on the time frame over which phosphorus would be regulated each summer. EPA was concerned that water quality concerns in Lake Oswego might be neglected, and directed DEQ to report on how enforcement from June to September of a 0.1

mg/L limit might affect water quality there. EPA also expressed a strong preference for a consistent limit as opposed to one scaled to flow conditions within the river as proposed by the sewerage agency, and sought regulation of the major tributaries as well as the main stem in order to address non-point source pollution (The Oregonian June 2, 1988).

- **The numeric criteria ultimately decided upon represented a compromise between the scientifically recommended limitation and the economically efficient recommendation, and was based on the limited but best available data provided regarding sources and transport of phosphorus within the system.**

In response to EPA concerns and those expressed at the public hearings, DEQ revised its proposed limit to 0.07 mg (TP)/L for phosphorus and extended the proposed period of regulation to May through October. (The Oregonian July 4, 1988) With a new TMDL in place, the sewerage agency anticipated changes to the NPDES permit and proceeded to consider options which would allow it to comply with a standard of 0.07 mg (TP)/L of phosphorus in released effluent. In 1988, the technology contemplated for removal of more ammonia and phosphorus was expected to increase production of sewage sludge to 1135 tons per day, at an additional cost of $6-8 million for on-site dewatering. Thus, in response to the 1988 TMDL, the sewerage agency initially continued to advance its proposal of piping 16 million gallons of water from treatment plants to the Willamette River every day instead of returning that flow to the Tualatin. Environmentalists and DEQ remained critical and skeptical, respectively, of plans to divert waste water effluent to another river, which would result in the loss of approximately 20% of the Tualatin’s flow in summer months (The Oregonian September 5, 1988).

After DEQ refused approval of this option, the sewerage agency had backed down and re-strategized, approaching the Washington County Board of Commissioners for funding of a comprehensive 2 year study of compliance options. Specifically, the funding would be used to test two methods of treating waste water (aluminum sulfate and lime) to meet the 0.07 mg (TP)/L phosphorus limitation, thus allowing discharge of the entire flow directly to the Tualatin. The sewerage agency planned to test lime treatment at the Rock Creek plant along with ferric chloride, and possibly aluminum sulfate at one of its other plants. Already, $20,000 had been invested in studies of the use of wetlands for tertiary treatment of waste water. The $400,000 study also included evaluations of the plan to export waste water flow to larger rivers, increasing flow augmentation to increase dilution and land application of waste water as irrigation water. Once the effectiveness and cost of these four options had been evaluated, the sewerage agency intended to have a plan in place by 1991 with capital improvements to enact the plan following soon after (The Oregonian February 14, 1989).

Planning moved to capital improvements far more quickly than anticipated. In July 1989, the sewerage agency, with funding from Washington County, began improvements to both the Durham and Rock Creek treatment plants to reduce flooding during the winter, handle increased capacity and improve treatment standards. The Durham plant in particular benefitted from improved technology to remove additional phosphorus from treated waste water. Construction of new sewerage lines allowed the agency to shut down older, inefficient plants and consolidate treatment at the renovated plants (The Oregonian July 26, 1989). The addition of more extensive alum treatment at the operating plants would provide a short term solution for removal of phosphorus to meet the newer limits, but presented problems of its own. The sewerage agency estimated, however, that even with the additional cost of dealing with the sludge, alum treatment translated to approximately $5 a month less in rate hikes than effluent diversion to a larger river, an option that was still considered on the table as part of a longer term plan being crafted by the sewerage agency.

- **Improvements to WWTPs aimed at meeting the new TMDL resulted in quantifiable improvements in ambient water quality and the reduction of phosphorus loads, although persistent problems remained that were difficult to explain based on existing information.  More comprehensive studies of the sources and transport of phosphorus undertaken during the early management years indicated that point source control of phosphorus may not be adequate to reduce the occurrence of nuisance algal growth.**

As a result of these efforts to manage water quality, costly and controversial though they were, ambient water quality monitoring near the end of the decade revealed vast improvements in both nitrogen and phosphorus loading.  However, problems emerged with temperature, dissolved oxygen and bacteria continued (Bonn 2008).  In June of 1993, water quality testing for the river revealed the ammonia and nitrogen standards were being met, while more time was needed to implement the total phosphorus TMDL.  Options beyond merely updating aging WWTPs and storm sewer systems had to be considered, particularly in light of emerging information about the source of nutrients in the river system.

For although progress under the assumptions of the first TMDL was steady, a 1999 report by USGS turned attention to a more comprehensive study of the sources and transport of nitrogen and phosphorus.  The study revealed substantial flaws in the assumption that wastewater treatment plants were the main source of these constituents and called into question particularly how realistic the .1 mg/L TMDL for phosphorus was (USGS 1999).  This timely revelation seemed to explain the limitations faced in efforts to improve water quality through compliance with that stringent TMDL such that in 2001, DEQ issued revised TMDLs for phosphorus and nitrogen meant to better address algae and dissolved oxygen problems in light of the better understanding of the system as a whole. New TMDLs were written for temperature and bacteria on both the main-stem and on its tributaries. In 2004, DEQ issued one integrated, municipal watershed-based NPDES permit to CWS covering all the WWTPs as point sources, the municipal separate storm sewer system (under the MS4 permit), and industrial stormwater from the Rock Creek and Durham facilities. By obtaining the MS4 permit, CWS was able to institute a system of water quality trading that allowed riparian restoration projects to be counted against the thermal load limits in the river. Such riparian projects provided multiple improvements in ecosystem services, including shading and cooling of the channel, increased filtration of overland flow (lowering temperature and nutrient content before entering the stream), reduction of erosion and stream bank stabilization. By holding the unified permit, CWS was further able to credit summer releases of water stored in Scoggins Reservoir against all of its permit requirements since such flow augmentation diluted concentrations of nutrients in the stream and lowered water temperatures (Bonn 2008).

Therefore, under the MS4 permit, t flow augmentation became a formal part of water quality management. This work will investigate these decisions about the pattern of releases of water stored in reservoirs to artificially enhance flow during the summer months more closely for their effect on water quality.

C. Description of the Study Area: Geology, Landforms, Climate and Water Resources

- **Understanding the physical characteristics of the watershed is essential to generating sound policies for today and for the future.**

When considering water quality from either a watershed approach or an ecosystem assessment, understanding the physical setting of the river and the landscape allows a better understand of how the river flows and what flows through it. A summary of more extensive data and research here helps the reader to understand conclusions drawn later, but more detailed information could certainly be obtained. The bird's eye view of conditions within the Tualatin River basin presented here is modeled on the presentation of the study area given in Willamette River Basin Planning Atlas: Trajectories of Environmental and Ecological Change, a compendium of information and research intended to inform the decisions of natural resource managers throughout the larger basin. Like our work, the Planning Atlas attempts to provide background information fundamental to good decision making within the basin while also providing information and analysis necessary to adapt to environmental changes such as population pressure and shifting climate. The information provided in the Planning Atlas on location of the basin, landforms, climate and water resources provides the basis for later discussion of larger factors. To these topics we add information regarding the geology and soils of the basin, which have largely contributed to the delivery of nutrients to the system.

Location of the Tualatin River basin:

The Tualatin River basin is a sub-basin of the Willamette River valley, located in Washington County in northwestern Oregon. Over 83 miles, the Tualatin River drains a 712 square mile (1,844 $km^2$) patchwork of woodland, cropland and urbanized landscape across varying gradients. It descends from the ancient, weathering Coast Range with its combination of marine deposits and basalt flows through the loess soils of the valley to join the Willamette River, which itself drains north to the Columbia River and onward to the sea. The overall basin is delineated to the west by the Coast Range, to the south by the Chehalem Mountains, to the north by the West Hills of Portland, and to the east by the Willamette River and the Tualatin Mountains. Lying between these ranges and the Willamette are miles of flat, rolling plain that make up approximately 60% of the basin and where streams experience little change in elevation with gradients well below 1%. One framework commonly used in the policy arena for conceptualizing the geography of the overall watershed is to consider various sub-basins: Upper (in the Coast Mountains above the Scoggins Creek Dam and Hagg Lake to Gales Creek), Middle (from Hagg Lake to Rock Creek), Lower (through the valley floor to the confluence with the Willamette), and Tualatin Mountain tributaries. The differences between these areas themselves are a significant factor in the water quality issues within the basin and thus deserve somewhat more attention.

- **The Upper course of the Tualatin River channels runoff from forested areas in a channel of cool water heavily shaded by a dense forest canopy moving at rapid velocity over a sheer basalt bed and is not heavily affected by algal growth.**

- **During its Middle Course, the Tualatin River loses velocity as it erodes more of its sedimentary bed and banks, meandering across the landscape and picking up nutrients.**

- **By its Lower course, the Tualatin River is broad and slow, laden in nutrients and exposed to significant sunlight due to the loss of riparian canopy; in these reaches, problems with algal growth begin to express themselves.**

The Upper reaches of the Tualatin River often reflect a greenish hue originating not from the growth of algae (which is restricted there not by nutrient limitations but by lack of sunlight and colder temperatures) but from the erosion of rock and transport of sediments downstream. This mobilized sediment can carry with it various forms of phosphorus, and thus land use practices in the Coast Range related primarily to forestry can be an important factor in the phosphorus budget. The gradient of the river changes substantially along its course, from a slope of 22 ft. /mi (24 m/km) in its headwaters to much gentler gradients of 0.08 feet per mile in the lower reaches.

When combined, the low lying, narrow alluvial plains of the Coast foothills make up more than a tenth of the watershed and exert their influence on the course of the river by dramatically reducing the gradient of the river and thus the velocity of the flow. Throughout this Middle sub-basin, the river meanders 29 miles, picking up several mid-gradient tributaries as it passes by the Tualatin and Chehalem Mountains.

In the Lower section of its course, the river continues to receive basin drainage through several tributaries while both its gradient and velocity continue to decline as the river widens and takes on a greater incidence of meander. This is where the problematic Reservoir Reach is located and where water quality suffers on an annual basis from algal growth of varying intensity, often resulting in the formation of blooms. Because the valley experienced little glacial activity during the Pleistocene, it is comprised of a vast wide plain with few hills of any significance. Like the remainder of the Willamette Valley, the Tualatin sub-basin was carved not by ice but by running water, resulting from the ever-present climatic influence of the Pacific Ocean to the west and the orographic influence of the Cascade Mountains to the east. The resulting 97 square miles of alluvial valley floor is marshy or swampy, with poor drainage where not otherwise anthropogencially enhanced for agriculture or development purposes.

Geology:

- **The geologic history of the Tualatin Valley strongly influences water quality within the basin.**
- **The layering of various basalt flows with deposits of organic material from the Bretts Floods and loess soils arriving from previously glaciated regions of Washington State combined to create perfect anaerobic conditions for the mobilization of phosphorus into the groundwater table.**

- **This phosphorus laden groundwater is funneled along the basalt lines to areas beneath the riverbed where it then seeps into the river system, contributing to high nutrient levels.**

The geology of the Tualatin valley is strongly influenced by the same forces that produced its geography, and is critical to understanding nutrient transport and cycling within the basin. The valley is essentially a broad bowl ringed by mountains, a result of tectonic forces warping the valley floor. This bowl has filled with igneous and sedimentary rocks covered over with wind-blown loess soils and which is underlain by a basalt basement. When considering the Tualatin Valley as a cross-section, three basic zones of parent material are observed: a basalt layer of bedrock, a layer of fluvial materials deposited by the Missoula floods, and a layer of loess soils eroded and transported from Eastern Oregon by wind.

The bottom most layer of this valley is comprised of basalt flowing from the same volcanic activity that formed the Coast Range. Like that from higher elevations within the basin, this basalt is rich in minerals containing magnesium, calcium and iron, but is slow to weather or erode. Above this at depths of 1000ft below the surface lies the younger and therefore less altered Columbia River Basalt lies in several layers so thick they rise to the surface in some places; these layers are almost entirely uninterrupted by the appearance of sedimentary rocks. A third, still younger basalt flow forms the top of the Portland Hills. The Boring Lava flow lies above the Troutdale formation (a layer of sediment overlying the Columbia River basalt, further discussed below) along the Tualatin Valley side of the Portland Hills from elevations of 350 feet extending down to elevations of 150 ft. (lying beneath 50 additional feet of valley fill).

Unlike the basalt found at higher elevations, most of the volcanic basalt in the valley has been shielded from the weathering effects of the atmospheric and hydrologic cycles by overlying layers of sediments and organic material. The deposition of pre-Columbia basalt and sediment was eventually covered over by the Columbia River Basalt, which was again layered over by sediment and finally by the Boring lava flow. The alternating of these layers reflects alternating periods of volcanic activity and of erosive activity. Again, the general pattern of geology over the entire catchment is more critical to our question of stream water quality issues than are the specifics at any given point within the catchment.

Over the volcanic basalt (or rather, between its layers) one finds primarily sediment, deposited in several ways. A small proportion of this sediment is local in origin, having weathered from volcanic rocks not shielded in the same manner as the basalt underlying the valley floor. The pattern of cooler, wetter climate augmenting glacial advance followed by warmer climate producing glacial retreats and concomitant flooding literally laid the valley floor with the shale, clays, sandstone and siltstone we see today surrounding the Tualatin River. This period of cooler temperatures and higher precipitation led to more erosion of mountain soils and deposition in alluvial areas – this sediment remains today in the terraces and floodplains of the valley. Marine sediments also play a role here, along with a sizeable proportion of more recent freshwater fill, deposited as the river works its floodplain back and forth, smoothing out the surface of the main valley floor.

It is important to know how the layers of basalt and sediment described above conforms to the syncline which gives the valley its bowl-like shape. As the sedimentary and basalt layers described above follow the path of the syncline, areas of greater conductivity for the flow of subterranean water move both to greater depth in the soil column and simultaneously towards the river bed. This in turn creates a pressure head on the water table beneath the bed which, when combined with oxidation activity in decaying organic material, leads to conditions that are favorable to the release of high concentrations of phosphorus to the river.

Soils:

Overlaying the deep geologic foundations is a final cap of fine grained highly erodible, intensely phosphorous laden loess, known more descriptively as 'rock flour', deposited from the breath of winds sweeping across former glacial plains in eastern Washington to be trapped in the bowl of the Tualatin Valley. As recognized by the earliest settlers on, these loess deposits provide highly fertile and productive soils which support millions of dollars of agricultural revenue annually so long as the naturally poor drainage patterns are altered to more favorable conditions.

The mountainous reaches of the Tualatin headwaters pass through soils dominated by inceptisoils, alfisoils and ultisols on steep, forested slopes that are characteristically dark, loamy or clayey. By contrast, the valley is dominated by alfisols, ultisols, inceptisols and vertisols near the West Hills and valley, where the floodplain deposits tend to be dark, silty and acidic.

The geographic relationship of the Tualatin Valley to the Pacific Ocean results in a hydrologic system driven primarily by precipitation.

Climate:

- **Oregon's Mediterranean climate further contributes to the growth of nuisance algae within the basin, creating low flow conditions during summer months.**

- **During the winter, Oregon receives the substantial precipitation its climate is most well-known for, but summer months tend to be hot and dry due to the orographic effects of the Coast Mountains, which trap precipitation in Tillamook County.**

- **Unlike other areas of the state, Washington County does not form a substantial snowpack to meet human water needs or to contribute to summertime river flow.**

- **Increased sunshine due to reduced numbers of cloudy days during summer months also contributes to higher rates of evaporation and transpiration within the basin.**

The forces of climate and weather help to mobilize these sediments and free nutrients trapped within these formations, both for transport within the stream channel and for uptake by algae, and therefore they must be considered along with the physical background of the basin. The Mediterranean climate of the valley resembles that of the larger Willamette Valley and of western Oregon generally, with cool, wet winters and warm, dry summers. Trapped between two mountain ranges, the Tualatin Valley suffers from reduced precipitation in the summer when the orographic effect of the Coast Range dominates humidity and precipitation patterns and from excessive rain in the cooler months when high levels of humidity overwhelm this barrier only to be trapped again by the much loftier Cascades. The presence of the ocean regulates seasonal temperatures as well, with highs averaging historically in the low 80s and winter temperatures too mild to support substantial snowfall in the low elevations of the Tualatin Valley.

Within the confines of the valley, precipitation and temperature patterns vary with elevation and developed land use, with the city of Portland and its suburbs subject to higher temperatures on average than the agricultural valley and forested uplands, and with greater precipitation falling at higher elevations. Annual precipitation across the basin reaches a high of 110 inches to the west where elevations are higher to a low of 37 inches deep within the valley. The effect of climate in the valley varies by season as well as by geographic location, with summers tending to be substantially warmer and drier than the cooler rainy season for which the region is known - 84% of the annual precipitin for the region falls between November and March alone. This seasonal precipitation results in a landscape dominated by seasonal tributaries draining the landscape with high flows during the rainy season but remaining nearly dry during the summer months. Although the Tualatin Valley receives some winter snowfall, particularly in the higher elevations of the Coast Range, the impact of snowpack on annual hydrologic budgets is negligible, with total snowfall for the valley ranging just 5-10 inches annually.

Water Resources and Land Uses:

- **The hydrology and geomorphology of the Tualatin River system greatly affect both water management and algal growth.**

- **The types and distribution of water resources within the basin have been heavily modified by human activity within Washington County, dividing the land uses into three belts: forested uplands, agricultural lowlands and urban development.**

- **The transformation of Washington County land-uses has impaired the natural floodplain through drainage and the introduction of impervious surface, which have led to a reduction of surface water storage in the form of wetlands and marshes.**

- **As a result, the system has become flashier over time, requiring the creation man-made reservoirs to capture winter time precipitation to prevent flooding. These reservoirs have become a key part of both the 'natural' and the managed hydrology of the system.**

- **Additionally, tributary streams within the system have been straightened and engineered to export water from agricultural and urban areas more efficiently, reducing stored flow that would otherwise reach the river during warmer months.**

- **The morphology of the Tualatin River itself through its various courses combines with these changes in storage within the basin to create lower, slower flows in the Lower reaches of the river during the summertime months unless flow is artificially augmented from reservoir supplies**.

An understanding of how this precipitation is channeled, stored or exported through hydrologic functions is the next essential step to forming an understanding of water quality issues within the basin. This cycle begins with precipitation falling on the hill slopes and valley floor, where it either percolates slowly to groundwater recharge or flows overland (or just below the surface) as urban, agricultural or forested runoff. This runoff makes its way to tributaries lying in the lowest points of the valley, which are consolidated into the main-stem river channel. Some of this precipitation is stored in both natural and man-made lakes and wetlands for future use; some is diverted for use directly from the channel itself. Water withdrawn in these ways for consumption is either lost to the system by the nature of the use or by evapo-transpiration, or it eventually makes its way back to the channel. Such returning flows can re-enter the system through the land (again as runoff from urban or agricultural uses) or through waste water treatment facilities. While within the system, the chemistry and quality of this consolidated rainfall is influenced by the characteristics of the channel flow, of its bank and of its bed, as well as by the river's relationship to its floodplain. Indeed, even the length of time during which the water is retained within the river channel before exiting the system into the larger Willamette River plays a role in the overall character of the system.

Under current conditions, 80% of the precipitation falling in the basin lands in the upland forested mountains, generating as much as 77,492,444.26 cubic meters of runoff from 136 square miles (352,238,383 square meters) of land, depending on how much infiltrated to groundwater storage. The remainder of the basin is split between agricultural use (79%, or 454 square miles, or 1,175,854 602.1 square meters) that is generally pervious but yields no return flow during summer, and urban uses (21%, or 122 square miles, or 315,978,549.46 square meter) which by contrast are nearly fully covered with impervious surface and during storm events, yields very flashy overland flows. Thus, nearly all of the water falling in the urban area during the summer will return to the stream-flow, rather quickly delivering up to 25,278,283.9568 cubic meters of flow. These figures illustrate the general trend of the system to export water from the upland hills to the valley floor throughout the year, to store or export water from the valley during the rainy season, and to export water from the basin during the summer months to extent that stored precipitation is available.

In addition to storage and export capacity of the system, the Tualatin River is subject to substantial loss due to evapo-transpiration and consumptive use during the summer months, particularly at the drinking water outtake in the headwaters of the stream and throughout the sparsely canopied lower reaches. Runoff in the basin is consolidated into the flow of the eight main tributaries of the Tualatin River, seven of which discharge into the middle course just above the reservoir reach and which together contribute most of the flow to the river, about 91% above Dairy Creek. The relative importance of each tributary varies during the drier months, with Dairy Creek dominating in late spring and early summer, shifting to dominance by Scoggins Creek later in summer as release of irrigation water from the Scoggins Lake reservoir increases. The contribution of Dairy Creek from July through September can drop below 20% of stream-flow. Similarly, the naturally occurring flow contributions from other creeks in the system diminish as summer heat and dryness persist (USGS 1999). Return flow within the Tualatin River basin during the summer is generally limited to water recycled to the system through treatment processes with very little flow return from agricultural fields due to careful management of sparse resources.

The current river system exists on the site of a former lake bed rich in sedimentary and organic deposits which have contributed over the decades to the emerging morphology of the river system. The river has slowly carved its course through the materials while at the same time plant material large and small has slowly worked its way downstream, periodically becoming log-jammed and creating temporary dams that forced the rivers course this way and that, reworking the flood plain and creating backwaters, marshes and swamps. Environmental change within the basin continued even as these deposits began to be purged from the system or buried beneath wind-blown loess deposits thanks to the presence of beaver, which reduced vegetation substantially, and the heavy winter rains, which resulted in annual flooding of the alluvial plain.

Human settlement has also directly affected the hydrology and morphology of the river, as Native American tribes once burned the flood plain to maintain better hunting grounds and early European settlers began to drain the land for agricultural uses. More modern alterations to the landscape have resulted in the increased presence of impervious surface, straightening of some sections of the channel and the removal of wetlands and other floodplain features in the course of urban development. Soil erosion and sediment delivery continue in modern times to be of particular concern in the Tualatin Valley due to the unusually high concentrations of labile phosphorus adsorbed to soil particle surfaces in valley soils – phosphorus that literally lies in wait of water in which it will be released until equilibrium is achieved (Abrams and Jarrell 1995). The heterogeneity of the landscape and land-uses surrounding the Tualatin River throughout its course translates to its current varied morphology along its course from narrow, fast moving headwaters to broader, slower segments in the foothills, then on to meander and reservoir reach before meeting with the Willamette.

Residence time, a critical factor in algal growth cycles, is directly related to characteristics of flow such as velocity which are in turn affected by both quantity of flow and channel morphology. In their 1999 study, CWS and USGS utilized dye-studies within the stream during low flow conditions to assess residence times to investigate the relationship between stream-flow and residence time (USGS 1999). When stream-flow is low (under 100 cfs), residence time in the reservoir reach ranges from 6 to 14+ days over 23 miles – by contrast, residence time for the entire river below mile 58.8 at moderate to high flow (100-300 cfs) can vary anywhere from 10 to 24 days. Put another way, in low flow conditions, a block of water can move through the reservoir reach somewhere between 1.6 to 8 miles per day, whereas the same block of water may move through the entire system under high flow conditions at 2.4 to 5.8 miles per day (USGS 1999).

In terms of both velocity and volume, stream-flow is a reflection of all the hydrologic processes discussed so far, including natural inflow, releases from the reservoirs, groundwater flows and return flows from waste water treatment. It varies seasonally with consumption and precipitation patterns. The volume and rate of flow are typically highest in the winter during periods of flooding, sustained at high levels in early spring with continued rainfall, and declining through the driest summer months to lows in August and September. These low, slow summer flows often exhibit thermal stratification, sedimentation and dissolved oxygen sags as well.

The naturally low summertime flow has been augmented in recent years by the releases of reservoir water owned by Clean Water Services which are the subject of this analysis. This water is released directly to the channel at Scoggins Dam to meet flow targets established in compliance with both the Clean Water Act and the Endangered Species Act which protect anadromous fishes and reduce the rate of algal growth and occurrence of algal blooms by controlling concentration of phosphorus, keeping temperatures and residence time low, and keeping velocity and discharge higher than natural. Such augmentation from Scoggins Reservoir within the basin and Barney Reservoir in the neighboring Trask Basin can exponentially increase the average natural summer flow (sometimes as low as 3 cfs) by 35 cfs or more to maintain a targeted average of 150 cfs, resulting in up to 3,000 acre feet of water per year imported from the Trask basin on average (typically in the late fall when reserved flow at Scoggins falls short of augmentation needs).

Due to the structure of the basin discussed above, seepage of phosphorus laden groundwater (generated by the movement of loess particles to anoxic zones created by decomposition of organic matter where phosphorus is easily released into the water column) through the streambed can be a surprisingly high source of phosphorus directly to the river. The rate of groundwater seepage into the channel is generally much lower in the basalt bottomed headwaters than in the sediment laden reservoir reach of the channel, and the contribution of phosphorus laden groundwater to the stream-flow during summer months in this reach can be of considerable significance when natural flows are otherwise lower in both volume and velocity. Doyle and Caldwell determined in 1996 that concentrations of phosphorus in groundwater could be quite high, and the CWS/USGS study confirmed that groundwater concentration of 0.15 milligrams per liter in shallow wells to 0.34 milligrams per liter in deep wells, with a maximum of 2.5 milligrams per liter at the interface between flood deposits and overlying sediments (USGS 1999). Interestingly, edge-of-channel wells near wetlands detected the lowest concentrations of phosphorus, most likely from shallow groundwater accumulated from very localized sources (indeed, many fed with WWTP tertiary effluent) and benefitting from additional phosphorus removal by wetland soils. All measurements taken in the study exceeded the TMDL of that time (0.07mg (TP)/L) but those near wetlands averaged 0.56 to 0.74 milligram per liter, whereas mid-channel wells yielded concentrations from 1.0 to 2.0 milligrams per liter (USGS 1999). Additional studies conducted by ORI and PSU confirmed these measurements, pointing to high concentrations of mobile P within 500 feet of the surface throughout the valley (USGS 1999; Wilson 1997). These studies indicate the important of stream-flow management in water quality management where natural background levels of phosphorus to the channel are high.

As a result of climate, population pressure and varying land use, surface water storage is extremely critical to water supply and water quality management in the Tualatin Valley. Seasonal variation in precipitation and evaporation in the Tualatin River basin drives such a reliance on lake, groundwater and reservoir storage of winter rainfall for those long dry summers, a situation which could become more severe as climate changes. Winter and spring rainy seasons contribute significantly the annual water budget and fluctuations in this precipitation affect both flooding during the rainy season and the likelihood of drought in the dry season. Recent trends indicate that the dichotomy between rainy and dry months is becoming sharper, with more of the annual rain falling during the winter in severe events. These trends also indicate that summers are becoming sunnier and warmer, with less precipitation and more evapotranspiration resulting in water deficits during these months. The combined effect of these changes in climate will be a shift in the plant and animal communities within the basin over time (Palmer 2004). With alteration of the landscape to foster hunting and agriculture historically, and growing population and urbanization in modern times, the naturally occurring surface water storage in wetlands and marshes has diminished over time, replaced by a system of man-made reservoirs, above ground storage tanks and other such devices. The loss of wetland and floodplain area has altered regulation of flow on the river as well, requiring management of wintertime flows to prevent flooding of economically valued land and in summertime to augment flows to improve water quality.

D. Life Cycle of Algae Present in the Tualatin System

- **Several traits of the green algae's in general can be exploited to control populations through flow management activities – thus, an understanding of their life histories and ecological niche is critical.**

Although management of nutrient pollution is certainly one key to curbing the growth of algae in the system and preventing blooms from developing, several other aspects of the algal life cycle can be affected by various water quantity and quality policies, particularly those related to interactions with other species and other chemical and physical factors affecting growth. An understanding of these relationships is particularly critical to consideration of flow management as a tool to maintain water quality. The following description of the life cycles factors critical to management of algal growth is modeled on similar discussions in other water quality management studies (Huggett 2010). That paper analyzed policy alternatives for the protection of anadromous fishes in the California Bay Delta. The life cycle description provided therein focused on the challenges of anadromous migration, smoltification, predation and species distribution that are particularly heightened by anthropogenic changes to the environment. Here, we explore the life cycle characteristics of green algae that are of particular interest when attempting to regulate that population, including morphology of algae and their motility, habitats and microhabitats, requirements for photosynthesis, relationship to the floodplain, temperature requirements, role in the riparian food web, positive and negative impacts on stream ecology, and the importance of flow regime.

Before discussing the aspects of algal life cycles critical to management of water quality issues, it is important to recognize how this issue has been approached to date by the designated management agencies within the basin. Because the community and state were concerned with the aesthetic, recreational and economic impacts of algal growth during the summer months within the Tualatin River, the TMDL process focused on regulating pollutants that influence the population dynamics of algae. Regulatory limits were set for total chlorophyll-a as an indicator of both the severity of algal growth and the underlying availability of phosphorus due to the assumption of a strong correlation between these factors. However, beyond distinguishing between the potentially toxic cyanobacteria (also known colloquially as blue-green algae) and the relatively benign but unsightly green algaes, the agency charged with monitoring these parameters (the U.S. Geological Survey) does not make further distinction between these types of phytoplankton. Instead, the focus is on monitoring for potential toxicity from cyanobacteria and for chlorophyll-a as a precursor of nuisance algal blooms, regardless of species. Nor is further distinction necessary for our purposes, since collectively the life cycle components and requirements of the various species comprising the phytoplankton of a stream are largely uniform. A general discussion of these overarching themes will suffice to support an analysis of large scale water management decisions within the basin.

- **Algae require high inputs of sunlight and nutrients for their photosynthetic activities, which are facilitated by warm water temperatures and long residence times, making summertime low flow conditions ideal of algal growth.**

- **The morphology of the green algae and their limited motility, particularly in the case of phytoplankton, can be exploited by using flow management techniques to increase disturbance of microhabitats, shorten residence times, decrease water temperature and dilute nutrient inputs.**

Algae as a group are highly diverse and serve a wide array of ecosystem functions, but their essential requirements and services can be generalized, particularly in the freshwater riverine environment. The green algae with which we are primarily concerned inhabit several different climates and terrains, including "temporary pools of water, waterfalls, ponds and lakes, rivers, slow flowing streams, marshes and estuaries (Wehr and Sheath 2003)." These unicellular or multicellular organisms are autotrophs, depending on an adequate nutrient supply in the presence of sunlight within an acceptable range of physical and chemical conditions.

Some members of the algae family are motile, others not, and their morphologies vary in interesting ways that are not germane to this research. Phytoplankton exist as unicellular, unanchored individuals within the water column, although they are generally not motile but rather drift with the current or settle in the benthos. Planktonic communities may develop from single cells seeded into an advantageous environment, and such seed cell may result from a variety of sources including upstream scour, reservoir releases or inflow from wetlands. Once floating freely within the water column, phytoplankton have access to many different resources than their benthic cousins, particularly to increased light, an advantage whose consequences are well expressed when during summertime algal growth rates are high enough to result in algal blooms.

Although the form and function of the various algae differ, all contain chlorophyll-a among their various pigments, which is to say, all are autotrophs producing their supply of energy from sunlight and nutrients. Within a stream channel, the communities of planktonic and benthic algae may compete for resources, with relative disadvantage to each strategy. Benthic communities may face greater interactions with other organisms within the sediments than do planktonic species in open water, whereas planktonic algae face the threat of export from the system with outgoing flow. The distribution between floating planktonic algae and resting benthic algae is a function of the relationships between channel dynamics such as residence time an turbidity, with plankton dominating lake like conditions and benthic algae taking advantage of refuge within the boundary layer of faster moving streams (Murdock and Dodds 2006). This fact is of great relevance to the study at hand, since regulation of flow augmentation directly influences these three factors.

Phytoplanktons tend to be particularly common in valley-bottom streams and higher order rivers, and the size of their communities tends to increase with stream order. Studies indicate that plankton growth in large river systems is controlled mostly by discharge so long as nutrients are not limiting and residence time is long. These conditions again relate to flow augmentation management, which can directly impact dilution of nutrients, turbidity and the mixing of cell within the water column (Wehr and Sheath 2003). Variation within the stream channel may create microhabitats in slower flowing reaches, particularly in areas where flow is inhibited by obstructions, diverted into side-channels or retained within 'dead-zones'. These microhabitats may foster algal growth and can be directly impacted by the release of large volume and velocity flows timed to 'flush out' the system (Petts and Callow 1996). Indeed, longitudinal diversity in micro-habitats favors planktonic communities over benthic ones as width and depth of the discharge increase in the downstream direction as depth works against the necessary input of sunlight (Petts and Callow 1996). The usual decreased summertime flow and velocity downstream in this system would tend to favor planktonic growth by increasing residence time while providing sufficient access to sunlight and nutrients (Petts and Callow

1996). As autotrophs, plankton rely on the normal foundations of photosynthetic activity for growth – light energy and dissolved inorganic nutrients. The algal life cycle responds to both seasonal and diel variation. As a community, algae thrive during the warm, sunny summer months and perish during the cold, dark winter months. Thus, water quality management strategies may target temperature and shading as well as volume and velocity of flow. Competition and grazing dictate which of these autotrophs thrive and which fail. Grazing and competition pressure can keep algal growth largely constrained even in nutrient rich systems. Research indicates that river conditions may favor species of plankton that have a high tolerance for frequent disturbance or perhaps faster growing opportunists that can flourish in low velocity, low turbidity, high nutrient situations such as those present during the summer months (Petts and Callow 1996). Coordination of flow management decisions throughout the day with diel cycles in planktonic growth, energy production and reproduction may further enhance effectiveness.

- **Flow management captures winter precipitation and redistributes flow throughout the year, interrupting the connection of algae to the floodplain and thus further impairing the development of large algal communities during summer months.**

Since planktonic algae can be seeded from algal communities hydrologically connected to the river throughout the watershed, the connections between lakes, wetlands and rivers throughout the basin are critical. Lakes provide nutrient inputs as well as refresh algal cells during floods (Murdock and Dodds 2006). Wetlands can provide an intermediary for this relationship between lake and river as well. Phytoplankton are more prominent where wetlands are connected to large lakes which provide both the initial algal cells and the nutrients needed for the community to grow. Because flow management in the Tualatin River basin serves to store and redistribute winter precipitation throughout the year, this pattern of flooding can be disturbed and thus another avenue for control of algal growth arises.

Once the river environment has received algal cells, the first requirement for growth of algae within the stream is that habitat within the channel itself. A few observations as to the general habitat preferences of algae have already been made – slower flow, longer residence time, shallower waters. Planktonic communities require equilibrium between sufficiently turbulent flow to maintain suspension of the individual cells and sufficiently slow flow to increase residence time (Petts and Callow 1996). As green algae are chlorophyll driven autotrophs, access to sufficient sunlight for photosynthesis is of course very important. Fluctuation in available light across channel depth, throughout the diel cycle and with the seasons affect planktonic growth to the extent that photosynthetically available light becomes a limiting factor for growth (Darley 1982). Depth of the water column can be a major factor, since refraction of the sunlight with increasing depth reduces photosynthetically useful wavelengths of light. Both the amount of suspended sediment clouding the water column and the depth of the water column increase downstream as well, further limiting useful light input. Conversely, because the width of the stream channel also increases downstream, canopy coverage of the channel is reduced and thus the total input of sunlight is increased. Photosynthetic production by suspended plankton represents a balance of these competing conditions. Exposure to light is affected not only by turbidity and depth, but by season as well since riparian shading and available daylight hours vary throughout the year.

When it comes to temperature, seasonal variation is the biggest control of algal growth, particularly in temperate zones like the Tualatin Basin. Seasonal changes in water temperature can affect algae directly through impact on metabolism, with warmer temperatures being more conducive to chemical processes, and indirectly through turnover of stratified waters (Darley 1982). However, longitudinal variation exists within the channel as well, with water temperature generally increasing in the downstream direction with occasional pockets of warmth in shallow backwaters or coolness in deep holes. Phytoplankton generally prefer water temperatures between 18 and 25 degrees Celsius and they have some capacity to adapt to temperatures outside the preferred range. During the winter in this temperate valley, algae will usually be limited by available light or nutrients long before they are limited by water temperature alone (Darley 1982).

The role of algae as primary producers, supporting the food chain from the bottom up, must be placed within the context of the stream continuum. Although there are few studies of the primary production of algae in wetlands, those that exist indicate that algae may account for up to 65% of primary production in some systems. Indeed, some riverine ecosystems derive most of their energy from plankton, primary production occurs more commonly in macrophytes and emergent plants (Murdock and Dodds 2006). Phytoplankton serve an important role as the base of the food chain, and may regulate the success of herbivores within the system (Petts and Callow 1996). Zooplankton (particularly rotifers and crustaceans) are the primary consumers of phytoplankton, but any number of benthic filter feeders may also be supported by this population (Darley 1982; Petts & Callow 1996). In turn, birds, bats and fish all subsist on the insect life of the stream. Thus, while the goal of reducing and controlling algal populations to improve anthropogenic stream values and prevent potentially harmful blooming is widely accepted by water quality managers, some caution must also be exercised to prevent total collapse of the ecologically important species.

- **Flow augmentation can be targeted both in time and longitudinally along the stream in accord with algae's shifting role along the stream continuum from upper to middle and finally lower reaches of the river.**

It is useful here to consider the stream system as a continuum along which energy is mediated by a number of factors since the delivery of flow augmentation must be seasonally timed as well as strategically located. Along the downstream trajectory, nutrients and microorganisms are delivered into the river system from the surrounding watershed as precipitation moves towards the channel. Low temperatures, low light and low presence of nutrients, particularly phosphorus, generally limit algal growth here, although blue-green algae can take advantage of nitrogen fixation to produce some organic matter. What little primary production is occurring becomes food for lichens, which combine with rainfall, freezing temperatures and wind erosion to break apart rocks and collect soil over time for riverside plants to colonize. This process in turn releases nutrients such as phosphorus to the stream, where they are exported to lower reaches where they may be more favorably accessible to algal growth. As the stream progresses longitudinally, it collects allochthonous inputs of nutrients from the waste materials of the riparian community as well (McKinney 2004). Available light increases as the channel widens. As light penetration within the water column increases in the downstream direction, so does the plankton population, which in turn drives increase in the zooplankton community.

By the middle course of the stream, bacterial and algal communities are beginning to thrive, particularly aerobic communities that benefit from waters what are turbulent enough to entrain large amounts of dissolved oxygen but are also warmed by wide, exposed channel lengths and that receive substantial nutrient inputs from upstream. As the valley transitions from forested lands to agricultural lands, the import of available nutrients increases due to human activity and riparian shading is reduced by removal of canopy species. Green algae can now begin to take advantage of sunlight as well as carbon dioxide and nutrients made available by bacteria in the water column and along the surfaces of rocks. As higher forms of life appear, they are dependent on the input from primary producers such as algae that supply energy through the chain of protozoa, freshwater crustaceans, other insects and macroinvertebrates and small fish and amphibians to sustain larger fish and other members of the riparian community (McKinney 2004).

- **Algae provide a number of benefits to both in-channel and floodplain communities in terms of underpinning the food chain, cycling nutrients and positively conditioning water quality during their growth; thus, management activities to limit growth must be balanced with other ecological goals.**

Algae's positive effect on the river environment includes facilitating geochemical cycling and habitat creation, two more factors to be considered in tempering actions to control their growth (Wehr and Sheath 2003). Throughout the middle and lower courses of the river, the activities of phytoplankton mediate nutrients into more accessible forms, releasing organic and amino acids as well as various sugars (Darley1982). Some of the effects of algae in the stream improve the functioning of the community overall, such as increasing dissolved oxygen as a byproduct of their respiration (benefitting fish), reducing carbon dioxide as it is consumed during photosynthesis, taking up nutrients and pollutants, and pinning down the substrate (macrophytic and mat forms) (Wehr and Sheath 2003). Oxygen production during growth is particularly important to the dissolved oxygen profile of the stream during the summer months when low flows fail to refresh the system in the way more turbulent flows would. Algae within wetlands facilitate nutrient cycles, temporarily store nutrients and reduce the occurrence of many pollutants. Because algae can reduce nutrient and pollutant loads within waters by trapping them, algae can also be used for waste water treatment on a small scale (McKinney 2004). The impact of flow management activities on both the stream channel and its connection to the flood plain can affect these roles significantly.

As water quality managers know, however, algae also play a detrimental role within the stream. With rapid, intensive growth of the algal community come inconveniences to many species, including impairment of the streams ecosystem services to human beings in terms of low quality drinking water supplies, the risk of toxic algal blooms and, upon the death of the community, low dissolved oxygen levels due to decomposition (Wehr and Sheath 2003). Excessive growth of algae where poorly treated wastewater discharge is released can be unsightly as well as odorous, and can inhibit recreation such as swimming and boating. It may result in fish or animal kills, and where the species of algae itself is toxic and its growth concentrated enough to alter water quality, may cause rashes in humans or even poison pets. Large algal blooms resulting from rapid, intense growth can increases costs of drinking water treatment [and for our purposes, industrial process water treatment at Intel], particularly during the fall when the algal community dies back and decays [less of an issue here where drinking water is drawn from shaded headwaters] (McKinney 2004).

- **Flow management efforts must focus on the interaction of low regime and the factors discussed above in order to generate suitable results.**

With a firm understanding of the requirements of algae in the stream channel and the nature of the basin, it becomes clear that flow management can be used to create habitat disturbance and thus help reduce the effects of algal growth. As a general rule, algae respond rapidly to increased nutrient inputs where other environmental factors are not limiting, but their populations decline equally rapidly in response to human-introduced stressors (Wehr and Sheath 2003). When the requirements of growth are disturbed by changes such as increased riparian shading (leading to decreased availability of light and temperatures), lowered nutrient availability, reduced residence times, the introduction of toxic substances and disconnection from the floodplain, the disturbance can either lead to a decline in the planktonic community or to a beneficial adaptation (Wehr and Sheath 2003). The response of planktonic algae to many types of disturbance is pretty limited due to their passive life strategy – their limited ability to slowly rise or fall within the water column provides some mobility, but not enough to cope with rapid changes.

Flow regime of a river is critical within the life history of planktonic communities, and often quite variable. Disturbance events such as high flows or even floods can be very problematic for planktonic communities. The flow of water upstream to down is both a blessing and a curse to algal communities. As we've seen, the flow of water downstream delivers nutrients as a relatively constant rate, and some turbulence is beneficial in allowing plankton to remain in suspension. However, high flows result in dilution of available nutrients, potentially high levels of turbidity and thus more suspension of substrates which create a shading effect, lower temperatures and shorter residence times, all disfavorable to algal growth (Petts and Callow 1996).

As we continue down the stream continuum from the middle to the lower course of the river, the occurrence of thermal stratification within the reservoir reach during low flow, warmer summer months merits some consideration. In the absence of flow augmentation, waters within this reach often stagnant during the summer, with a very gentle movement of flow in the downstream direction. This creates conditions comparable to the thermal stratification in lakes, and algae in this system respond in a manner similar to algae within lakes. In lakes, the degree of mixing dictates which types of algae are more likely to dominate, with smaller forms succeeding in oligotrophic lakes and larger forms succeeding in shallow, mixed eutrophic lakes. The non-motile green algaes can thrive early in the stratification process when sunlight is abundant and just enough disturbance occurs to cycle nutrients. Stratification of the lake disadvantages the non-motile greens though, who are doomed to burial on the bottom of the lake beneath sediment if not actively re-suspended. Some non-motile greens have developed some adaptations to overcome this fate by improving buoyancy (Wehr and Sheath 2003). To tailor the flow augmentation strategy within the Tualatin River, then, would require a better understanding of the various algaes present in summer water quality samples.

The reservoir reach on the Tualatin during the summer months bears characteristics both of a stratified lake and of a moving lotic environment. There is, of course, some flow through the reach, but at a very low velocity. Thus, although residence time may reach up to two weeks, nutrients are constantly refreshed by the very gentle current as well as by tributary and point source inputs. Additionally, the flow rate though slow is sufficient to suspend both algae and sediment near the surface of the water column, particularly in light of morphological adaptations making certain species of green algae more likely to remain suspended in such low currents. So long as summer conditions remain caught between these two environmental extremes, providing the benefits of both a lotic and a stratified lentic environment, multiple communities of plankton with various adaptations can actual thrive. Disturbance of these conditions, either in the form of more mixing and shorter residence time created by greater flow, or in the form of less mixing and slower delivery of nutrients due to lower flow, could greatly harm the plankton population.

E. Water Quality Then and Now: A Snapshot

- **Understanding trends in water quality within the Tualatin basin since 1986 is another important factor in assessing the impact of water quality and flow management on ecosystem services and human well-being. Tualatin basin water quality reflects the impact of several human activities within the basin, and over time, has been improving in most areas.**

Getting a picture of what water quality in the Tualatin River basin has been like since 1986 highlights the challenges of water quality management that might be alleviated by including a comprehensive ecosystem assessment as a policy tool, especially where competing water quality concerns generate tradeoffs. In 2001, Department of Environmental Quality (DEQ) published its first comprehensive Oregon Water Quality Index (OWQI) report covering data from 1990 to 2001. In annual reports thereafter, DEQ scores water quality in the streams and rivers of the state on a range of 10 (worst) to 100 (best) utilizing several measurable variables such as temperature, nitrogen and phosphorus. These measurements derive from a network of ambient water quality monitoring sites. These indicators give an essential snapshot of the changes in water quality conditions achieved by point source regulation and other water quality management strategies to date (Cude 2004).

According to DEQ, many anthropogenic activities such as logging, agriculture, commercial nurseries and urban land uses affect water quality in the Tualatin River basin in addition to the natural environment described in the foregoing sections (Mrazick 2008). Thus, one might expect that water quality would be variable over time in the basin as both human land use and climate change have an effect, and particularly as management efforts to improve water quality are instituted.  Indeed, although water quality in the basin has been poor in the past, since management efforts began in 1988, DEQ has observed significant improvement even as population growth has steadily increased in both total population and rate of growth (Cude 2004).  Yet by 2008, the WQI indicated serious declines along the Tualatin River that were inconsistent with the rate of decline elsewhere in the state (Tualatin Riverkeepers Citizen Action Committee 2008).

Overall, segments of the Lower reaches of the Tualatin that we are concerned with were ranked between fair to very poor in the 1990s, with some difference between their summertime scores under low flow and their scores during the remainder of the year at high flow, with summertime averages of particular interest to this research.   In the lower reaches, water quality was ranked as poor, reflecting anthropogenic input of nutrient pollution from nonpoint sources such as silviculture, agriculture, container nurseries, confined animal feeding operations, erosion, and city runoff (Cude 2004). This reach suffered from high levels of phosphates, nitrates and fecal coliform, as well as a high biological oxygen demand beginning in the late fall when the upstream WWTPs come back online, leading to slightly better summertime water quality scores when the treatment plants are offline (Cude 2004).  On its slow, meandering course through the Middle course of the river, the Tualatin collects drainage from mostly agricultural land, carrying with it large amounts of organic material and sediment loosened from the landscape.  These inputs as well as nutrient inputs from the Rock Creek wastewater treatment plant resulted in very poor water quality scores in the 1990s.  However, these scores have improved over time due in part to improvements to the WWTPs in the area.   In 1989, the Rock Creek plant began converting ammonia to nitrate before releasing effluent, having no effect on total nitrogen but significantly lowering the biological oxygen demand and increasing dissolved oxygen in the process. In 1990, the plant began to lower phosphorus levels in the effluent through biological phosphorus removal, thus reducing total nutrient load to the stream. Both of these processes increased total dissolved solids as a byproduct of treatment but this effect was counterbalanced by the overall improvements in water quality, resulting in the most significant water quality improvements in the basin over that time period (Cude 2004).

Since the publication of the 2001 report, DEQ has published annual updates. In its 2004 report, DEQ noted the importance of management efforts to improvement of the general water quality in the Lower reach, especially due to reductions in point source pollutants and due to WWTP upgrades (Cude 2004). Of course, not all of the improvement came solely from these changes – implementation of best management practices, also known as BMPs, at various point sources accounted for improvement at sites where the WWTP did not directly affect water quality, particularly upstream of the WWTPs. Factors such as voluntary reductions in non-point source pollution and riparian restoration projects furthered these improvements but DEQ indicated in 2004 that flow management would continue to be a key factor underlying the effects of point and non-point source inputs alike, especially as the climate of Oregon shifts in the future (Cude 2004).

DEQ studies provide a timeline of water quality conditions throughout the period of management that illustrates the general trend of improvement. More detailed information on nutrient pollution and algal growth in the basin over the dry summer season and across years, however, helps to fill in this general sketch. In preparation of its 1999 report on sources and transport of phosphorus in the basin, USGS performed extensive water quality monitoring concurrent with flow measurement, providing a comprehensive survey of nutrient inputs and water quality (USGS 1999). Surface water was sampled over three years on the main-stem and the tributaries, while groundwater was sampled at numerous in-channel wells and shallow wells throughout the basin over four years. More ephemeral sites such as tile drains and seeps were measured during a week-long synoptic survey in 1992 (USGS 1999). Sites were chosen for their relationship to known sources such as wastewater treatment plants and for their accessibility. Sampling for nutrients, pH, temperature, specific conductance and DO occurred twice daily at most sites to capture suspected diel variations, and at various points throughout the channel in order to capture quality within the entire flow. A more detailed description of the study can be obtained from the report (USGS 1999).

Clean Water Services also produces an annual report of water quality in the basin as part of their permit compliance efforts. Operating under a TMDL for phosphorus and ammonia since 1988, CWS assumed responsibility for the area stormwater permit in 1990 in order to address best management practices affecting phosphorus delivery to streams. CWS then is required by these permits to produce an annual report marking their progress in addressing the rivers of water quality in the basin. The report relays and analyzes the information gathered by the comprehensive ambient water quality monitoring program, begun in 1988 and extended to a coordinated water quality monitoring program in 1994, managed by the designated management agencies under the TMDL plan. This monitoring has always included measurements of chemical parameters such as phosphorus and ammonia on the main-stem and at tributaries, and has included stormwater monitoring since the early 1990s. Biological indicators of stream health, such as fish and macroinvertebrates, were also added during the 1990s on a cyclic basis. The latest of these reports (2008) marks the most current information published regarding water quality in the Tualatin River (Bonn 2008).

- **Research by the US Geological Survey in the Tualatin basin indicates that algal growth in the Lower section of the river as measured by chlorophyll-a can reach problematic levels when stream-flow declines below 300 cfs in conjunction with other favorable summertime conditions.**

When considering control of summertime algal growth, phosphorus is often indicated as the primary driver of growth and therefore the most readily available for limitation. During the summer, when stream-flow is low, and light and nutrient conditions are favorable for algal growth, the relatively long residence time in the lower reservoir-like reach of the river supports the growth of large populations of phytoplankton. According to the 1999 USGS report, these populations begin to develop below RM 30, and can increase by up to eightfold (as measured by concentrations of chlorophyll-a) over the course of the next 25 miles. Chlorophyll-a concentrations in 1999 reached their maximum in the lower river, observed at RM 5.5 and exceed 30 micrograms per liter for long periods during the summer (as a point of reference, the State action level of 15 micrograms per liter). Peaks in chlorophyll a concentrations often exceeded 50 micrograms per liter at this site and occasionally exceed 100 micrograms per liter. Generally, extended periods of stream-flow less than 300 cfs are necessary for the growth of large algal blooms. When flow, light and nutrient conditions are favorable, these blooms persist for long periods, sometimes several months (USGS 1999).

In 1965, total phosphorus concentration in the Tualatin River was exceedingly high – unsurprising in an era when water quality impacts from the WWTPs had not yet been considered. Indeed, USGS observed in prior to efforts to manage these input, WWTP effluent historically contributed large loads of phosphorus to the river (USGS 1999). Total phosphorus in September could exceed 2 mg/L near the confluence with the Willamette River, and consistently exceeded 1 mg/l in the reservoir reach generally (Bonn 2008). Conditions in the tributaries were even worse – where WWTPs were located, total phosphorus could approach 6 mg/L or more (Bonn 2008). After consolidation of the WWTPs in the 1970s, total phosphorus in both the reservoir reach and the tributaries declined to a range of .25 mg/L to .4 mg/L during the summers of the 1980s, which still provided more than enough phosphorus for algal growth (Bonn 2008). This abundance of food to fuel growth is reflected in the chlorophyll-a figures from the late 1980s, which despite the beginning of management efforts still approach 40 mg/L on average over the course of the summer (Bonn 2008).

- **By the late 1990s, it became clear that these poor water quality results were driven by additional phosphorus inputs beyond the point source discharges from WWTPs, including such disperse anthropogenic sources as urban and agricultural runoff as well as environmental inputs from tributaries and in-channel seeps of phosphorus-laden groundwater.**

By 1999, water quality in both the main-stem and the various tributaries and inputs had changed and needed to be quantified, particularly as they related to summertime algal bloom conditions in the reservoir reach of the main-stem. During the summer months with which we are concerned, the reservoir reach of the river is subject to thermal stratification. The upper thermal layer is warmer and contains much of the phosphorus entering the system upstream of the WWTPs. During the course of the summer in 1999, the phosphorus concentration upstream of the treatment plants rose steadily in the downstream direction from an acceptable 0.03mg/L in the headwaters to the less desirable 1.0 mg/L just before the WWTP effluent joins the river's course. During the 1991-1993 portion of the study, phosphorus concentrations held steady in the river throughout the reservoir reach until the WWTP was reached, where concentrations spiked to 0.25mg/L due to less developed treatment technology at that time, which has since been remedied. Over the course of the summer, measurable levels of orthophosphate (that is, soluble organic phosphate available for uptake by algae) will decline as it is taken up and consumed during algal growth (USGS 1999).

In that critical reservoir reach, mid-channel wells revealed concentrations in excess of 1.0 mg/L or 2.0 mg/L seeping directly into the river's flow; edge-of-channel wells revealed concentrations between 0.56 to 0.74 mg/L entering the flow after passing through the wetlands at Jackson Bottom (UGSG 1999). These in-channel wells indicated that groundwater phosphorus could actually be a significant source of phosphorus to the river, and that where shallow groundwater is processed by wetlands, nutrient concentrations could be significantly lower. Phosphorus concentration in ground water also varies throughout the valley floor, most likely due to the complex nature of the flow of groundwater, but nowhere did they dip below the 0.07mg/L limitation original set in the law. At such concentrations, USGS concluded that even a small leakage of this phosphorous laden groundwater could strongly influence concentration in the river channel during low-flow (USGS 1999).

Phosphorus was also discovered in 1999 to be entering the system via surface waters, but with great variability. During the USGS survey, most creeks were usually above the TMDL criterion of 0.07mg/L, sometimes as much as fourfold. Creeks and tile drains further upstream draining agricultural and forestry uses, such as Scoggins and Gales Creek, tended to have the lowest total phosphorus concentrations. The nutrient load in tributaries and tile drains increased as the USGS worked its way down the valley through nursery operations and into the suburban areas, with the highest concentrations occurring in the tributaries draining Jackson Bottom wetlands. Phosphorus concentrations in surface seeps was somewhat lower than in the other sources, possibly due to uptake mechanisms such as adsorption to ferrous oxides or utilization by plants. Anywhere from one-quarter to two-thirds of the total phosphorus in these streams occurred as orthophosphate (USGS 1999). Ultimately, USGS concluded that the overall contribution of bioavailable phosphorus from agricultural fields was no more significant than that from shallow groundwater (USGS 1999).

- **WWTP return flows, valued by water quality managers for the volume of flow returned to the system within the critical Lower reach, continued to deliver a significant proportion of phosphates during the 1990s despite plant improvements, particularly where plant upgrades had not yet been completed.**

Despite vast improvements in the treatment of wastewater effluent, treatment plants continued in 1999 to have significant effect on phosphorus concentration in the river, accounting for as much as 20-40% of inputs – this is due largely to the high proportion of stream-flow made up of effluent during the summer (USGS 1999). The concentration of phosphorus in effluent fluctuates over time and throughout the day in response to cyclic use – from 1991 to 1993, phosphorus limitations for the river were exceeded during late August and early September on occasion at Rock Creek. Fluctuations in the algal bloom corresponding to the fluctuation of temperature over the course of the summer depict the seasonal uptake of phosphorus within the river, as indicated in the graphs on the following page. (Today, USGS continues to monitor water quality on the river continuously at some of its gauging stations and periodically at other sites. Of all the sites monitored along the reservoir reach, the Oswego Diversion Dam site provides the most useful data for this research, the most recent of which is depicted in the time series on the following page.) Throughout the course of the day, both volume and phosphorus concentrations tend to be higher when people are awake during the day.

- **The relationship of the summertime algal bloom and dissolved oxygen levels presents complicated flow management concerns throughout the course of the summer as the Lower reach of the river has tended to display low dissolved oxygen levels over time.**

The Durham plant was much more likely to exceed the limitations at the time of the study due to less advanced treatment technology, an issue that has now been resolved (USGS 1999). For the most part, technological advances now keep wastewater effluent from all plants at or below the 0.07 mg/L standard and thus far below the ground or surface water inputs throughout the year. Of course, management of the algal bloom itself is driven by other water quality and usage concerns. While algal growth directly affects quality issues such as aesthetic, recreation and drinking water uses, it also indirectly affects the suitability of the ecosystem to many fish species, particularly through its relationship to dissolved oxygen. Ordinarily, in a free flowing river, dissolved oxygen is not of particular concern since turbulence within the channel continually adds more oxygen to the water column, as do inputs from tributaries. Dissolved oxygen is a water quality parameter more often monitored in lakes and reservoirs, where thermal stratification and low circulation of water can result in hypoxic zones, that is, areas where dissolved oxygen is too low to support respiration in plants and animals that require its presence. While the Tualatin River has not quite reached hypoxic conditions, dissolved oxygen during the low flow periods of late summer and into the fall can be a sufficient problem to require monitoring. In very basic terms, while algae is alive and conducting photosynthesis early in the summer, it generate oxygen as a by-product, increasing dissolved oxygen within the reservoir reach where it would otherwise be low due to the low flow.

Towards the end of the algal season, however, as these populations begin to die off, algae sinks to the bottom of the reservoir reach, where it may lay for a period of days or even weeks before slowly flushing out of the system. This algae is consumed by detrivorous bacteria within the sediments, which consume oxygen in the process, creating what is known as a sediment oxygen demand within the channel similar to the low-oxygen conditions often found in lakes. Thermal stratification of pools during summer months results in increased sediment oxygen demand (SOD) from accumulated organic matter resting within them – as these materials are consumed by detrivores, dissolved oxygen (DO) levels decline and release of nutrients increases (Rounds and Doyle 1997, USGS 1999). Thus, a relationship between algae and dissolved oxygen implies a relationship between phosphorus, climate, flow and dissolved oxygen as well. (Note that the load of nitrogen to the system also affects dissolved oxygen levels, a factor not discussed extensively in this paper but which complicates management decisions somewhat.)

Concentration of DO exhibit a distinct diel cycle during the summer as a result of algal photosynthesis and respiration as well as shifts in human activity – that is, it fluctuates over the course of the day as algae consume oxygen during nighttime respiration and release oxygen during daytime photosynthesis (Bonn 2008). A range of 3-5 mg/L between minimum and maximum values is commonly observed in the lower river during the height of algal growth. Supersaturated conditions of DO can result from the high rates of photosynthesis and the slow rate of re-aeration; peaks as high as 200 percent of saturation have been observed on occasion during the 1990s. When skies are overcast, however, phytoplankton populations decline substantially, resulting in a precipitous drop in concentrations of both chlorophyll a and DO (USGS 1999).

As a consequence, violations of the Oregon State minimum DO standard of 6 milligrams per liter (the standard in effect during the USGS study cited here) periodically occur in the lower river. For example, in July 1991, chlorophyll a concentrations dropped from greater than 120 to less than 10 micrograms per liter in one week; these values were associated with a concomitant reduction in maximum DO concentrations from 21 to 5.6 milligrams per liter during the same period. In-river nitrification can also contribute to oxygen depletion when waste water treatment plant ammonia loads are large and water temperatures are warm enough to stimulate the growth of nitrifying bacteria. The effect of algal decline and nitrification on DO is augmented by sediment oxygen demand resulting from bacterial decay of the organic-rich bottom sediments, a major sink for DO in the Tualatin River. Several interacting factors are involved: first, the reduced rate of stream-flow in the lower river during the summer increases the exposure of the overlying water column to the sediment, both in terms of exposure time and the ratio of water volume to bottom surface area. Second, the effect of sediment decay is compounded by warm water temperatures characteristic of the summer, often great than 20 degrees Celsius, which support rapid growth and metabolism of benthic bacterial communities. Finally, the rate of re-aeration from the atmosphere is low as a result of the sluggish water velocities (USGS 1999).

In the 2008 report, CWS gave an extensive analysis of the improved conditions related to dissolved oxygen over the last 20 years. During this time, improvements to the WWTPs resulted in significant decreases in both phosphorus and nitrogen (ammonia) loads from the plants to less than ¼ the earlier amounts, reducing the oxygen demand created directly by these inputs. This is reflected in the 30 day floating average of dissolved oxygen near the Oswego Dam, which hovers just above 6 mg/L. More strikingly, the absolute minimum daily measurement increased to nearly 5 mg/L by 2007 – together these figures depict a range of dissolved oxygen that is more tolerable to aquatic life and less variable over time. However, the picture of improved water quality is confused by data reflecting a decrease in the percentage of time when dissolved oxygen levels are acceptable from a high in the 1990s (Bonn 2008).

Dissolved oxygen was near or exceeded acceptable levels almost consistently in 1999, whereas in 2003-2005, it did so for less than 75% of measured hours. That percentage is actually a decrease from the conditions early on in the management, when dissolved oxygen levels were acceptable at least 80% of the time. The reason for this shift is somewhat unclear, since as CWS indicates, nutrient inputs to the river have remained steady or declined over the years. These figures may actually represent a disturbing trend that results from the increasingly efficient management of summertime algal growth, an unanticipated side effect of management decisions analyzed in this research. Management of the WWTPs along tributaries and management of flow augmentation are also significant factors in the management of both algal growth and dissolved oxygen (Bonn 2008).

# Chapter 3 Analysis of Major Flow Management Decisions under MEA

## A. Summary

Water resources, including the flow on the Tualatin River during summer months, are managed through partnerships between several agencies and authorities. After introducing the concept of flow management and describing the basic divisions in climactic patterns (wet versus dry years), this section analyzes flow management decisions. Focus is given to decisions made by the sewerage agency regarding the timing of releases of flow throughout the summer months to improve water quality. Such decisions balance available supply with predicted summer climate, and present two major challenges: spreading out releases of flow over the course of the dry season without running out, and creating sufficient storage space for the next rainy season. A longer-term consideration taken up by the entire consortium, planning for additional storage in the basin, is added to the analysis.

Oregon's system of water rights, combined with climatic factors, creates a distribution and timing of precipitation and flow that requires management to balance between multiple municipal, corporate and environmental uses. After creation of the phosphorus TMDL, the need to regulate releases of flow from the Scoggins Dam to meet water quality goals while fulfilling these competing uses while preventing flooding led to creation of target flows and the interagency Flow Management Committee, whose seasonal flow management decisions aimed at meeting those targets are contemplated in this report.

Both seasonal and decadal climate cycles, as well as climate change, converge to influence a pattern of wet and dry summer conditions – the Flow Management Committee is challenged to meet demands and flow targets during dry summers and wet summers, as well as to attempt to balance storage of precipitation between years as insurance against drought as well as maintain adequate storage potential to prevent winter and spring flooding.

This analysis focuses on the differences between management strategies in wet years and in dry years, and will examine the impact of each approach on ecological services and human well-being. Challenges arising within the inter-year flow budget will also be examined as they create potential feedback between current management strategies, the changes they drive and future management strategies. Baseline conditions within the Tualatin River basin prior to the start of water quality driven flow management included low summertime flows primarily augmented by return flow from WWTPs, high nutrient levels, low levels of dissolved oxygen, warm temperatures, abundant sunlight to the channel and little precipitation. The volume and velocity of flow within the river channel throughout the summer months, as well as the diurnal and daily variations in that flow, greatly impact supporting, regulating, provisioning and cultural services within the system.

Low summertime flows within the Tualatin River channel have several impacts on the timing and severity of algal growth by altering the conditions which most directly impact algal growth (available sunlight, nutrients, water temperature, and residence time). Over the course of a typical summer, algal growth alters the ecological balance of the river channel, with ancillary effects on the riparian community and human well-being.

Summertime flow management activities in the Tualatin Basin primarily act to curtail algal growth by increasing flow throughout the summer (both by diminishing variability in flow between weeks and by reducing the length of the low flow period), which in turn decreases water temperature, dilutes nutrients and effects several other conditions critical to algal growth. Flow management also has direct impacts on water quality within the channel either unrelated to or indirectly related to algal growth such as dissolved oxygen and suspended sediment. Flow augmentation during summer months creates direct benefits for human well-being such as increased access to recreation and indirect benefits to human well-being through the reduced impact on other ecological services. Human well-being is also impacted by flow management decisions throughout the year and between years as a trade-off exists between storage of water for augmentation and sufficient storage space to prevent winter flooding.

During wet summers, flow managers face three primary challenges: long duration of spring rains lead to excess storage in the spring, summer rains reduce need for flow augmentation, and the late onset of drier months. While reducing the pressures associated with the normally dry summer months, all three of these scenarios reduce available storage during the next rainy season and reduce the ability to protect against flooding during the next season. Conversely, excess rain in the spring and summer months can provide insurance against longer-than-typical dry seasons in the fall (late onset of winter rains). Balancing these two concerns for human well-being has led in some years to flow experimentation and other activities designed to utilize excess flow in strategic ways; at other times, excess flow was less well managed, with serious impacts to human well-being and ecological services due to subsequent increased flooding. One strategy for balancing the need for storage of flow for flood protection and storage of flow for augmentation during both wet and dry years has been to increase use of inter-basin water storage and transfers.

While more common, dry summers can present specific flow management challenges, particularly when the length of the summer season is extended (spring rains end early or winter rains come late) or when drier than average conditions throughout the year (or in consecutive years) lead to flow deficits. Under these conditions, the primary concern is calibrating the timing and volume of flow throughout the summer season to meet either flow targets or water quality goals while fulfilling all other contracted uses without running short of stored water before the agricultural and flow augmentation seasons end. Effects on ecological services are compounded during dry summers which tend to be also sunnier and warmer than average summers, creating conditions favorable to rapid algal growth and thus increasing the need for preventative flow augmentation to reduce the effect of such growth on other ecological services and human well-being. Human well-being during dry summers is significantly impacted when stored flow fails to meet all uses throughout the dry season and when the rights of some water users are curtailed prior to the end of the year.

The challenges of individual or consecutive dry seasons can only be met through careful inter-agency planning and may also require increases in the efficiency of water delivery to agricultural and municipal uses, reduction in demand for water resources during summer months through voluntary or regulated conservation measures, and development of additional storage within this basin or neighboring basins. Increased storage may also reduce the risk of winter/spring flooding; however, increasing storage itself has significant implications for ecological services and human well-being, particularly where creating new dams and reservoirs is concerned.

## B. Water Rights and Uses

- **Oregon's system of water rights, combined with climatic factors, creates a distribution and timing of precipitation and flow that requires management to balance between multiple municipal, corporate and environmental uses.**

- **After creation of the phosphorus TMDL, the need to regulate releases of flow from the Scoggins Dam to meet water quality goals while fulfilling these competing uses while preventing flooding led to creation of target flows and the interagency Flow Management Committee, whose seasonal flow management decisions aimed at meeting those targets are contemplated in this report.**

Like many Western states, water resources in Oregon are managed through a system of property rights known as prior appropriation. Under this system, rights to water stored in reservoirs can be newly created but cannot override the pre-existing rights of downstream owners to in-stream-flow. Additionally, the state of Oregon has set in-stream-flow criteria which must be met simultaneously with managing the rights of various users. Thus, the Flow Management Committee in the Tualatin basin is required to balance these competing needs and rights. Beginning in 1987, a technical committee representing the major uses of the Tualatin basin's stored water and comprised of representatives from the sewerage agency, the irrigation district, the joint water commission, Lake Oswego and the Oregon Water Resources Department (the agency which houses the so-called 'water masters') began to more carefully and collaboratively manage these releases of stored water during the summer to increase efficiency, respond to changes in climate and weather, and to protect the health of the river.

They produced detailed reports on how summertime flow in the river was managed under their care. Using a continually evolving system of in-stream-flow monitoring, this committee of experts met from March through November to devise strategies to improve water quality while managing stored precipitation for a variety of uses. The reports generated at the end of each season summarize the challenges and actions taken by the committee that year, as well as collect detailed flow measurements from various points along the main-stem and its tributaries throughout the basin into numerous detailed hydrographs. Detailed records of temperature throughout the season at these locations were added to the report as the sewerage agency's permit obligations for that parameter kicked in. (United Sewerage Agency 1993)

Managers in the Tualatin Valley focused on two parameters as indicators of water quality: phosphorus and chlorophyll-a. Phosphorus measurements reflect most directly the inputs of phosphorus from various sources, and have little direct relationship to flow management. Chlorophyll-a, however, indicated the presence, extent and location of algal growth each summer. This parameter became a very critical measuring stick for the flow management committee as a whole and the sewerage agency specifically. Although the flow committee could not control overall compliance by non-point sources with waste load allocations for phosphorus, its activities in regulating the flow of the river could have a substantial and direct effect on algal growth management. Such activity did not improve compliance with the TMDL, but it did improve water quality.

The reports indicated reductions in phosphorus discharge downstream of the WWTPs but no corresponding decline in algal growth. The reason for this became clear with revelation of evidence indicating that the natural background levels of phosphorus were themselves sufficient to promote algal growth. However, the report also showed overall decline from 1989 to 1998 in the size of the algal population downstream of RM 40. Throughout this period, the pattern of growth along the longitudinal profile of the river channel remained the same, becoming peculiarly constricted around RM 10. (United Sewerage Agency 1998) These trends indicate that flow management might be having a significant effect on water quality in the river even if non-point source emissions are not under control. (United Sewerage Agency 1999)

One good reason to manage flow to reduce chlorophyll-a (that is, diminish the growth) is related to management of dissolved oxygen to support fish and other aquatic populations. Dissolved oxygen levels reflect many interacting conditions. The sheer velocity and volume of flow can affect dissolved oxygen levels by increasing mixing within the river channel. Cooler water temperatures support higher levels of dissolved oxygen than do warmer waters. Even algal growth alone has a strong impact on DO, increasing its level during periods of photosynthetic activity (daytime) and decreasing its level during respiration (at night). When algae dies off, consumption of the remains by detrivores consumes dissolved oxygen as well.

Thus, increased flow augmentation has potentially complex implications for DO as well as algal growth. Natural summer flows in the Tualatin River would be quite low, resulting in slow moving, sunlight warmed waters abundant in algae. Under these conditions, despite production of oxygen during the day by algae, overall DO levels would be quite low. As flow augmentation delivers increasingly larger volumes of cold storage water to the channel, water temperatures decline and velocity increases mixing. Thus, DO will rise with increasing augmentation. As flows become higher and higher, algal growth will be inhibited by short residence times, colder waters and scouring in the channel. However, the loss in oxygen production from algae is more than compensated for by the increased DO due directly to the mechanics of flow augmentation. One would expect that as increased flows speed into the reservoir reach, they deliver high levels of DO. Flow through the reservoir reach, however, cannot be considered fast or furious at any level of normal augmentation. It may be the case that algal growth then supports DO levels during the productive summer in these reaches. As light wanes in the fall, algae die off, which can create a dissolved oxygen sag if volume and velocity of flow do not prevent it.

Summertime flow targets aid in meeting both the phosphorus and DO requirements for the river, and overtime, the pattern of summer flow release has been adjusted to varying conditions. From 1991 to 1994, the flow management committee observed the impacts of various flow management periods on both algal growth and on levels of DO in the channel. 1991 to 1994 may be characterized as years with relatively lower flow augmentation, whereas between 1995 and 1999, the agency experimented with higher flow targets. DO was certainly higher during the increased flow target years than in the early 1990s. However, 1999 was an especially good year for DO even though the flow targets were not that much different than 1995 through 1998. The agency identified lower water surface elevation at the diversion dam (reflecting less impoundment of flow there), lower withdrawals of flow for Lake Oswego (indicating high volume of flow remaining in the main-stem channel), and a higher than usual proportion of augmentation water (perhaps indicating cooler temperatures) as potential factors in the improved DO levels (United Sewerage Agency 1999). In 2001, persistent drought so restricted available stored water that flow targets couldn't be met at any time (Clean Water Services 2001).

Monitoring and balancing water rights in Oregon falls under the purview of the ‘water master', but these decisions play an integral part in overall flow management for the Tualatin River. A basic understand of who the various water users are and the nature of their rights is useful in analyzing water quality management. However, due to the complexity of prior appropriate law and the disarray of public records, creating a comprehensive list of users and rights is at least a long term project of its own, if not impossible. The following is a summary of the major uses recognized by the drafters of the flow report as critical to their decision making processes.

*Cities of Hillsboro and Cherry Grove*: These cities have a right to extract flow released upstream from Barney Reservoir at RM 73.2 for consumptive uses (residential and industrial).

*Hagg Lake/Scoggins Reservoir*: Although most of the stored water within the lake is subject to water rights created by contract between users and the BOR, the lake itself has a recreational use as well as providing flood control.

*Tualatin Valley Irrigation District (TVID)*: An agricultural water service agency serves the irrigation needs of its users on 20,000 acres of cropland, including in the Wapato Lake area. About half these acres are served by withdrawals directly from the river channel. TVID removes flow from Scoggins Creek via the Patton Valley Pump Station at RM 5 of Scoggins Creek. Water removed from Scoggins Creek by the TVID is pumped over the hills and released to the Tualatin at RM 63 and RM 64 for withdrawal by individual agricultural irrigators downstream. TVID also has a natural flow right within the stream which is used for irrigation needs early in the summer. The remaining 10,000 acres is served by a system of irrigation pipelines serviced with water withdrawn from the Spring Hill pump station. TVID also has the responsibility for operating and maintaining Scoggins Dam under contract with BOR.

*Joint Water Commission*: Supplies water for consumptive use to Hillsboro, Beaverton and Forest Grove under both its natural flow rights and rights to water stored in Scoggins Reservoir. Along with TVID, it operates a second pump station at Spring Hill at RM 56, where water is diverted directly from the river and delivered to agricultural and municipal users. Water released from the dam for use by the JWC is withdrawn from the river at this point.

*United Sewerage Agency / Clean Water Services*: The sewerage agency releases water from Scoggins Reservoir for flow augmentation in an effort to maintain 150 cfs at RM 33.3, the head of the reservoir reach.

*Lake Oswego Corporation*: The organization holding the water right for diversion of flow from the Tualatin River at RM 6.7 to fill Lake Oswego. This water is then used for recreational and aesthetic purposes, as well as for electrical generation (the use for which the water right is held). The corporation has rights both to in-stream-flow (one of the oldest rights on the river) and to water in storage at Scoggins Reservoir pursuant to its contract with BOR.

C. The Pattern of Wet and Dry Years

- **Both seasonal and decadal climate cycles, as well as climate change, converge to influence a pattern of wet and dry summer conditions – the Flow Management Committee is challenged to meet demands and flow targets during dry summers and wet summers, as well as to attempt to balance storage of precipitation between years as insurance against drought as well as maintain adequate storage potential to prevent winter and spring flooding.**

One challenge faced by the Flow Management Committee is the unpredictability of summertime precipitation. Even under normal circumstances, Oregon's summertime precipitation patterns can be unpredictable, resulting in abnormally wet years as well as years of drought above and beyond normal summertime aridity. During the management period of 1992 to 2003, 5 years were characterized in the flow report as ‘wet' years, 4 as ‘dry' years, and 3 described as within normal limits.

Even in relatively wet years, however, the late summer months of July through September presented low natural flows on the river requiring augmentation. The management challenge, then, was to try to assess how much moisture would be stored before the dry period began (which in turn depended largely on whether the end of spring rains was early, on time or late) and how long & to what degree flow would need to be augmented during the drier months.

Along with these long term planning considerations based on factors related to climate, the flow committee also has to pay attention to daily and weekly weather. For although late summertime rain is unusual, it does occur. Because flow takes some time (days to a week) to travel from its release point near Hagg Lake to the problematic section of the river, the sewerage agency must make decisions about flow management days in advance of the anticipated storm.

If they accurately predict a storm's occurrence, water can be saved, extending their ability to manage flow further into the fall. This ability, useful in any year given the sewerage agency's quantity limited right to withdrawal, is particularly useful in years when water stored during the rainy season is lower than normal and summers are drier than normal because the sewerage agency's water right is junior to many of the other uses along the river. If during the late summer the water master determines that the sewerage agency had lost the right to augment in-stream-flow in order to protect senior rights, the sewerage agency may find itself in the difficult situation of being unable to meet its permit requirements. On the other hand, there is a risk in withholding the scheduled release of flow in anticipation of a storm that never materializes, thus failing to meet flow requirements under the permit at that time.

A potential management issue in both wet and dry years stems from necessary maintenance to the Scoggins dam and reservoir structure. Construction in these areas is best conducted during the dry summer and often requires drawdown of the lake or reduced outflow from the lake for long periods of time. In 1998 and 1999, flows continued to be quite high at the Dilley station, fostering further concerns about future flooding in the area. During the release season, flows up to 250 cfs were observed at that station (United Sewerage Agency 1998).

D. Analysis

- **This analysis will focus on the differences between management strategies in wet years and in dry years, and will examine the impact of each approach on ecological services and human well-being.**

- **Challenges arising within the inter-year flow budget will also be examined as they create potential feedback between current management strategies, the changes they drive and future management strategies.**

The annual flow management decisions tend to fall into two major strategies, those for wet years and those for dry years. Each of these strategies has been refined over the last decade, particularly with respect to taking into account interactions between wet and dry years in terms of flood control and water supply throughout the basin. It is important to understand how these flow management strategies impact ecological services and human well-being in the basin to full understand their effect on water quality in the basin. Additionally, it is a good idea to consider the impact of actions undertaken to facilitate flow augmentation by the sewerage agency. Such flow augmentation requires the storage of large quantities of water for summer release, as well as the management of an excess water in storage at the end of the augmentation season. In order to store such large quantities of water, agencies involved in water quantity management within the basin (Washington County, the irrigation district, the municipal water provider and the sewerage agency, among others) were compelled to consider the expansion of existing reservoirs as well as the creation of new reservoirs. The growing need for stored water during summer months for all uses (agricultural, municipal and flow augmentation) was also met by the expansion of Barney Reservoir and the increase interbasin transfer of flow. The impact of this decision on annual water budgets in each basin translates into an impact on water quality, ecological services and human well-being.

- **Baseline conditions within the Tualatin River basin prior to the start of water quality driven flow management included low summertime flows primarily augmented by return flow from WWTPs, high nutrient levels, low levels of dissolved oxygen, warm temperatures, abundant sunlight to the channel and little precipitation.**

- **The volume and velocity of flow within the river channel throughout the summer months, as well as the diurnal and daily variations in that flow, greatly impact supporting, regulating, provisioning and cultural services within the system.**

- **Low summertime flows within the Tualatin River channel have several impacts on the timing and severity of algal growth by altering the conditions which most directly impact algal growth (available sunlight, nutrients, water temperature and residence time).**

- **Over the course of a typical summer, algal growth alters the ecological balance of the river channel, with ancillary effects on the riparian community and human well-being.**

The relationship between flow management and water quality can be described by considering the impact of changes in flow on various ecosystem services and human well-being. The volume and velocity of flow within the river channel throughout the summer months, as well as the diurnal and daily variations in that flow, greatly impact supporting, regulating, provisioning and cultural services within the system. In terms of supporting services, the level of flow within the river impacts nutrient cycling and primary production both within the channel and within the larger river basin. Flow also regulates algal growth and sediment transport. Because of its direct impacts on regulating and supporting services, the level of flow within the river channel often impacts provisioning services by altering relationships within the ecosystem, favoring some species while disfavoring others. This impact also affects cultural services such as spiritual and cultural identity in the region tied to specific species populations such as salmon. Recreation, ecotourism and aesthetics are often also impacted by physical changes in the river's form and appearance. Finally, human well-being is impacted by the socio-economic effects of fluctuations in riverine flow on land value and the costs of adaptations, mitigations and regulations of flow.

Within the Tualatin basin during summertime conditions of high temperatures, high evapotranspiration and low precipitation, extremely low riverine flows are currently regarded as the natural or background condition during summer months. While it is clear that anthropogenic changes in the landscape (e.g. changes in land use cover, alteration of the hydrology of the basin, increased impervious surface, decreased return flow due to agricultural practices, increased storage of winter precipitation, etc.) have irrevocably altered whatever the pre-human state of the river may have been, this current trend of low background flows during the summer in the absence of human intervention is relatively stable from year to year regardless of minor weather variations and therefore represents the ‘norm'.

The low summertime flows within the Tualatin River channel have several impacts on the timing and severity of algal growth by altering the conditions which most directly impact algal growth (available sunlight, nutrients, water temperature and residence time). Lower flows produce a narrower river channel – as the main body of the flow recedes from the banks, a greater proportion of water surface is exposed to direct sunlight. This is the case even in areas where the natural riparian coverage remains intact or has been intentionally restored. Because winter time flows are consistently much higher in volume, the banks of the river are maintained at a much greater width than the summertime channel effectively fills. Thus, even in areas with superior riparian coverage, when summertime flow is low, relatively little of the water surface within the channel is shaded. Because more of the flow is exposed to sunlight, available energy for photosynthesis reaches as greater proportion of the channel, increasing primary production. The warmer water temperatures resulting from the lessened impact of shading are also metabolically favorable to the growth of algae, as is increased residence time within the reservoir reach – algae are exposed to more nutrients and sunlight in more favorable conditions over a longer period of time without significant disturbance or removal from the system, which allows for a larger and more established bloom of plankton.

Because these conditions favor algal growth, the algal population an opportunity to alter the ecological services within the river system. Larger algal blooms temporarily increase dissolved oxygen but later lead to oxygen sag during decomposition. The impacts of the dissolved oxygen sag on riverine ecology are unavoidable and particularly ill timed to coincide with potential fish migration. Similarly, although the algal community provides a seemingly attractive boost in dissolved oxygen during its life time, the negative impacts of the size of the bloom (where one occurs) on the dynamics of the ecological communities within the channel far outweigh any potential advantage conferred by the increase in oxygen. While the primary production of larger algal growth could support the bottom of the food chain, algae's voracious consumption of resources causes it to outcompete the other primary producers upon which zooplankton and macroinvertebrates more commonly rely for food sources, thereby lowering overall stream diversity.

As mentioned above, when stream-flow is low, the channel width is constricted. Such channel constriction not only does increases the proportion of water surface receiving direct sunlight but also results in increased exposure of banks. The impacts of a restricted channel on bank stability are complicated. On the one hand, by reducing the amount and velocity of flow that passes by the bank, the impact of erosive force on the bank's stability is reduced. However, if enough flow reaches the bottom of the bank to increase undercutting, the entire bank may collapse under its own weight. The exposed banks may also be subject to greater erosive force from other weather conditions such as wind and rain, as well as from overland flow of runoff in urban areas.  If the reduced channel width tends to encourage erosion overall, an increased sediment load can impact phosphorus concentration in the stream over time. Keeping in mind that much of the soil comprising the banks of the Tualatin River is fine grained loess, it is reasonable to expect that mobilized sediment remains suspended within the channel for quite some time, especially so long as any substantial velocity remains within the flow.

This suspended loess carries along with it phosphorus compounds adsorbed to the surface – with sufficient time, the hitchhikers are likely to be released to the water column until the concentration of phosphorus within the water column is in equilibrium with that on the sediment grains.  When the velocity of the flow drops sufficiently to allow deposition of the loess (typically within the slowest flowing section of the river, the troubled reservoir reach), these sediments could accumulate along the bed, altering the structure of the channel and perhaps even further slowing flow throughout the reach.  Such depositions of sediment may also represent storage of sediment and phosphorus that can be later mobilized by high winter flows – because winter conditions are disfavorable to algal growth (darker, colder, more dilute), the problem of sediment storage is less directly connected with an impact on the algal growth management, Instead, such stored and remobilized sediment may interfere with the life cycles of other species within the river, particularly fish species requiring low suspended sediment loads and high clarity for migration and spawning purposes.

With lower volume of flow comes lower velocity of flow, which translates to a  variety of impacts within the stream system.  A slower moving flow has a longer residence time, which in turn allows a number of processes to unfold that would otherwise be curtailed – algal growth become more established, adhered phosphorus is released to the water column in greater concentration, and so forth. The longer residence time therefore disturbs some supporting services such as nutrient cycling while favoring others such as primary production (albeit with favor for one form of production over others). Regulating services are also disturbed by longer residence times within the reservoir reach – a faster moving flow enhances water purification and regulation services, whereas a slower moving flow may favor erosion control services. The slower moving flow favors some cultural services over others. On the one hand, slower flows are less likely to produce recreational hazards that could result in injury or death. On the other, extremely low flows prevent recreational activities such as boating, swimming and fishing altogether. Even moderately low flows may impact these recreational services by allowing for the formation of persistent blue-green algae mats, which produce toxins irritating to the skin and harmful to smaller pets. The appearance and odor of the slower moving river is aesthetically displeasing and creates a disharmony with the image of a river which most Oregonians best identify their state and their values: crisp, clean, quick and productive. This may disturb a sense of place and other spiritual values that the river provides during periods of higher flow.

The gentler flow also reduces mixing within the water column, which in turn reduces the input of dissolved oxygen and during the warmest summer months, could generate localized thermal stratification. Furthermore, with a lower volume of flow reaching the reservoir reach from upstream and refreshing the system at a slower rate, the proportional contribution of groundwater to the flow would be higher, leading to the potential for increased phosphorus concentrations. Less in-stream-flow also leads to greater impact of return flows from WWTPs and stormwater. This may increase the need for infrastructure and treatment process improvements, raising the cost of sewerage service for those residents within the district. This economic cost could translate into a disincentive for business and residential development, depressing local urban economies. It may also drive additional conflict between rural and urban residents along lines of areas incorporated into the sewerage district and those that are not.

Conflict over costs and availability of water resources can also be heightened by the mere fact of reduced in-stream-flow. Decreased in channel flow can heighten tensions over in-stream delivery of water rights due to illicit withdrawals of flow along channel by residential users. Conflicts between advocates of protecting in-stream-flow and water users whose livelihoods or residential consumption depend on the river may arise as well. While lower flow does not have a significant impact on salmon migration during the low flow season, it may have persistent effects on higher flow seasons which inhibit salmon migration, leading to greater advocacy for protection of in-stream-flow. Conflicts between downstream and upstream users (which in this watershed track the urban-rural divide as well as a gradient of socio-economic status) may also arise from reduced in-stream-flow. As algal growth increases over the summer and in some cases as the algal community develops into a bloom, the potential impact on Lake Oswego tends to increase, leading to risk of reduced property value there and heightened conflict between that community and other stakeholders in Washington County

Low summertime flow is usually characterized as a undesirable state due to the negative effects on water quality and the costs to these ecological services and to human well-being. However, low summertime flow does represent the impact of seasonal changes in climate on the ecosystem, and may provide benefits to some species other than algae. Low summertime flows expose niche habitats along banks which certain members of the ecological community may depend on, as well as in-stream conditions that may be timed to specific life cycle events such as migration, reproduction, growth and development. During the remainder of the year, these species may provide a necessary food source or other ecological service and thus further the productivity of many species. Thus, the seasonal nature of the low flow conditions may increase overall biodiversity within the system and further a balance in the utilization of resources over the course of the entire year. Unfortunately, due to a lack of comprehensive ecological assessment within the basin (as most of the research has been focused on algal and anadromous fish ecology in accordance with the beneficial uses designated for the system), it is difficult to do more than speculate on the potential benefits of these otherwise seemingly adverse summer conditions.

**Impacts of Flow Management on Algal Growth**

- **Summertime flow management activities in the Tualatin Basin primarily act to curtail algal growth by increasing flow throughout the summer (both by diminishing variability in flow between weeks and by reducing the length of the low flow period), which in turn decreases water temperature, dilutes nutrients and effects several other conditions critical to algal growth.**
- **Flow management also has direct impacts on water quality within the channel either unrelated to or indirectly related to algal growth such as dissolved oxygen and suspended sediment.**

Because summertime weather typically produces so little precipitation and thus creates conditions of low flow that are favorable to rampant algal growth, the sewerage agency utilizes its rights to water stored behind Scoggins Dam each year to purchase the release of additional in-stream-flow. This flow management (the intentional increasing of flow during summer months to maintain an artificially high minimum flow using stored water) not only increases the flow of water but alters many of the conditions within the stream habitat that contribute to algal growth. As flow is increased, residence time decreases, nutrient concentrations are diluted, stream temperature is lowered, velocity increases and the channel both deepens and widens as flow reaches towards the banks once again. In terms of the supporting services provided by the stream, increased flow volume, velocity and decreased residence time all enhance the ability of the stream to manage higher levels of phosphorus by diluting the load and flushing it from the system rather than allowing nutrients to be stored in the sediment. This in turn helps the stream perform regulating services in relationship to the algal community, limiting the growth by reducing inputs of light (limited by increased shading of portions of the channel near the banks and by diffusion within the deeper water column) and lowering water temperature (metabolically disfavorable). This may in turn have the unfortunate drawback of limiting primary production by algae within stream but at the same time opens the door to a competitive advantage for other primary producers within the channel. The increased flow should, overall, improve provisioning services by increasing the diversity of habitat and resources within the stream, as well as by providing conditions more favorable to fish populations resident during the summer. Increased flow helps to maintain channel widths and prevent deposition of excess sediment, but may increase erosion due to increased velocities.

- **Flow augmentation during summer months creates direct benefits for human well-being such as increased access to recreation and indirect benefits to human well-being through the reduced impact on other ecological services.**

- **Human well-being is also impacted by flow management decisions throughout the year and between years as a trade-off exists between storage of water for augmentation and sufficient storage space to prevent winter flooding.**

Flow management impacts human well-being as well as ecosystem services. In order to provide increased flow during the summer, greater levels of flow must be stored during the winter. Increasing the available storage in reservoirs translates to costly expansions of existing dams or siting of new dams. These projects result in a direct cost to tax payers or sewerage customers, but do improve the economy in the short run by creating construction related jobs and in the long run with fewer but more permanent management positions. Recreation is improved both by the increased summertime flow in the channel (which allows more fishing, boating and swimming by reducing algal flow, improving balance within the riverine community and improving general water quality and boating conditions) and by the construction of new reservoirs (utilized for boating and swimming recreation). However, other recreational uses of former valley floors and forests are decimated by flooding to create a reservoir. Indeed, as we will see in the deeper discussion of reservoir expansion and creation, the potential loss of communities and ecosystems generates considerable apprehension in the community regarding impacts on local well-being. While siting of a new reservoir directly threatens the area on which it is slated to be constructed, the new reservoir also represents increased flood and drought mitigation for other communities within the county, and this tradeoff generates considerable debate.

Reducing winter and spring flooding itself is associated with ecological costs as the channel becomes more disconnected from the flood plain. Seasonal flooding may provide an important link to floodplain resources and habitat, and thus reduction of winter flooding may reduce overall biodiversity within the channel, possibly the floodplain as well. The impact of reduced flooding on the flood plain may include dramatic reduction in the delivery of sediment and nutrients (beyond what is desirable, leading to degradation of the channel banks), loss of biodiversity, and may yield a more static environment than one naturally reworked by the migration of the channel. However, preventing the migration of the channel may be perceived has improving human well-being since it protects human safety and property values, investments, reduces potential liability and insurance costs within the floodplain. Conversely, when flow is stored for augmentation and not utilized the following summer, the next winter's flood storage is greatly diminished.

In order to get a better idea of how well flow management in the basin is contributing to the greater water quality efforts throughout the basin, we can consider the impacts of strategies employed in wet years and in dry years, as well as the potential impacts of efforts to increase winter precipitation storage.

**Strategies for Wet Years**

- **During wet summers, flow managers face three primary challenges: long duration of spring rains lead to excess storage in the spring, summer rains reduce need for flow augmentation, and the late onset of drier months.**

- **While reducing the pressures associated with the normally dry summer months, all three of these scenarios reduce available storage during the next rainy season and reduce the ability to protect against flooding during the next season.**

- **Conversely, excess rain in the spring and summer months can provide insurance against longer-than-typical dry seasons in the fall (late onset of winter rains).**

- **Balancing these two concerns for human well-being has led in some years to flow experimentation and other activities designed to utilize excess flow in strategic ways; at other times, excess flow was less well managed, with serious impacts to human well-being and ecological services due to subsequent increased flooding.**

- **One strategy for balancing the need for storage of flow for flood protection and storage of flow for augmentation during both wet and dry years has been to increase use of inter-basin water storage and transfers.**

Three primary management issues rise during summer's with higher than average precipitation. First, the extension of the spring rainy season can delay the need for flow augmentation beyond the typical June start date. When this happens, natural flows in the river remain too high to create the need for, or even allow, flow augmentation to occur until mid or late July. Secondly, precipitation throughout the summer months may reduce the need for flow augmentation during those months. Finally, a rainy spring and summer can delay the onset of the fall dry season or prevent it from occurring at all. Thus, in rainy years, the challenge of what to do with excess stored flow can arise.

Having too much flow retained in storage at the end of a flow augmentation season reduces the capacity of the reservoir systems to store winter flow and prevent winter and spring flooding. During years with more rain than average, the reservoirs fill above the curve earlier, sometimes exceeding the storage requirements under the various BOR contracts. Rainier summers tend to also be cooler, resulting in less demand for irrigation water by TVID, who will often leave flow remaining in the Scoggins Reservoir at the end of such wet seasons. Similarly, municipal water demand falls during summers where evaporation of recreational waters (pools) and lawns reduces the need for consumption. Much of the water stored for municipal uses can therefore remain at the end of a rainy summer as well.

Only the sewerage agency has a strong continuing need for its stored flow during these rainier summers, and even that need is diminished. Thus, the sewerage agency can the dilemma of how to reduce stored flow behind Scoggins Dam to create more available storage for flood prevention the next season. The sewerage agency has little ability to simply ignore the problems posed by diminished storage capacity. The threats posed by potential uncontrolled flooding both to the ecological services of the stream and to the well-being of county residents could undermine progress made in water quality management throughout the area. Impacts on ecological services from increased winter and spring flooding may include damage to the channel form, increased sediment mobilization, increased bank erosion, increased storage downstream of phosphorus laden sediments, damage to niche habitats, alteration of in-stream bars and debris that contribute to the creation of summertime refuge pools, and interference with seasonal breeding and development of some species, among others. Conversely, some winter and spring flooding may benefit the ecological services of the stream, particularly the provisioning and cultural services, by enhancing the access of certain species to the floodplain at key points throughout their life cycle.

Increased flooding nonetheless poses significant economic damage to farmers and urban dwellers alike, as well as threatens to destroy physical improvements to the storm sewer system and other water management infrastructure. The cost of this destruction falls first on the sewerage agency, and ultimately would be passed to water consumers through unpopular increases in the sewerage rate. These direct effects on human well-being, combined with the potential setbacks in water quality improvements that in turn may diminish the appearance of benefits from the flow management system, could result in significantly diminished public and stakeholder support for flow management projects should the connection between summertime flow decisions and reduced winter storage become clear to the public.

Thus, it is in the flow management community's interest to balance the need for flow augmentation at appropriate times and in appropriate volumes with the need to remove all or most of the stored flow from the reservoir before the end of the season. This balance can present some tricky decisions. On the one hand, excessive flow augmentation too early in a rainy summer could lead to localized flooding in low lying agricultural lands. The impact of such flooding on the economic value of the land at that time would be devastating to that summer's overall farm productivity – while alleviating the risk of flooding throughout the basin by ensuring reduced flooding in the next season, such a strategy places all of the ecological costs and losses of human well-being on the backs of a few unfortunately located farmers within the floodplain. In turn, such a strategy would risk losing the support of the agricultural community for nutrient management efforts. Such support can be vital to reduction of phosphorus loading from eroded soils within the agricultural corridor because agricultural water management plans are by and large still voluntary.

If the sewerage agency elects to delay the start of augmentation until late July, they are faced with the challenge of having to disperse the entire stored flow before the end of the season. As we will see in the discussion of dry years, anticipating the start date and duration of drier fall weather (when augmentation becomes critical not for the prevention of algal growth but for the removal of decaying algae and prevention of a DO sag) can present its own challenge for balancing the level of flow augmentation throughout the summer. However, during wet years, the challenges of an early arriving and long lasting dry season have proven over the years unlikely to materialize.

A picture of a potential management strategy for summer months begins to emerge from this type of consideration. Any such management policy must be monitored on a daily basis and respond flexibly to changes in weather conditions to prevent disastrously high or low flows. In years where storage in the reservoirs (Scoggins and Barney) exceeds contract amounts, flow augmentation should begin at a moderate level as early in the season as possible, with careful attention paid to prevent flooding or critically low flows. Because the threat of diminished storage capacity within the basin leads to the risk of flooding within the basin, water stored within Scoggins Reservoir should be utilized before any storage available within Barney Reservoir. Waters stored in Barney should be reserved in the event of an unexpected turn in weather later in the season that requires longer or more voluminous flow augmentation in the fall. The sewerage agency should also hedge its bets by applying for the purchase of any possible excess flow stored behind the dam, which may later be used for continued experimentation or increased fall flow augmentation should the parties for whom the water was intended (TVID, JWC) fail to make full use of it.

Flow management during a wet summer should prioritize removal of the algal community during fall months to prevent DO sag. Wet summers generate smaller and less devastating algal communities by nature of reduced temperatures, increased flow and reduce sunlight on rainy days. Still, even under these ideal conditions, total prevention of the occurrence of algal growth is not feasible. Nor is it desirable. During the hotter months of July and August, when algal growth can be diminished but not eliminated, a moderate level of flow augmentation assists in increasing velocity, reducing residence time, increasing mixing, increasing shading, reducing water temperatures and diluting nutrient concentrations. It allows for the continued draw down of stored water to increase available storage for the following winter while reserving stored flow for fall augmentation.

By contrast, fall augmentation in wet years should begin in September and should continue aggressively with high levels of augmentation until natural flows resume. An aggressive high flow augmentation regime in September and October (and sometimes through November) will prevent the decay of algae from creating a debilitating DO sag in the reservoir reach of the channel by flushing such decaying matter out to the larger Willamette system. A high flow regime at the normally drier time of year does have potential draw backs for the greater ecosystem functioning. In particular, supporting and regulating functions tied to seasonal life cycle patterns of various species may be harmed, interfering with migration, reproduction, or growth. Aggressive fall augmentation can also pose risks to channel stability. However, these risks and interferences are likely to be significantly less than those posed by uncontrolled flooding during the winter and spring months.

From the perspective of wet years, additional storage of water in extrinsic basins for inter-basin transfer to augment flow within the Tualatin basin is considerably less risky than the storage of excess flow within the Tualatin basin at the end of the summer augmentation season. While this may make expansion of the Barney reservoir and other inter-basin transfers more appealing, expansion of reservoir capacity in the Tualatin Basin could create enough storage capacity to avoid inter-season storage complications. It may additionally serve to help meet growing population and industrial demands for water, as well as potentially higher demand for irrigation water as climate regimes shift. These potentials are discussed further below.

**Management Strategies for Dry Years**

- **While more common, dry summers can present specific flow management challenges, particularly when the length of the summer season is extended (spring rains end early or winter rains come late) or when drier than average conditions throughout the year (or in consecutive years) lead to flow deficits.**
- **Under these conditions, the primary concern is calibrating the timing and volume of flow throughout the summer season to meet either flow targets or water quality goals while fulfilling all other contracted uses without running short of stored water before the agricultural and flow augmentation seasons end.**

- **Effects on ecological services are compounded during dry summers which tend to be also sunnier and warmer than average summers, creating conditions favorable to rapid algal growth and thus increasing the need for preventative flow augmentation to reduce the effect of such growth on other ecological services and human well-being.**

- **Human well-being during dry summers is significantly impacted when stored flow fails to meet all uses throughout the dry season and when the rights of some water users are curtailed prior to the end of the year.**

Like their counterparts, dry seasons pose a handful of specific management challenges. Dry conditions during the summer usually begin around the middle of June, when spring rains finally peter out. However, there is considerable variation between years in the precise patterns of temperature and precipitation. In some years, the dry season begins early or ends late (extended dry season issues). In others, the problem is not merely the duration of the absence of rain, but the extent of its absence – that is, in some years, so little rain falls as to cause even more drastically reduced natural flows (drought issues). The occurrence of unusually dry conditions in subsequent seasons present unique issues as well, as can a drier than normal spring preceding the summer (inadequate storage issues). Finally, sometimes the combination of extremely high temperatures with low precipitation increases the impact of evaporation and transpiration on the basin, driving up demand for water consumption at the same time that supplies are low (supply-demand issues). These circumstances share common themes faced time and again in flow management during dry summers: is there enough supply to meet normal demand? Will demand be enhanced by low precipitation, hot temperatures or a combination of the two? And will the fall flow augmentation season be unusually demanding this year?

The decisions required to balance concerns about running out of stored water and flow augmentation needs are more difficult to make in dry years than in wet years – the blessing of abundant stored flow may create the risk of reduced storage capacity the next year, but wet summers tend to be more predictable. When summer weather conditions are dry, flow managers need to attempt to predict how long dry spells will last and when relief will come (and in what volume). TVID and JWC manage their flows primarily in response to predicted user demand – both must try to guess how much water will be needed for irrigation or municipal consumption throughout the summer, and when additional precipitation might refresh stored reserves. Because the sewerage agency utilizes its stored water for flow augmentation with the goal of improving water quality, it must consider a wider variety of factors. The sewerage agency must first meet its permit obligations for the augmentation of flow or face a reduction in the nutrient load allowed within its effluent. The latter option is costly and depending on the limitation, possibly infeasible (more so in the case of ammonia than phosphorus), thus potentially exposing the sewerage agency to further NPDES litigation.

Thus, the agency must assess how to meet its permit obligations for flow augmentation throughout the season based on the anticipated natural flow each month. In order to do that, the agency must consider the same weather factors that TVID and JWC consider in predicting consumer demand, namely temperature and precipitation. The sewerage agency must also consider, however, the release of flow by TVID for irrigation and JWC for municipal use. All of the water released for these uses travels within the channel for at least a portion of its course – in order to prevent localized flooding due to too high a release, the sewerage agency must be careful to monitor the orders for release of both TVID and JWC, while still delivering sufficiently augmented flow to the reservoir reach downstream of the withdrawal points of irrigation and municipal use. These decisions are balanced very carefully each summer in response to the three patterns of conditions that we have noted, and each should be considered in turn.

*Low storage due to low spring rainfall:*

When faced with low initial storage of water due to less productive winter and spring rains, the sewerage agency has little hope of making up the difference over the course of even a normal summer, let alone a dry one. Anticipating that they may run out of water before the late summer, the sewerage agency's response is often to reduce daily augmentation in an effort to try to spread out what precipitation has been stored over the course of the season. This occurred in 1994 when spring storage was so worryingly low that flow targets were reduced from 150 cfs during the height of the algal growth season (June through August) to between 100 cfs and 120 cfs. The sewerage agency hoped thereby to ensure sufficient storage to last until the end of the fall dry season, typically in October.

As noted above, this reduction in flow augmentation triggers a trade off under the NPDES permit. Flow augmentation is intended to alter the environmental conditions that favor algal growth such that the concentration of phosphorus in the channel is no longer the limiting factor. Although there are high natural background levels of phosphorus in the channel, reduction of anthropogenic loading of phosphorus to the background level did yield positive results in algal growth control during the early years of water quality management. Flow augmentation, then, is designed to allow the WWTPs to operate at a cost efficient level of phosphorus removal while at the same time ensuring that gains in water quality are not compromised by limiting algal growth through a variety of changes in environmental factors.

To reiterate the points made above, flow augmentation increases velocity and decreased residence time, as well as increasing the depth and width of the channel to more bankfull conditions. The concomitant increase in shading along and within the channel as well as the constant refreshing of water with cooler augmentation flow reduces the temperature within the channel as well as the input of light. Combined, these factors greatly reduce the influence of the algal growth even with a slightly higher than desirable input of phosphorus from anthropogenic sources. In terms of the sewerage agency's NPDES permit obligations, this trade off when effective allows for less rigorous phosphorus treatment (although with advances in bio-P removal, the cost factor has become decreasingly important). This trade off also plays a role in the agency's combined MS-4 permit obligations as increased flow countervails the effects of stormwater and other NPS sources of nutrients.

In terms of the MEA tool, the strategy of limiting flow augmentation during the summer months to save flow for the fall months causes a number of shifts in ecosystem services as compared to both consistent high flow augmentation and no flow augmentation. To generalize, some flow augmentation is always better than no flow augmentation. Even when augmentation only results in a target of a mere 100 cfs, the augmented flow far exceeds what the natural flow in the channel would have been. We have described above how any level of flow augmentation contributed to the streams ability to regulate both the phosphorus cycle and the conditions favorable to algal growth. Even low flow augmentation also has positive benefits on the cultural services of the river. While the algal growth may not be as well controlled as it would have been under high flow conditions, the lower level of flow augmentation still mitigates algal growth and keeps large mats from forming as the velocity continues to move colonies through the system.

The mere addition of flow the channel itself increases recreational and spiritual opportunities during summer months in the reservoir reach, and protects the value of property along the river and near Lake Oswego. Treatment costs for Lake Oswego diminish substantially in years where any flow augmentation occurs. Supporting services are also enhanced as the competitive advantage of algae is reduced allowing for greater diversity of primary producers. Even a slightly increased summer flow increases habitat diversity within the channel and the ability of species dependent on higher levels of dissolved oxygen and cooler temperatures to survive the summer months. The improvement of these ecological services translates to the improvement of human well-being as costs related to water quality maintenance are reduced, recreational opportunities are increased and the identity of the region, tied to its landscape and environmental values, is reaffirmed.

Reserving flow to the fall offers a number of environmental benefits as compared to a strategy of releasing high flows early in the summer at the risk of having no fall augmentation. Although the decision to augment more heavily in summer or in fall is primarily a choice between two unfavorable options, the loss of flow augmentation during the fall season can in fact be more devastating to ecosystem services and human well-being than low flows during the summer. Flow augmentation in the fall is directed more at removing the remains of the collapsed algal communities than preventing further algal growth. As fall progresses, primary production in the stream channel begins to shut down due to the loss of photosynthetically available light. As days shorten, ambient air and water temperatures also decline, further retarding growth of the algae. This loss of productivity occurs whether flow levels are high or low. Nor does the concentration of nutrients within the water column matter much at this point.

The seasonally optimal conditions for algal growth have ended and climate becomes the limiting factor.

The death of the algal community, however, causes problems of its own. As growth declines and is replaced by senescence and mortality, decaying algae accumulate along the channel bottom, where they are consumed by detrivores. This bacterial community consumes vast quantities of oxygen during its metabolic functions – if inputs of oxygen to the system from the atmosphere are low (as can be the case in the reservoir reach when sluggish low flows fail to mix additional oxygen into the system mechanically), this consumption of oxygen can resulting in a DO sag sufficient to suffocate out other aquatic life forms, particularly invertebrates and vertebrates that depend on DO for respiration. If the rate of flow in the channel is low, the mass of decaying algae will remain largely in place and a DO sag is virtually inevitable. However, fall flow augmentation can correct this imbalance by flushing decaying algae from the system. Indeed, this mechanism does occur at some point in the late fall as the weather patterns shift to increasing amounts of precipitation, causing natural flow to increase sufficiently to remove the decaying algae. Flow augmentation during the summer months can cause algal growth to decline early, however, and often the need to remove algae to prevent a DO sag arises long before the rains resume.

Thus, fall flow augmentation between the end of the algal growth season and the beginning of the rainy season supports many ecological services. We have already seen that flow augmentation in every case supports the river's ability to regulate nutrient cycles and primary production, as well as cultural services such as recreation and community identity. These effects on ecosystem services continue to have similar effects on human well-being. Fall flow augmentation in particular supports regulation of dissolved oxygen within the stream channel, both by increasing the mechanical input of oxygen (in-channel mixing as well as at the time of release from the reservoir to the channel at the dam) and by reducing the consumption of oxygen by detrivores. Fall flow augmentation may have the additional benefit of helping to maintain channel structure and prevent sedimentation. As velocity within the reservoir reach declines, suspended sediment delivered from upstream (which has remained in suspension due to the very fine nature of loess particles) begins to have time to settle out of the system. Settlement of these soil particles reduces delivery of sediment to the Willamette system, and there may be some long term effect of such reduction should that larger riverine system become sediment starved, possibly leading to increased erosion there or upstream within the Columbia basin.

The impact of the Tualatin system on the vastly larger Willamette and Columbia basins, however, is unknown and would be purely speculative without significantly greater work. We do know that deposition of these particles within the Tualatin in effect stores phosphorus laden sediment which will release phosphorus to the system slowly over time in balance with the concentration within the water column. Such sediment will also be stored until the next significant flood event, which may occur in late spring, exposing more sediment to the greater water column and potentially hastening the release of phosphorus immediately prior to the next algal growth season.

The tension between the need for summer flow augmentation and fall flow augmentation unsurprisingly leads to the tendency to be overly conservative in apportioning water throughout the season. For example, in 1994 19% of the sewerage agency's stored flow remained at the end of the season. Over the years, the agency has accumulated more experience managing flow and communication between the three major stakeholders in flow management has improved such that this tendency to over-reserve flow has diminished. As we have seen, the overall paradox facing the flow manager for the sewerage agency is to guess when it is going to rain and respond quickly to stop release of flow and prevent flooding (or, to anticipate the release of flows by TVID and JWC to achieve the same purpose), as well as to predict how long the dry season will last to apportion the water over the course of the summer. When storage is low at the beginning of the season, the issue of reduced storage capacity for the following winter is not much of a concern, and the sewerage agency can rely on other agencies to utilize all of their available portion of water over the course of the summer. Instead, apportioning flow throughout the course of the summer in balance with other uses becomes the challenge. Illegal withdrawals of water outside of or beyond a water right make it difficult to ensure adequate stream-flow reaches the reservoir reach. These illicit withdrawals can rise during dry summers, driven by a number of factors including reduced storage on individual properties, increased cost of municipal water, misunderstanding of the law regarding water rights, and of course pressure from evaporation and transpiration to apply more water to crops and lawns.

*Long dry seasons:*

Even when the reservoir at Scoggins Dam fills completely by the start of the flow augmentation season in June, extended dry weather conditions during the fall threaten to upset the balance between summer and fall augmentation schedules. This very event occurred in the dry season, which began as usual in late June with normal storage but extended into November with below normal natural flow requiring greater augmentation late in the season. Typically, rains in the Tualatin River basin resume during September or October – even a few weeks delay in resumption of the rain can cause significant problems when reserved water has already been used for high levels of summer flow augmentation. By the end of the 1999 season in November, the reservoir was drawn down below normal as a result of full use of all water rights. By extension, the depletion of the reservoir entailed adequate storage available to prevent the winter and spring flooding in 2000.

It would seem, then, that an extended dry season might be viewed as a positive thing so long as the water holds out, since it decreases the reservoir water level and thereby increases flood protection for the following year. However, this season coincided with an increase in the flow augmentation requirements under the NPDES permit meant to address temperature and DO. Although a long dry fall can never be predicted with accuracy, such an event occurred with sufficient frequency to raise caution within the sewerage agency. Wary of the possibility that a long dry season could require additional flow augmentation and that a hot, dry summer could reduce the amount of excess irrigation and municipal water remaining for purchase to make up for any shortfall, the sewerage agency attempted to balance summer and fall needs without any certainty as to what would transpire. Thus, the agency managed in 1999 to balance the entire season by beginning with less flow augmentation in July and August, then increasing to a max of 200 cfs through November to flush the system. Heightened late season augmentation was supported by water stored in the Barney Reservoir due to expansion there to increase capacity to store municipal water reserves.

In terms of ecosystem services, we have seen that fall flow augmentation is critical to preventing DO sag, but that lowering summertime flow augmentation as insurance against fall needs comes at a cost to regulation of algal growth and cultural services, as well as increasing water treatment costs. Dry seasons also entail daily flow monitoring by the sewerage agency with the potential for daily adjustments in the order, as opposed to the weekly or less schedule in wetter years. This comes no doubt at a cost of time and other resources, but provides more detailed information for management decisions, which combined with communication between the major users, enhances decision making under pressure. It also helps to provide abundant information for forecasting and planning for the season as a whole, allowing managers to identify potential issues early on.

*Consecutive dry seasons:*

The years 2000 and 2001 provided consecutive dry summers, which entail the additional problem of inter-year water budgeting. We have already noted the potential benefit to flood protection of using most or all of the water reserved behind Scoggins Dam during a flow augmentation season. This option may appear appealing, perhaps unavoidable during hot, dry summers followed by extended dry conditions in the fall. However, failing to store water between seasons within Scoggins Reservoir poses serious risks for future flow augmentation seasons. The over-withdrawal of water during 2000 combined with a drier than normal winter resulted in a deficit of water at the beginning of the 2001 season, a condition which combined with a long, dry summer in 2001 to create a dangerously difficult management situation that fall.

When inter-year reserves of water are not maintained, ecological services are severely hampered by the inability to augment flow adequate in either summer or fall. Under these conditions, algal growth is not curtailed by regulation of the phosphorus cycle or limitation of growth factors during the summer, and the decaying algal community is not removed by flow augmentation in the fall. Diversity within the stream channel is severely hampered by algal growth, which given perfect conditions outcompetes all other primary producers during the summer. In the fall, the DO sag created by the activity of the detrivores severely constricts the range of species which can survive in the channel. Curtailing the diversity of primary producers and other stream life in turn curtails all related ecological communities within the watershed, and the potential harm to fish populations threatens recreational opportunities and other cultural services. Indeed, the low reserves of water in Scoggins Lake hamper not only recreational opportunities lost along the Tualatin River channel due to diminished flow, but recreational opportunities such as boating, water skiing and fishing on the lake itself.

Low reserves of water between years translate to reduced water availability for all uses, and thus impacts human well-being pervasively. When stored water is insufficient to meet irrigation needs, many irrigators retain rights to withdraw water directly from the stream channel. However, in a dry summer, these rights must be curtailed by the water master to protect more senior rights as well as to maintain state mandated in-stream-flows. Increased in-stream withdrawals both legal and not have a tendency also to increase direct conflict between neighbors over water resources as well as political tensions in the area. Thus, agricultural productivity is often hit hard by the reduction in stored water caused by a failure to reserve between years. Municipal water resources can similarly be curtailed, although the expansion at Barney Reservoir was designed to prevent interruptions in service and rate hikes under these conditions. As the JWC increasingly relies on Barney, however, the potential use of water reserved there for late fall flow augmentation diminishes, increasing the risk to the sewerage agency of running out of water. When municipal and irrigation flows from storage and the channel run low, reliance by those who have wells on subsurface storage increases as well, threatening to lower the water table dramatically during extended dry spells and leading to increased management problems related to groundwater and increased community tension.

The problems posed by extended dry seasons are confounded by increased demand for water resources as just the same time that supplies are low. Why is absolute demand for water increased in dry years? Increased sunlight and heat lead to greater rates of evaporation and transpiration (as a result of both increase total productivity and increased metabolism within individuals). Lawns brown, trees wilt, crops fail. Municipal demand for water during a hot summer increases as homeowners attempt to protect their property value by water lawns and citizens seek relief from the heat through artificial water recreation activities such as swimming pools and waterparks (which represent a significant loss to evaporation over the season). Agricultural demand increases both in traditional field agriculture (where loss to both evaporation and transpiration increase as temperatures and available sunlight climb) and in nursery production. Container nurseries in particular, a booming industry in the Tualatin River basin due to long growing seasons and generally abundant water supplied, pose a significantly increased need for irrigation water in hot, dry months as soil within containers has little ability to retain moisture over time. Only industrial demand for processing water may remain relatively constant over the course of a summer.

**Recommendations**

- **The challenges of individual or consecutive dry seasons can only be met through careful inter-agency planning and may also require increases in the efficiency of water delivery to agricultural and municipal uses, reduction in demand for water resources during summer months through voluntary or regulated conservation measures, and development of additional storage within this basin or neighboring basins.**

- **Increased storage may also reduce the risk of winter/spring flooding; however, increasing storage itself has significant implications for ecological services and human well-being, particularly where creating new dams and reservoirs is concerned.**

Due to the risk of consecutive dry seasons, several precautionary measures could be taken in managing flow over the course of a given summer. Currently, stakeholders place primary importance on co-operating to fulfill the needs of their respective constituents while improving water quality to the degree possible each summer. While the level of inter-agency communication and coordination is admirable, and the approach collectively taken certainly adjusted to the watershed scale, a problem of perspective arises when the focus is on a single season. This narrow focus misses the relationship between years, and as we will see, it is this very relationship of water stored between seasons and over time that may become a significant challenge in the face of environmental changes. To avoid problems like those faced in the 2000-2001 seasons, water should be conserved between seasons in Scoggins reservoir to the greatest extent possible. Setting a concrete minimum inter-season minimum storage goal will help managers include inter-season conservation in their planning decisions. However, given the legal and regulatory framework in Oregon, such an agreement would likely be purely voluntary on the part of each agency – this may be for the best as reducing inter-season storage when high levels of precipitation are anticipated the following year could help prevent flooding. Such predictions may be based on decadal climatic patterns discussed in the following chapter.

Of course, conservation of stored water is only possible if sufficient water to meet the absolute minimum needs has been stored prior to the beginning of the flow augmentation season. Therefore, increasing storage capacity within the basin is advisable. Storage capacity within the basin includes both surface water storage and groundwater storage. Traditionally, efforts to improve water storage have focused on surface water storage, primarily in the form of building dams or expanding existing reservoirs. Significant debate has surrounded options such as raising the height of Scoggins Dam or building a new large dam in the Cherry Grove area, and this debate will be considered more carefully below. Additional surface storage options may include building a series of smaller reservoirs at lower cost and risk, restoring and conserving wetlands, and building above ground storage tanks and towers. Some discussion has been made of restoring ground water storage as well by means of injecting wells, but insufficient data exists regarding the safety and risks of such an action to analyze it adequately here. Overall, increasing storage capacity serves the dual goals of transferring water wealth from the abundant winter and spring months to the drier summer and fall as well as reducing the risk of flooding during the rainier season. The transfer of water wealth between seasons serves the additional function of preparing the watershed (and the county) for future population growth and expanding land use conversion.

Water wealth can also be conserved through the re-use of various types of water currently considered to be waste. With help from the county, the sewerage agency should consider storage of gray water from winter months for commercial use during summer to reduce demand. This could create an increased cost during the winter/spring treatment months as stricter standards for removal of phosphorus could be required. Storage for this gray water would need to be created, and significant efforts made at public education and marketing. Traditionally, recycling of municipal waste water for commercial irrigation has been largely misunderstood by the public, leading to ungrounded fears of food system contamination and so forth. However, with adequate public education and marketing strategies, such gray water could be used for commercial purposes not related to food production, especially lawn maintenance, thus reducing pressure on the reservoir in dry summers.  This does occur to a limited extent within the basin (e.g. some golf courses) but could be significantly expanded.  Such gray water could also be used to foster groundwater recharge by nourishing wetlands.  Indeed, the sewerage agency is experimenting with such projects on a small scale already.  The key to conserving water wealth between seasons, however, would be to store winter effluent generated by the treatment plants for use during summer months.  WWTP effluent generated during the summer months is already calculated into the required flow targets – redirecting that effluent to other purposes would handicap efforts to manage flow rather than ease demand burdens.  Thus, storage and re-use of winter gray water would generate additional benefits in existing gray water projects.  Similar projects could be applied to industrial process waste water (which is generally treated to a very high level of purity and handled separately from the remainder of the county's waste water) and potentially to winter/spring stormwater runoff (if such were captured, treated and stored for summer use).

Storage and use of precipitation falling within the basin itself for flow augmentation is ideal as it reduces the impacts of inter-basin transfers on other watershed.  For example, the expansion of Barney Reservoir came as a cost to the Trask River watershed and its coastal estuary in terms of ecological services and may have diminished human well-being in the basin as well.  While the governments within the watershed were compensated for at least some of this loss through the purchase of water by JWC and others, no comprehensive ecological assessment has yet been done to identify all of the losses entailed.  Despite this potential negative impact on the Trask, inter-basin transfers do serve an important function within the Tualatin watershed during times of drought. The Trask watershed often receives rain in dry years when the Tualatin does not due to its location on the coastal side of the Coast Mountains. Free from the rain shadow created by the mountains, the Trask basin remains humid throughout most years. Thus, flow managers should continue to identify and maintain ability to access stored flow from other similarly situated basins in case of emergency, but not as a primary source of flow augmentation.

Considering the vast amount of water stored and released from Scoggins Reservoir each summer, it seems somewhat counter intuitive on the face of things that sometimes insufficient flow reaches the reservoir reach to prevent algal growth. After all, if all of the irrigation and municipal water released daily were to remain in the channel past the reservoir reach, the need for flow augmentation by the sewerage agency on many days would be greatly reduced or eliminated. Of course, the flow for irrigation and municipal use is withdrawn upstream both as a matter of convenience (closer to the need) and to avoid water quality problems that develop further downstream. If these hurdles could be overcome in a cost efficient manner, it might be beneficial for the flow management committee to reconsider withdrawal locations for irrigation and municipal flow. With the creation of several smaller new reservoirs throughout the valley, some of this flow could be redirected through tributaries as well, improving the temperature and quality of water entering the Tualatin. Changes such as these would represent major reinvestments in infrastructure even under the lowest cost scenarios, but could also improve local economies through job creation and reduce the costs associated with maintaining water quality in the long run. Retaining irrigation and municipal flows within the channel through the reservoir could allow the sewerage agency to release a more consistent rate of flow augmentation throughout the summer season and prevent the risk of flooding as well. Potential difficulties in engineering and potentially high costs in terms of delivering the water back upstream via pipelines to agricultural areas or in terms of treating drinking water that has been exposed to algal growth may prohibit adequate consideration of this option.

However, there is one kind of withdrawal from the river channel upstream of the reservoir reach that can and should be more directly managed: illegal water withdrawal in the absence of or in excess of a permitted water right. Keep in mind that under Oregon water law, an owner of property bordering a river is not necessarily entitled to the use of water in the way she might be on the East coast under the reasonable use doctrine. Rather, riparian owners can only withdraw water to which they have acquired a right, and only subject to the rights of more senior rights holders. It is the job of the water master to keep track of these rights and enforce priorities throughout the summer months. Most large scale water withdrawers adhere to the rules of game because they are being carefully monitored, and this is especially true of agriculturalists who derive their irrigation water primarily from the reservoir and secondarily from their water rights. As the watershed urbanizes, however, small scale agriculture and residential properties dominate the river banks. Often, illicit water withdrawals are the result of a misunderstanding of Oregon water law – increasing existing educational efforts could only help. Enforcement against small time water withdrawals is generally viewed as ineffective because the total water withdrawn by these users is negligible in contrast to the flow targets.

In a situation where every gallon of water becomes extremely precious due to drought and meeting even minimal flow targets is difficult, small time water withdrawals can matter. Identifying and prosecuting each of these small water withdrawals is time consuming, and the total effort costly.  By increasing enforcement over time, public awareness of the law and understanding of its consequences could rise and therefore reduce the number of illicit withdrawals that occur each summer, even in summers of increased climatic pressure.

*Increasing Storage*

The recommendations above for addressing inter-seasonal storage concerns related to flow management highlight the increasing need for further precipitation storage within the basin. Since European settlement, the landscape of the Tualatin valley has been manipulated to remove wetlands and marshes to produce productive agriculture lands along the valley floor (and later, for suburban development projects).  Additionally, the seasonal flooding of the river has been controlled, disconnecting the river from its floodplain.  Combined these actions significantly reduced surface water storage within the watershed as well as limited recharge of groundwater systems while increasing the proportion and rate of stormwater runoff during rain events.  In so doing, settlers altered the hydrology of the Tualatin valley system from one which naturally stored water between the wet and dry season (and potentially between years) to one which exports this precipitation to the Willamette river system more efficiently.  The reduced natural storage has created a paradox in which abundant winter and springtime precipitation are followed by a deficit of water during the summer and fall months.

The impacts of this land use transformation are manifest in the many environmental problems of the basin.  In terms of ecological services, disrupting the natural hydrology of the basin (which was once in balance with the area's climatic patterns) has interfered with the basin's ability to regulate the availability of water for various plant and animal communities as well as the surface and subsurface capacity to store fresh water, thus reducing the basin's ability to provision this resource year round. The many regulating and supporting functions performed by wetlands have been lost, including their ability to regulate nutrient cycles within the watershed and retard the addition of nutrients to the river from runoff. As the relationship of the river to the floodplain has been virtually disconnected, species dependent on seasonal flooding for reproduction, feeding and habitat have declined, restricting provisioning services of the basin as a whole. As wetlands and marshes have declined, so too have related hunting, fishing, hiking and wildlife viewing opportunities. These lost recreational activities represent a loss of cultural services, as does the diminishment of the landscape from which area residents derive part of the identity as Oregonians.

The loss of these ecological services translates to real losses of human well-being as well. Some of these losses could be assessed in terms of increased costs – increased cost of providing clean drinking and irrigation water, increased cost of replacing exported nutrients, increased cost of replacing recreational opportunities by traveling to other locations. Other losses are harder to quantify in terms of their economic impact. Disputes over water rights are heightened by diminishing water storage within the basin. Community identity tied to the landscape is harmed by loss of key features of that landscape. Family and local traditions may be impinged by the loss of particular species valued for hunting, fishing or wildlife viewing opportunities. Although more difficult to assess, these losses greatly impact the quality of life of area residents.

*Increased Storage at Scoggins Dam:*

Scoggins Dam was built in an attempt to correct at least the economic troubles caused by the loss of storage capacity by storing winter and spring precipitation for summer use by cities and irrigators. Expansion of the Scoggins Dam to increase the storage capacity of Lake Hagg has been explored at various times and rejected primarily due to the geological risk associated with the area. (A larger dam is calculated to pose a greater threat to downstream communities in the event of a earthquake or other geologic disturbance – while such events are unlikely, the increased potential for damage due to the expansion diminishes the level of risk deemed acceptable by both the county and the federal government, who would partner to fund any such expansion.) Those who advocate expansion however sight the numerous benefits increased storage would provide. It is clear that population growth within Washington County will continue to increase the demand for municipal water and waste water treatment, regardless of the urban growth boundary limitations discussed later in this paper. Increased storage of any kind would help to alleviate this population pressure both in terms of providing more storage of water for municipal consumption and in terms of increasing the amount of water available for flow augmentation in the summer. In the event that further significant improvements in phosphorus withdrawal cannot be made, total loading of phosphorus to the river as waste water volume increases may become an issue requiring dilution. As the flow of waste water to WWTPs increases, so too will effluent flow to the river system, which is generally viewed as a positive thing. So long as the relative concentration of phosphorus in the effluent remains constant, such a situation would benefit flow management concerns. However, should phosphorus loading to the treatment plants exceed the capacity for biological phosphorus removal and thereby increase the concentrations in the effluent, the balance between flow and phosphorus concentration will become increasingly important.

If Scoggins Dam were raised to increase storage in the reservoir, it could also be concurrently upgraded to allow withdrawal of water from various depths within the lake for various purposes, thus allowing warmer surface waters to be utilized for crop irrigation, mid-temperature waters (which due to depth would contain less algal growth and therefore require less treatment than surface waters) to be used for municipal supply, and the deepest and therefore coldest water to be used for flow augmentation. Such a scheme might improve the impact of flow augmentation on controlling algal growth within the river channel provided that the colder flow augmentation entered the system proximately enough to the reservoir reach to remain cold within that section of the river's course. If released at the Scoggins Dam, such water would surely warm as it passed through wide, shallow and unshaded sections of the river above the reservoir reach. At least theoretically, such water could be piped to the reservoir reach in order to directly augment flow there and maintain the benefits of colder water. Such an option would also bypass factors which could diminish flow before it reaches the area where it is most needed such as illegal water withdrawals from the channel or evaporation from the channel.

Additionally, larger volumes of flow could be added to the channel directly at the reservoir reach without risking increased erosion in the upper reaches of the river due to increased velocity of flow over time. Piping colder flow directly to the reservoir reach would be a costly option though and may come at the expense of riparian restoration projects throughout the basin which stabilize banks (reducing erosion and sedimentation problems) and shade the stream channel. It may also increase already surprisingly high sewerage rates for consumers.

Increasing the capacity of Scoggins Dam has direct effects on the ecological services provided within the Tualatin Basin beyond the increased risk of catastrophic flooding and the impact on flow augmentation. Raising the level of Hagg Lake would improve recreational opportunities on and in the lake, and possibly improve regulation of algal growth within the lake itself (thereby reducing ‘seeding' of algae to the river and to Oswego Lake). However, increased boating, swimming and fishing opportunities would come at a cost to some housing developed near the lake (which would be removed prior to flooding of that land) as well as recreational opportunities of the surrounding forest.

Thus, the impact of the reservoir on human well-being would be shifted by any expansion. If the reservoir's capacity is increased, users of municipal and irrigation water benefit from lower costs and higher certainty that water will be available during the summer, although all county residents pay a portion of the county's share of the expansion costs (the remaining burden being born by BOR and the federal government, thus by extension, by tax payers nationwide). The sewerage agency would benefit at least from the increased capacity to store flow for augmentation, thus reducing management pressure during the summer and potentially alleviating inter-seasonal and inter-year deficits. The sewerage agency may also be able to effectively utilize the colder temperature of the flow by directing it through pipes to the reservoir reach. This would come at an increased cost to constituents of the sewerage district, and would entail the loss of flow augmentation through the upper reaches. The effects of that change would be mixed, reducing the potential for flooding caused by mismanagement of flow and erosion from increased volumes and velocities, but also reducing the benefits of additional flow to habitat and water quality in the upper reaches. Recreationalists who use the lake's body and surface for water sports would benefit, but other recreational uses would be diminished. Home owners near the lake would receive some monetary compensation but face loss of their homes and property. Future residents of Washington County would also benefit from the increased provisioning of water to meet their projected needs. Overall, if the increased risk of catastrophic flood were deemed tolerable (again, the risk of geologic disturbance remains consistent but the potential devastation of an event is increased), the expansion of Hagg Lake would be beneficial to human well-being but would cost certain members of society more than others. It is possible that several smaller reservoir projects or the use of more above ground storage tanks could provide similar benefits in terms of storage without increased potential for catastrophic flood and without shifting the cultural services currently provided by the lake and surrounding areas.

*Reservoir Expansion at Barney and Increased Inter-Basin Transfers*

Expansion of the Barney reservoir on the Trask River no doubt posed similar tradeoffs within that basin. However, Washington County residents and water users were shielded from those ecological impacts and changes in human well-being. In this way, an inter-basin transfer of water externalizes the costs associated with increasing storage of water between seasons. Instead of bearing a balance of costs and benefits, Washington County users paid a monetary premium for increased access to stored water for a variety of uses. The addition of this stored water from the Trask basin to the Tualatin basin produced changes in ecological services and human well-being in Washington County that were, for the most part, positive. Perhaps the biggest loss of human well-being related to the project was the financial investment made in raising the Barney reservoir itself. Water purchased from Barney ensured sufficient water for municipal use regardless of the status of Hagg Lake (as noted, the Trask basin receives more consistent precipitation due to its geography), thus improving human well-being.

The additional storage of water also ensured that water could be purchased for flow augmentation when Hagg Lake provided insufficient storage. In turn, the additional storage then acted like a form of insurance for the sewerage agency against poor winter and spring rainfall, and helped to stabilize flow augmentation, ensuring ecological benefits to the area. Despite these clear localized benefits to the Tualatin basin, responsible regional planning would require a much more thorough ecological assessment of the impacts of this inter-basin transfer on the Trask and its estuary.

*Cherry Grove Dam Proposal*

Perhaps the most highly contested proposal for expanding storage capacity within the basin, however, was the option of siting a dam downstream of the community of Cherry Grove. Placing a dam in the area would benefit the county as a whole while significantly harming the local community. In fact, siting of the dam downstream of Cherry Grove would require the community to be completely relocated and the area surrounding Cherry Grove inundated. We have discussed extensively above the general benefits to ecological services and human well-being that increased storage capacity would entail. Of all the options for locating dams throughout the basin, the Cherry Grove site was identified as the most affordable and lowest cost option for storing a large quantity of water within a reservoir, making it an appealing option to everyone except those who lived in the community.

The MEA provides a good basis for analyzing the impacts of the dam on the community of Cherry Grove and surrounding lands, many of which are less positive than the impacts of increased storage for the basin as a whole. By inundating the area, the dam and its new reservoir would not merely alter an ecosystem but would transform one landscape (valley floor) into an entirely different geographic feature (a lake) with an entirely different community of species. Because of the lack of any comprehensive ecological study of the basin, it is hard to determine which species and services would be displaced with any precision. Obviously, in gaining storage of water, the area would lose the communities associated with forests, fields and streams within the area. Species of aquatic life associated with lakes would take their place, and communities along the lakes edge would change to reflect the new interface between lake and field rather than, for example, forest and field. Increased storage of water in the valley would also change the character of the river upstream of the dam for up to several miles. The reservoir when full would essentially back up the flow of the river entering into it, slowing the velocity of the flow as well as widening and deepening the channel.

These changes in channel form would impact water quality and temperature as well as habitat, and could result in changes in the riverine community as well. Just as the channel upstream of the reservoir would be impacted by its creation, so too would the channel downstream of the river. Depending on how outflow from the reservoir were managed and directed, the entire flow regime of the river downstream of the reservoir could be altered in much the same way that the flow regime of the Tualatin River has become somewhat dependent on the management of Hagg Lake. No matter how the flow is managed, water exiting the reservoir and rejoining the stream down river will carry less sediment than the unimpeded flow did previously as the new reservoir serves to trap sediments behind its dam. This sediment starved flow could reduce the river's ability to regulate erosion and contribute to greater downstream sedimentation where flows slow within the reservoir reach. The lake could also become a trap for nutrients entering the system from the landscape, thus disrupting nutrient cycles and feeding algal growth within the reservoir itself.

Beyond these shifts in provisioning, regulating and supporting services, the utter loss of the community of Cherry Grove would pose a significant loss of cultural services associated with the valley in its natural state.  Cherry Grove is a primarily agricultural and rural residential area – if its lands were flooded, the displaced population of Cherry Grove would rejoin bordering agricultural communities where affordable land was for sale or relocate to suburban areas, increasing development pressures there.  The identity of the community itself would be lost, a factor which cannot be quantified by the mere compensation value of the properties to be inundated.  Investment in infrastructure and development of community resources such as schools and roads would become a total loss.

# Chapter 4 Looking Forward - Predictions for Climatic Change in the Pacific Northwest and Impacts on Water Quality Management

## A. Summary

Analysis of past trends in flow management provides one sort of useful insight into the effectiveness and appropriateness of such measures. However, proposals for new policy measures are short sighted if they fail to anticipate and adapt to impending changes in the most critical environmental factor involved in flow management, namely, precipitation. This section reviews the current literature to assess the effect of both short and long term climate patterns on flow management decisions, as well as the potential for climate change to affect precipitation in the region. Policy recommendations are then assessed in terms of this information utilizing the MEA framework.

The climate of the Pacific Northwest is influenced by decadal cycles as well as long term climate change. Although this research is limited to the impact of changing climate on ecosystem services, human well-being and sound management decisions, the interactions of land use change with these factors should also be considered in future studies. Decadal long climate cycles, caused by shifts in the course of the global thermohaline current and its associated weather patterns such as the El Nino, produce variations in temperature and precipitation in the Willamette Valley (of which the Tualatin Valley is a sub-basin) which during the 1980s and 1990s pushed conditions towards a warmer and drier state than during the preceding two decades (without, however, creating record warm & dry conditions). The El Nino Southern Oscillation (ENSO) itself impacts climate cycles in the region on a less than decadal frequency (approximately every 3-7 years), disrupting the normal delivery of several wet weather events during a typical winter (via the so-called Pineapple Express), blocking delivery of precipitation during el Nino years and increasing it in la Nina years.

Global climate change has also had a measurable effect on local climate patterns over the past few decades, and climate models call for increased temperatures which may increase the frequency of severe weather precipitation events during the winter while increasing demand for water resources during summer months, thus increasing both the risk of flooding during the winter and the risk of drought during the summer. Models at the global and local scale accounting for different geographic and anthropogenic factors give a wide range of predicted outcomes for the Pacific Northwest; for several reasons, global models tend to underpredict regional changes in temperature and overpredict regional increases in winter precipitation. Thus, the impact of global climate change in this region may result in an even greater deficit in the annual water budget than predicted.

In managing flow augmentation and flood prevention, then, careful attention must be paid to the impacts of long term climate cycles and global climate change on the annual water budget for the Tualatin basin. One way to address the challenges caused by shifts in precipitation between years in the Tualatin basin would be to employ models which attempt to predict the interaction of these climate variables and the resulting patterns of precipitation they may yield in any given year or over a period of several years. Consideration of longer term shifts in climate would also allow water quality and quantity managers within the basin to plan for the likelihood of more severe winter precipitation events combined with more frequent and longer summer droughts by increasing long term storage within the basin. These considerations may also lead to indirect water quantity management strategies aimed at increasing return flow to the river (while continuing to decrease the load of various pollutants) and decreasing demand for consumption of water during critical summer months, as well as riparian restoration efforts that may make conditions less favorable for algal growth.

B. Anticipated Climate Change

- **The climate of the Pacific Northwest is influenced by decadal cycles as well as long term climate change.**

- **Although this research is limited to the impact of changing climate on ecosystem services, human well-being and sound management decisions, the interactions of land use change with these factors should also be considered in future studies.**

- **Decadal long climate cycles, caused by shifts in the course of the global thermohaline current and its associated weather patterns such as the El Nino, produce variations in temperature and precipitation in the Willamette Valley (of which the Tualatin Valley is a sub-basin) which during the 1980s and 1990s pushed conditions towards a warmer and drier state than during the preceding two decades (without, however, creating record warm & dry conditions).**

- **The El Nino Southern Oscillation (ENSO) itself impacts climate cycles in the region on a less than decadal frequency (approximately every 3-7 years), disrupting the normal delivery of several wet weather events during a typical winter (via the so-called Pineapple Express), blocking delivery of precipitation during el Nino years and increasing it in la Nina years.**

Understanding the current climate of the Pacific Northwest allows us to understand the current hydrology, but what of tomorrow? Changes in global and regional climate cycles directly impact levels of precipitation, which is itself the primary driver of flow through a watershed. Put another way, changes in climate combined with the characteristics of a watershed and the uses to which humans put its resources lead to changes in watershed health. Thus, it is useful to consider longer terms trends in Oregon's climate. There is no better place to begin understanding such long term trends than with a consideration of the major climatic changes of the past which helped to shape the landscape in which the current river network exists as well as the ecological community in place today.

Perhaps the climate period that most impacted the character of the Pacific Northwest was the period of continental glaciations. These glaciers not only resurfaced the land, but displaced the routes of storms, as well as compressed and intensified storms, resulting in a climate that was colder and wetter than the current climate. Summer temperatures were likely 10 degrees C lower than current conditions due to higher frequency of summer rain events – even though winter snowfall in the region was not much different than today, glaciers were able to grow throughout the higher elevations of the Cascades. Increased summer precipitation and storage of winter precipitation resulted in increased erosion, transport and deposition of sediment in the valleys. The impact of these climate shifts is seen today in the high levels of available phosphorus in Tualatin valley soils and the ease with which this nutrient is transported to the stream. .

In a 2003 paper exploring the impacts of climate change, past and future, on water quality and other natural resources in the Pacific Northwest, Mote and others acknowledged the relationship between the impacts of climate change and the impacts of other human-driven environmental change:

> "Our assessment of the regional impact of climatic variation and change is placed in the context of other regional stresses… Population has nearly doubled since 1970, a growth rate nearly twice the national average. Human activities strain the natural environment in many ways, including direct human interventions in the landscape through such activities as dam building, timber harvest (which has also widely replaced diverse natural forests by single-species plantations) and land-use conversion… the consequences of include loss of old-growth forests, wetlands and native grass and steppe communities; urban air pollution; extreme reduction of many salmon runs; and increasing numbers of threatened and endangered species (Mote 2003)."

While we begin in this research only examining the relationship between climate and water quality in the Tualatin River, the concurrent impact of changing land use may be of even greater consequence. The combined impacts of both forces could be both more intense and perhaps novel, warranting consideration of land use as a factor as well. Integration of land use change analysis with the MEA tool would yield stronger results but is beyond the scope of our initial investigation.

Even in the absence of long term global climate change, the Pacific Northwest experiences decade long cycles in climate which greatly impact the region's hydrology. Willamette Valley temperatures were significantly warmer in the 1930s and 1940s than they are today. Throughout the 1950s and 1960s, temperatures were cooler, warming again during the 1970s and 1980s (although not reaching the highs of the 1930s and 1940s). Considering water year precipitation for Oregon Climate Zones during the 20th century, changes in long term trends are apparent. Annual variation in precipitation has become more extreme since the 1970s, with higher precipitation totals in extreme wet years and lower precipitation totals in extreme dry years. The periods between these pronounced extremes are shorter than in years prior, and no longer exhibit the two year alternating wet-dry cycle of decades past. Instead, these intervening periods manifest more as steps towards the next extreme period, be it wetter or drier. These trends are smoothed out somewhat in the five year running average trendline, which indicates a larger pattern of decade long wet and dry cycles since about 1960.

One factor that greatly impacts global climate cycles is the global thermohaline current circulating throughout the oceans. This ‘conveyor belt’ transports warm water from the Pacific Ocean through the Indian Ocean, around Africa and to Europe, where it sinks as it cools. This sinking current displaces colder water below it, causing a deeper counter current of cold water to run a southerly course through the Atlantic and back to the Pacific. The strength of activity in the conveyor belt is correlated with several climatic cycles, including frequency and intensity of hurricanes, precipitation in the Sahel, occurrence of el Nino events and according to Taylor and Hannan (1999), wet and dry cycles in the Pacific Northwest. Based on these observed trends, Taylor and Hannan anticipate that as we enter a more active cycle in the global conveyor, coastal Oregon and the Willamette Valley will experience wetter winters with more frequent flooding. Summers are expected to continue to be warm and dry overall (Taylor and Hannan 1999).

Climate cycles in the Pacific Northwest are also impacted by the el Nino – Southern Oscillation (ENSO) approximately every three to seven years. In an ordinary year, cool waters off the Western coast of South America extend along the equator into the Pacific Ocean, concentrating warmer water, and thus evaporation and precipitation, in the western portion of the Pacific and leaving the west coast of South America relatively dry. Combined with the polar jet stream (which delivers cool wet air to the Pacific Northwest), the subtropical jet stream delivers warm humid air from the southwestern Pacific to the Oregon coast. Known as the 'Pineapple Express,' this jet stream can deliver multiple severe wet weather events to the region in a typical winter. In an el Nino year, however, warming of the waters off the South American coast disrupts the usual delivery of warm moist air to the subtropical jet stream as the western Pacific correspondingly cools. The changes in sea temperature induce corresponding changes in precipitation as the South American coast experiences uncharacteristic rainfall and the western Pacific becomes drier. The polar jet stream will then dip to the south before returning north over Alaska, diverting weather patterns northward away from Oregon and resulting in less frequent precipitation and milder temperatures than in average winters.

Conversely, during la Nina events, the waters off South America cool even more than usual and as a result of all the corresponding effects, winter precipitation in the Pacific

Northwest tends to increase. These cyclic shifts in precipitation driven by the ENSO primarily impact winter totals, and thus are of more direct concern to planning issues related to flood control than summer water quality. However, because flood control planning decisions can have a direct impact on summer water quality, either positive or negative, the impact of these decadal winter season precipitation cycles on the hydrology of the area is of great importance.

- **Global climate change has also had a measurable effect on local climate patterns over the past few decades, and climate models call for increased temperatures which may increase the frequency of severe weather precipitation events during the winter while increasing demand for water resources during summer months, thus increasing both the risk of flooding during the winter and the risk of drought during the summer.**

- **Models at the global and local scale accounting for different geographic and anthropogenic factors give a wide range of predicted outcomes for the Pacific Northwest; for several reasons, global models tend to underpredict regional changes in temperature and overpredict regional increases in winter precipitation. Thus, the impact of global climate change in this region may result in an even greater deficit in the annual water budget than predicted.**

These decadal long climate cycles, however, do not fully explain more recent shifts within the weather of the Pacific Northwest. The local perception of warmer, drier summers that last longer and wetter winters with increased likelihood of flooding are supported by observed weather data. These shifts may be attributed to anthropogenic climate change – in fact, they are consistent with the effects climatologists would anticipate seeing in this region. Changes in winter precipitation can affect the year-long water budget, a critical factor in valleys like the Tualatin where summer stream-flows are augmented with stored precipitation. The effect of less precipitation and warmer temperatures earlier and over a long spring-summer season are clear. As we have seen above, precipitation patterns in Western Oregon are strongly driven by the combined effect of air temperature over the Pacific Ocean and the combined orographic effects of the Coast and Cascade ranges – layering over these influences issues of climate change can increase water supply stress to severe levels during summer months in years where the el Nino cycle is already in effect.

Global warming could therefore have direct impacts on the precipitation cycles in the area as well as simply increasing average air temperature. The International Panel on Climate Change (IPCC) predicts a global average surface air temperature increase of 1.8 to 4.0 degrees Celsius from 1990 temperatures by 2100, while possibly also altering the frequency, intensity and distribution of rain events as well as patterns of flooding and drought. More locally, the Pacific Northwest should experience a rise in mean temperature of about 1.5 degrees Celsius by 2020 and 2.3 degrees Celsius by 2040 from observed temperatures in 2000, leading climatologists indeed to expect increased annual precipitation concentrated in the winter months with reductions in already low levels of summer precipitation.

Franczyk and Chang (2009) modeled the potential impact of both climate change and land use change on hydrology in the area, relying on simulated temperature and precipitation adjustments from the Climate Impacts Group at University of Washington. Note that this data itself is the result of a somewhat conservative model predicting climate change and downscaled from global projections to the watershed level. The results for the Rock Creek basin (a sub-basin of the Tualatin River basin and a tributary stream to that network) give a good indication of the potential for climate change throughout the basin, considered in light of projected increases in population and development. These models projected net annual increases in both temperature and precipitation, with increase in temperature distributed throughout the year but increase in precipitation restricted primarily to the wet season. The dry summer season is projected to become both hotter and drier, with an increase in temperature of 1.57 degrees Celsius and a decrease in precipitation over these months of 0.33 cm. Throughout the year, the month of February will see the highest monthly decrease in precipitation (1.16 cm), but the 0.72 cm decrease in June will have the largest impact on net seasonal precipitation.

Mote, Salathe and Peacock (2005) similarly predict warming in the region between a likely 0.3 degrees Celsius (0.5 degrees Fahrenheit) increase per decade in average temperature, up from the 0.1 degree Celsius changes seen in the 20th century. While in each instance their model predicts more rapidly increasing temperatures in coming decades, the degree of that increase of rate varies from negligible to almost 6 times as fast (Mote, Salathe and Peacock 2005). Although trends in temperature already “stand out above natural variability," predicted changes in precipitation are not likely to be noticeable until the end of the century. Mote and his colleagues concur in the prediction that winter precipitation will increase while spring and summer precipitation generally decrease (Mote, Salathe and Peacock 2005).

Mote, Salathe and Peacock (2005) reviewed ten global climate models to determine which scenarios best reflected the trends occurring in the Pacific Northwest, determining that the relationship between global warming and climate variability in the northwestern US are not closely related (Mote, Salathe and Peacock 2005). . In order to model global climate change accurately, much local geographic detail must be smoothed out. Thus, in the global models, the PNW is represented as a coastal area on a "fairly smooth planet with similar land-sea distributions and large smooth bumps where Earth has major mountain ranges” (Mote, Salathe and Peacock 2005). Due to the strong orographic effect controlling precipitation in this area, global climate models at best are able to demonstrate the general trend of warming in the area.

Mote, Salathe and Peacock (2005) found that these models tend to generate results that consistently under-predict observed temperatures and can over-predict increase in winter precipitation. On the whole, these models can give a very general picture of seasonal cycles of temperature and precipitation in the PNW, but fail to depict fine scale shifts in the levels of precipitation and temperature change as well as length and start/end dates of these seasons (Mote, Salathe and Peacock 2005). Each of these are critical factors in flow management decisions and thus global scale climate models prove of little help to local watershed management. Although the models may disagree on many particulars, in general there is consensus that total annual precipitation will increase as climate changes, but will do so in a way that exaggerates the existing distribution between winter rains and summer drought. Over the next three decades, summertime temperature increases will be most dramatic during those months of the year that are already warmest and driest (June, July and August, increasing water demand and fire risk during those months (Mote, Salathe and Peacock 2005). At the same time, supply of water may decline during June, July and August as summer precipitation declines, particularly in areas like the Tualatin River basin where winter and spring precipitation occurs primarily as rain and very little is stored in snow pack to melt in warmer months (Mote, Salathe and Peacock 2005). Previous models of precipitation that were based on 10 year averages may have indicated more variability due to the influence of decadal climate cycles like ENSO and the thermohaline circulation belt. Although project changes in precipitation decrease as the average period increases to 30 years, seasonal precipitation continues to diverge into an increasingly wet winter and increasingly dry summer.

VanRheenen, Palmer and Hahn (2011) also utilized climate and hydrology models to investigate the potential climate change impacts on the Bull Run system, from which the majority of Portland's water supply is drawn. They characterized the Bull Run system as a 'transient watershed', or one with a seasonal two peak hydrograph following winter rain and spring snowmelt. Although the Tualatin River basin is clearly not transient in this way (it is not a snowmelt dominated regime and thus its hydrograph is influence predominately by rainfall), climate change impacts to spring flow will follow a similar if diminished trend. More importantly, climate change stress to the Bull Run system directly impacts water withdrawal from the Tualatin River basin at Hagg Lake by increasing demand for water from the Tualatin Valley Water District which provides necessary water to meet summer demand in Portland. VanRheenen, Palmer and Hahn also investigated a second type of watershed with greater demand for water withdrawal than annual income in the water budget. In these watersheds, which are more similar to the Tualatin River basin, the timing of precipitation and runoff can be less significant than in snow-pack dominated systems so long as storage capacity within the basin can be used to regulate seasonal flow variability (VanRheenen, Palmer and Hahn 2011). The analysis of these high demand watersheds might provide some insight to the relationship of increasing development stress imposed by land use change with climate change in the Tualatin River basin.

When considering impact of climate change alone on hydrology, Franczyk and Chang (2005) predicted significant reductions in mean monthly runoff depth during the months of July, August and September, as well as seasonally in summer and fall. Because the mean annual precipitation and runoff figures will increase, with substantial concentration of this activity during the wet season, much planning effort must be directed at responding to seasonally higher flows and increasing flood frequency (Franczyk and Change 2005). However, in addressing the summertime water quality issues in the Tualatin Basin, some consideration must also be given to these reduced summertime precipitation and runoff figures, predicting a monthly loss in flow varying from 0.1 to 0.4 cm and a total seasonal loss of flow ranging from 0.1 to 1cm (Franczyk and Change 2005).

C. Analysis

- **In managing flow augmentation and flood prevention, then, careful attention must be paid to the impacts of long term climate cycles and global climate change on the annual water budget for the Tualatin basin.**

- **One way to address the challenges caused by shifts in precipitation between years in the Tualatin basin would be to employ models which attempt to predict the interaction of these climate variables and the resulting patterns of precipitation they may yield in any given year or over a period of several years.**

- **Consideration of longer term shifts in climate would also allow water quality and quantity managers within the basin to plan for the likelihood of more severe winter precipitation events combined with more frequent and longer summer droughts by increasing long term storage within the basin.**

- **These considerations may also lead to indirect water quantity management strategies aimed at increasing return flow to the river (while continuing to decrease the load of various pollutants) and decreasing demand for consumption of water during critical summer months, as well as riparian restoration efforts that may make conditions less favorable for algal growth.**

Climate variability, then, comes to the Tualatin River basin in two potential forms: the long term shifts in total precipitation and temperature expected due to global climate change and the shorter term climate cycles along the Pacific Coast. These shorter term climate cycles prohibit the formation a single flow augmentation strategy that can be used in every year because they strongly impact both the level of precipitation falling during the rainy season and the intensity of the need for water resources during the dry season (through impacts on rainfall timing and intensity as well as on temperatures and sunlight). Yet short term climate cycles are not entirely unpredictable, and by reference to both the last decade's experience with flow management and to the existing literature, the need to increase storage for flood prevention during more intense rain year may be predicted.

Flow management basin-wide entails two fundamental activities: the storage of precipitation and the allocation of its release throughout the dry season. It is advisable that a third consideration be made routine: storage of precipitation between years as insurance against extended dry periods. Low precipitation during the rainy season cannot be perfectly predicted, but decadal long cycles within Pacific climate can be anticipated and used to mitigate potential water shortages in future years. For example, intentional ground water recharge through a variety of measures (e.g. increase pervious surface proportion, reduction in stormwater runoff via retention ponds and wetlands rehabilitation, direct injection of wells and aquifers for recharge) can assist in storing water between decadal long cycles of high and low precipitation years, alleviating stress during dry summer following low precipitation rainy seasons. An understanding of long term climate patterns related to the geography of the region help to justify and strategize such long term management projects.

Changes in precipitation will, ultimately, result in changes in surface and subsurface runoff to the stream channel, as well as changes in storage of water within the basin. Increasing storage within the basin through a number of smaller dams and reservoirs or above ground storage tanks would allow flow managers more flexibility during increasingly unpredictable summer months. Increasing such storage may be necessary to cope with changes in winter and spring precipitation levels as well. The climatic patterns above clearly indicate a trend of periods of intense winter rains extending for several years, followed by years with lower precipitation. Even in the absence of long term global climate change (which is expected in increase levels of precipitation in the rainy season as well as the intensity and duration of storm events), these climate cycles require careful wintertime flood management. Increasing the ability of the groundwater table to recharge is helpful for addressing long term inter-seasonal and inter-year water deficits but can be a risky strategy in terms of surface water management for flood control. A combination of above ground and surface water storage managed for flood control alongside groundwater recharge activities would favor a balance between the need to slowly store water between years and the need to quickly store water in response to a flood event. As mentioned in the last chapter, storage of excess precipitation during the winter months for activities other than flow augmentation (i.e. municipal and irrigation uses) also reduces the pressure during the dry season on the flow regime of the river and on older reservoirs from which flow augmentation is drawn.

While decadal climate cycles tend to impact the duration and intensity of the rainy season, long term global climate change is anticipated to impact the duration and intensity of the dry season, particularly by increasing the frequency of long, hot and dry summers. The prediction implies a necessity to increase storage within the basin, particularly in the face of continued population growth and urban expansion. Currently, a few summertime storm events can be relied upon to assist in flow management even if their timing cannot be accurately predicted.

As summers become increasingly clear and warm, the reliability of these summer storm events will decrease as the demand for irrigation and municipal water supply increases. Increased storage of water in various forms (above ground tanks, reservoirs, ground water) can alleviate these pressures by increasing supply. However, the demand aspect of the equation must also be addressed through education and adoption of increasingly sophisticated technology aimed at reducing consumption of water during the summer months. Ultimately, reducing the demand for water during summer months may entail adjusting market pressures to alter consumptive behavior (through the increase of user fees to reflect the increasing water scarcity or through increasing taxes to support water storage facility development) or through regulations designed to curtail summertime consumption (such as watering restrictions, design limitations for new construction, and so forth). Washington County is already a nationally recognized leader in water-wise land use planning and conservation development. Responding to the pending climate crisis may force them to emerge as a leader in climate change adaptation and mitigation as well.

# Chapter 6 Conclusions, Policy Recommendations and Areas for Further Research

- **This research ultimately indicates that use of a comprehensive ecological assessment tool might enhance water quality management in certain cases.**

- **In the case of the Tualatin River, use of a comprehensive ecological assessment tool would help to assess the impacts of management decisions on both the ecological and the human communities.**

- **Use of a comprehensive ecological assessment tool here would also help to identify areas where further research is needed in terms of establishing baseline conditions, monitoring change and predicting outcomes.**

- **Such a tool may also help to identify and address potential feedbacks from management decisions as these changes effect ecological services and human well-being, driving further changes in policy decisions.**

- **The Millennium Ecosystem Assessment, although designed for use in different parts of the world, can provide the basis for developing such an assessment tool.**

- **The use of a comprehensive ecological assessment tool would also help promote the 'watershed approach' as it more comprehensively identifies stakeholders and the effects of various management decisions on them, as well as incorporates a perspective of overall watershed health.**

- **An ecological assessment tool may ultimately increase the efficiency and efficacy of watershed-wide water quality management by providing a framework under which to assess existing knowledge, identify needed knowledge, analyze and compare various management scenarios, and finally monitor and assess their success.**

- **The absence of such a framework for processing the large amount of information involved in assessing basin-wide policies may lead to increased delay in decision making, unnecessary conflict over alternatives and implementation of mistaken policies not based in the best available science.**

- **Going forward in the Tualatin basin and in other watersheds, use of a comprehensive ecological assessment tool may help to assess the potential effects of climate change and land use change on ecological services and human well-being, as well as to identify and assess potential policies to adapt to or mitigate these effects. Predicting potential interactions between policy decisions, ecological services and human well-being may help to identify and avoid potentially undesirable feedbacks in policy making.**

A number of conclusions about water quality management in the Tualatin River basin and about the use of a comprehensive ecological assessment tool such as the MEA to enhance watershed management emerge from this result. Use of a comprehensive ecological assessment tool that links changes in management strategy to their impacts on ecological services and human well-being has the potential to improve each step of water quality management: goal setting, identification of pollutants and sources, planning of regulatory limits and restoration activities, identification of stakeholders and prioritization of workable solutions. Water quality management in the Tualatin River would have benefitted in many ways from a comprehensive and strategic study of ecological services prior to setting the first TMDL. Such an assessment would have called into question the very premise of regulating algal growth by restriction of a single nutrient (phosphorus). It may also have drawn attention to the lack of knowledge regarding the sources of phosphorus to the river channel – as history illustrates, a more accurate understanding of background levels of phosphorus in the channel would perhaps have led to a water quality management strategy that focused on other factors which can constrict the growth of algae.

It is clear that such a focus is in place now, as the system is managed both for nutrient inputs and other limiting factors such as flow, temperature and residence time. A comprehensive ecological assessment tool would allow managers to consider each management strategy (flow management, riparian restoration, phosphorus limitations, erosion reduction, urban growth restriction, etc.) individually and as a collection of actions. Such an assessment would identify both the positive impacts on the system (including but not limited to any activity's ability to limit algal growth as well as other benefits to ecological services) and human well-being, and the unintended negative consequences of such activities which may in turn lead to human responses that further impact the environment. Walking through the steps of an ecological assessment for each decision forces managers to identify not only this potential for feedbacks but also areas where current knowledge regarding interactions within the system is weak. The risk posed by these gaps in knowledge varies depending on the potential negative impact of each decision – a comprehensive ecological assessment helps to illustrate how each decision is related to a host of impacts, and thus helps to prioritize research activities to bridge those gaps.

Use of the MEA would be particularly beneficial to flow management decisions made each summer by members of the flow management committee and storage decisions made by Washington County, particularly in face of pending environmental changes in climate and land use. Current variability in climate and continued population growth have already made it difficult for managers to plan for the needs of any one season in advance, let alone to manage storage of water between seasons. Yet past experience has demonstrated a need to conserve water in storage from years of greater precipitation for use during years of lesser precipitation. This need will be conflated as decadal climate cycles interact with global climate change to produce longer, drier summer seasons and less predictable levels of precipitation during the rainy seasons. Pressures from climate change will be heightened by pressures from increasing urbanization and land use change as well. Management of flow will increasingly come to mean more than merely managing summertime flow augmentation (itself a sufficient challenge) and will with environmental change come to require inter-year planning for storage and release of water to maintain desired conditions within the watershed. A comprehensive ecological assessment tool highlights the costs of failing to do so and provides some insight into strategies such as increasing and diversifying storage that will mitigate the impact of these environmental changes. Similarly, use of an ecological assessment tool could help land use planners more effectively incorporate water quality concerns into long term land use planning restrictions and permit review of current development plans, as well as lend a sharper focus to management of agricultural return flow.

Thus, use of the MEA assessment tool in water quality management imposes the desired watershed perspective by bringing into focus the impacts of various decisions on a broad spectrum of ecological services and tracing their effects on human well-being. It is particularly apt when considering the often difficult to model impacts of environmental change on total watershed health. This analysis can provide a qualitative assessment of potential impacts, drawing attention to the need for the development of specific areas of research to better understand changes within the watershed. The MEA assessment tool can allow for the quick prioritization of pending projects where the knowledge base to quantitatively assess the benefits is less than complete. It can also demonstrate the relationships between various projects, reducing the likelihood of duplicated or conflicting efforts.

As a general rule, watershed planning requires an understanding of the relationship between land and stream within the watershed. In effect, land use planning translates directly to water quality management in basins where NPS problems exist. Water quality management for nutrient pollution also entails water use, storage and flow management within a watershed. The MEA demonstrates that the management of flow impacts many different ecosystem services, themselves either directly or indirectly related to management of phosphorus and algal growth. Use of the MEA to compare options for land use planning, response to climate change and seasonal flow management helps to trace these impacts and relate them to associated changes in well-being.

When considering the impact of climate and land use change on water quality, it is important to consider the potential impact of aggregate individual responses to changes in the ecosystem and in human well-being, which can create unintended consequences and further environmental change. Once again, the MEA provides a useful framework for considering such relationships.

This research would have benefitted from review of information regarding the basin not readily available at this time. A complete and useful ecosystem assessment must adequately capture the ecosystem services within the basin and their impacts on human well-being. Several aspects of each must be more thoroughly quantified to fully capture the change created by flow management and by potential climate change. A more thorough inventory of ecosystem services must be done to capture the effect of water quality management and climate change on all species within the basin rather than simply higher order, charismatic and protected species. Studies of algae within the basin should go beyond mere chlorophyll-a counts to assess the types and community dynamics both of algae and of grazers present in the system. A solid study of macro-invertebrate species within the basin would assist in tracking changes within the food web as well. Because the river and its floodplain provide services to waterfowl, amphibians and terrestrial species as well as to the targeted fish species, an assessment of their population dynamics would be useful as well.

All of these environmental services provide benefits to human well-being in terms of cultural and spiritual services as well as directly impacting water quality and provisioning. An assessment of the value of various recreational activities, such as lake recreation versus river recreation, could help to assess the impact of changes to these services. Personal interviews with residents of the basin aimed at identifying and somehow measuring the spiritual services tied to a sense of community identity would also be helpful. Finally, a more comprehensive study than the one at hand here would better assess the linkages between human population dynamics, urban development and climate change utilizing existing predictions for land use change based both on models and on the urban growth boundary plan. Additional information to bolster this assessment could be obtained by comparison of current land use patterns to those of the past by use of aerial photography and careful review of the historical record as well. In the end, as more information is compiled and analyzed to generate a clear picture of where the watershed has been and where is going, the assessment of the total costs and benefits of management decisions will become clearer and more accurate.

REFERENCES:

Abrams, Mary Margaret and Wesley Jarrell, 1995. Soil Processes and Chemical Transport: Soil Phosphorus as a Potential Nonpoint Source for Elevated Stream Phosphorus Levels. Journal of Environmental Quality 24:132-138.

Anderson, Chauncy and Stewart Rounds, 2003. Phosphorus and E.Coli and their Relation to Selected Constituents During Storm Runoff Conditions in Fanno Creek, OR 1998-1999. US Geological Survery. Water Resources Investigations Report 02-4232. U.S. Gov. Print. Office, Washington DC. http://pubs.usgs.gov/wri/wri024232/pdf/wri024232.pdf accessed July 10, 2011.

Bishop, Ellen Morris, 2003. In Search of Ancient Oregon: A Geological and Natural History. Portland, OR: Timber Press.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2003. Tualatin River Flow Management Technical Committee 2003 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2004. Tualatin River Flow Management Technical Committee 2004 Annual Report. Hillsboro, OR.

http://www.co. washington.or.us/Watermaster/SurfaceWater/upload/FlowReport2004.pdf accessed July 10, 2011.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2005. Tualatin River Flow Management Technical Committee 2005 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2006. Tualatin River Flow Management Technical Committee 2006 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2007. Tualatin River Flow Management Technical Committee 2007 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/upload/FlowReport2007.pdf accessed July 10, 2011.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2008. Tualatin River Flow Management Technical Committee 2008 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/upload/FlowReport2008.pdf accessed July 10, 2011.

Bonn, Bernie for Clean Water Services and Oregon Department of Water Resources, 2009. Tualatin River Flow Management Technical Committee 2009 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/upload/FlowReport2009.pdf accessed July 10, 2011.

Bourke, Paul and Donald DeBats, 1995. Washington County: Politics and Community in Antebellum America. Baltimore, MD: The Johns Hopkins University Press.

Butler, Colin, 2003. Ecosystems and human well-being: a framework for assessment: Chapter 3. World Resources Institute. Washington, DC: Island Press. http://pdf.wri.org/ecosystems _human_wellbeing.pdf accessed July 14, 2011.

Chopra, Kanchan, 2005. Ecosystems and Human Well-Being: Policy Responses: Findings of the Responses Working Group United Nations, Millenium Ecosystem Assessment Responses Working Group. Wasington D.C.: Island Press.

Churchill, Jack and Michael Wade, 1988. West Linn Backs Tualatin River Pollution Standard, May 5, 1988. The Oregonian, O-3 and O-6.

Clean Water Services and Oregon Department of Water Resources, 2001. Tualatin River Flow Management Technical Committee 2001 Annual Report. Hillsboro, OR.

http://www.co.washington.or.us/Watermaster/SurfaceWater/upload/FlowReport-2001.pdf accessed July 10, 2011.

Clean Water Services and Oregon Department of Water Resources, 2002. Tualatin River Flow Management Technical Committee 2002 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

Cude, Curtis, 2004. "Oregon Water Quality Index Summary Report Water Year 1992 through 2001." DEQ May 2004.

Darley, W. Marshall, 1982. Algal Biology: A physiological approach. Oxford, England: Blackwell Science Publications.

DeLorme Mapping, 2004. Oregon Atlas and Gazetteer. Yarmouth, Maine: DeLorme.

DEQ Experts Discuss Tualatin R Pollution. August 15, 1987. The Oregonian, WB-05.

Dicken, Samuel and Emily Dicken, 1979. The Making of Oregon: A Study in Historical Geography. Portland, Oregon: Oregon Historical Society Press.

Dodds, Gordon , 1986. The American Northwest: A History of Oregon and Washington. Wheeling, Illinois: Forum Press Inc.

Franczyk, Jon and Chang, Heejun, 2009. The effects of climate change and urbanization on the runoff of the Rock Creek basin in the Portland metropolitan area, Oregon, USA. Hydrological Processes, 23: 805–815. doi: 10.1002/hyp.7176

Fytianos, K., E. Evgenidou, and G. Zachariadis, 1999. Use of Macroalgae as Biological Indicators of Heavy Metal Pollution in Thermaikos Gulf, Greece. Bulletin of Environmental Contamination Toxicology, 62:630-637.

Gopelrud III, Peter, 1995. Water Pollution Law: Milestones from the Past and Anticipation of the Future. Natural Resources & Environment. 10 Nat. Resources & Env't. 8.

Green, Ashbel, 1988. Consultant Estimates Costs to Clean Up Tualatin River\Figures Range Up to $82 Million for Project. January 20, 1988. The Oregonian, B04.

Green, Ashbel, 1988. Phosphorus Stimulates Algae Growth in Tualatin River\How Much Must Go to Reduce the Algae is Subject of Debate. April 22, 1988. The Oregonian, C-04.

Green, Ashbel, 1988. Phosphorus, Ammonia Limits in Tualatin Questions]Enforcement Seasons Consideration Points in EPA Letter to DEQ. June 2, 1988. The Oregonian, B-08.

Green, Ashbel, 1988. DEQ Seeks Stricter Limits on Tualatin River Pollutants. July 4, 1988. The Oregonian, B-05.

Green, Ashbel, 1988. County to Propose Dumping Treated Sewage in Willamette\$20 Million Plan is Intended to Help Improve Quality of Water in Tualatin River. September 5, 1988. The Oregonian, E-09.

Green, Ashbel, 1989. Approval Expected for Sewage Tests. February 14, 1989. The Oregonian, B-04.

Green, Ashbel, 1989. County Awards Sewer Contracts Totaling $13.5 MILLION. July 26, 1989. The Oregonian, C-02.

Guiry, Michael, 2007. New Survey of Clare Island Volume 6: The Freshwater and Terrestrial Algae. Dublin, Ireland: Royal Irish Academy.

Hassan, Rashid M, Robert Scholes, and Neville Ash, 2005. Ecosystems and human well-being: current state and trends: findings of the Condition and Trends Working Group of the Millennium Ecosystem Assessment. Washington DC: Island Press.

Hatton, Raymond, 2005. Portland Oregon: Weather and Climate, A Historical Perspective. Bend, Oregon: Geographical Books.

Hawksworth, John, 1999. Dairy-McKay Watershed Analysis. Washington County Soil and Water Conservation District, Salem District Office of the Bureau of Land Management, U.S. Department of the Interior. Tillamook, Oregon. http://www.blm.gov/or/districts/salem/plans /water_ dairy_ mckay.php accessed July 14, 2011.

Hawksworth, John, 2000. Upper Tualatin-Scoggins Watershed Analysis. Washington County Soil and Water Conservation District, Salem District Office of the Bureau of Land Management, U.S. Department of the Interior. Tillamook, Oregon. http://www.trwc.org/tualatin-info/upper/tualatin_scoggins_wa.pdf accessed July 14, 2011.

Hawksworth, John, 2001. Middle Tualatin - Rock Creek Watershed Analysis. Washington County Soil and Water Conservation District, Salem District Office of the Bureau of Land Management, U.S. Department of the Interior. Tillamook, Oregon. http://www.trwc.org/tualatin-info/middle/middle.html accessed July 14, 2011.

Hawksworth, John, 2001. Lower Tualatin Watershed Analysis. Washington County Soil and Water Conservation District, Salem District Office of the Bureau of Land Management, U.S. Department of the Interior. Tillamook, Oregon. http://www.trwc.org/tualatin-info/lower/lower.html accessed July 14, 2011.

Heider, Douglas and David Dietz, 1995. Legislative Perspectives: A 150 Year History of the Oregon Legislatures from 1843 to 1993. Portland, Oregon: Oregon Historical Society Press.

Huggett, Robert, 2010. A Scientific Assessment of Alternatives for Reducing Water Management Effects on Threatened and Endangered Fishes in California's Bay Delta, Committee on Sustainable Water and Environmental Management in the California Bay-Delta; National Research Council . Washington D.C.: National Academies Press.

Jarrell, Wesley, 2003. Water Monitoring for Watershed Planning and TMDLs. Yellow Springs, Ohio: YSI Incorporated.

Lansing, Jewel, 2005. Portland: People, Politics and Power 1851-2001. Corvallis, Oregon: Oregon State University Press.

Loy, William and Stewart Allan, 2001. Atlas of Oregon, Second Revised Edition. Corvallis, Oregon: University of Oregon Press.

Loy, William and Stewart Allan, 1976. Atlas of Oregon, First Edition. Corvallis, Oregon: University of Oregon Press.

Many County Residents May Pay to Fund Storm-Water Runoff Plan. January 5, 1988. The Oregonian, B-05.

Martinazzi, Loyce and Karen Lafky Nygaard, 1994. Tualatin From the Beginning.1994. Tualatin, Oregon: Tualatin Historical Society.

McCormick, Paul and John Caims, 1994. Algae as Indicators of Environmental Change. Journal of Applied Phycology 6:509-526.

McKinley Corning, Howard, 2004. Willamette Landings: Ghost Towns of the River. Portland, Oregon: Oregon Historical Society Press.

McKinney, Ross, 2004. Environmental Pollution Control Microbiology. Chapel Hill, North Carolina: Marcel Decker Inc.

Moberg, Dean and Neil Rambo, 2000. Farm Effects on Runoff Quality in Oregon's Tualatin River Basin. Part 1: Farm Survey. Corvallis, Oregon: Oregon State University.

Mote, Phillip, Edward Parson, Alan Hamlet, William Keeton, Dennis Lettenmaier, Nathan Mantua, Edward Miles, David W. Peterson, David L. Peterson, Richard Slaughter and Amy Slover, 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Climatic Change **61:** 45–88.

Mote, Phillip, Eric Salathe and Cynthia Peacock, 2005. Scenarios of Future Climate for the Pacific Northwest.,Climate Impacts Group. Seattle Washington: University of Washington. http://cses.washington.edu/db/pdf/kc05scenarios462. pdf accessed July 14, 2011.

Mrazick, Steve, 1995. Oregon Water Quality Index Summary Report Water Year 1995 through 2004. DEQ May 1995.

Mrazick, Steve, 2004. Oregon Water Quality Index Summary Report Water Year 1994 through 2003. DEQ May 2004.

Mrazick, Steve, 2006. Oregon Water Quality Index Summary Report Water Year 1996 through 2005. DEQ May 2006.

Mrazick, Steve, 2007. Oregon Water Quality Index Summary Report Water Year 1997 through 2006. DEQ May 2007.

Mrazick, Steve, 2008. Oregon Water Quality Index Summary Report Water Year 1998 through 2007. DEQ May 2008.

Murdock, Justin and Walter Dodds, 2006. Large Rivers and Eutrophication. Kansas State University. http://n-steps.tetratech-ffx.com/PDF&otherFiles/literature_review/Eutrophication%20effects%20on%20large%20rivers.pdf accessed July 14, 2011.

Nabors, Murray, 2004.  Introduction to Botany.  San Fransisco, California: Pearson Education, Inc.

Palmer, R.N., E. Clancy, N.T. VanRheenen, and M.W. Wiley, 2004. The Impacts of Climate Change on the Tualatin River Basin Water Supply: An Investigation into Projected Hydrologic and Management Impacts. Department of Civil and Environmental Engineering, Seattle, Washington: University of Washington.

Risley, John, 2000.  Effects of Hypothetical Management Scenarios on Simulated Water Temperatures in the Tualatin River, OR.  Portland, OR.  US Geological Society and US Department of Interior.  USGS Supplement to Water Resources Investigations Report 97-4071. Washington DC: U.S. Gov. Print. Office.  http://content.lib.utah.edu/cdm4/item_viewer.php?CISOROOT=/wwdl-er&CISOPTR=45  accessed July 14, 2011.

Peterson del Mar, David, 2003.  Oregon's Promise: An Interpretive History.  Corvallis, Oregon: Oregon State University Press.

Peterson, G. D., T. D. Beard Jr., B. E. Beisner, E. M. Bennett, S. R. Carpenter, G. S. Cumming, C. L. Dent, and T. D. Havlicek, 2003. Assessing future ecosystem services: a case study of the Northern Highlands Lake District, Wisconsin. Conservation Ecology **7**(3): 1. http://www.consecol.org/vol7/iss3/art1/  accessed July 14, 2011.

Petts, Geoffrey and Peter Calow, eds. 1996. River Biota: Diversity and Dynamics. Oxford: Blackwell Science.

Posewitz, Brian, 1988. Hearings to Decide River's Fate. April 25, 1988. The Oregonian, B-05.

Risley, John, 1997. Relations of the Tualatin River Water Temperatures to Natural and Human-Caused Factors. US Geological Society and US Department of Interior. USGS Water Resources Investigations Report 97-4071. Washington DC: U.S. Gov. Print. Office. http://or.water.usgs.gov/pubs_dir/Pdf/97-4071.pdf accessed July 14, 2011.

Rounds, Stewart and Tamara Wood, 2001. Modeling Water Quality in the Tualatin River, OR US Geological Society. USGS Water Resources Investigations Report 01-4041. Washington DC: U.S. Gov. Print. Office http://or.water.usgs.gov/pubs_dir/Pdf/01-4041.pdf accessed July 14, 2011.

Rounds, Stewart, Tamara Wood and David Lynch, 1999. Modeling Discharge, Temperature and Water Quality in the Tualatin River, OR. US Geological Society. USGS Water Supply Pap. 2465-B. Washington D.C.: U.S. Gov. Print. Office. http://or.water.usgs.gov/pubs_dir/Pdf/01-4041.pdf accessed July 14, 2011.

Ryder, Darren and Emilie Mascarenhas, 2007. Algal biofilms: developing biological indicators to assess river restoration. African Journal of Aquatic Science, 1727-9364, Volume 32, Issue 2, 01 August 2007, Pages 215 – 218.

Shubert, L. Elliot, ed., 1984. Algae as Ecological Indicators. San Diego, California: Academic Press, Inc.

SRI (Scientific Resources, Inc.), and Walker and Macy, Inc., 1990. Tualatin River Ecological Assessment. Appendix E3, Volume III. Wastewater Facilities Plan. Report Prepared for the Unified Sewerage Agency of Washington County, and Tualatin Basin Consultants. Hillsboro, OR.

Strong, Ruth and Emory Strong, 1995. Seeking Western Waters: The Lewis and Clark Trail from the Rockies to the Pacific. Portland, Oregon: Oregon Historical Society Press.

Taylor, George and Chris Hannan, 1999. The Climate of Oregon: From Rain Forest to Desert. 1999, Corvallis, OR.: Oregon State University Press.

Thake, Brenda and G.E. Fogg, 1987. Algal Cultures and Phytoplankton Ecology. Madison, Wisconsin: University of Wisconsin Press.

Tualatin Riverkeepers Citizen Action Committee, 2008. Summary of Findings:

Investigation into Declining DEQ Water Quality Index for Tualatin Basin Sites http://www.tualatinriverkeepers.org/text/TRK-DEQ-WQI-Summary.pdf accessed July 10, 2011.

Ullsten, Ola, Stuart Chapin III and James Gustave Speth, , 2004. Options for enhancing the resilience of northern countries to rapid social and environmental change: A message to policy makers. Ambio 33:343.

United Sewerage Agency, 1992. Tualatin River Flow Management Technical Committee 1992 Annual Report.Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater /upload/FlowRpt_1992.pdf accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1993. Tualatin River Flow Management Technical Committee 1993 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1994. Tualatin River Flow Management Technical Committee 1994 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1995. Tualatin River Flow Management Technical Committee 1995 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/upload/FlowRpt_1995.pdf accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1996. Tualatin River Flow Management Technical Committee 1996 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1997. Tualatin River Flow Management Technical Committee 1997 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1998. Tualatin River Flow Management Technical Committee 1998 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 1999. Tualatin River Flow Management Technical Committee 1999 Annual Report. Hillsboro, OR.

http://www.co.washington.or.us/Watermaster/SurfaceWater/tualatin-river-flow-technical-committee-annual-report.cfm accessed July 10, 2011.

United Sewerage Agency and Oregon Department of Water Resources, 2000. Tualatin River Flow Management Technical Committee 2000 Annual Report. Hillsboro, OR. http://www.co.washington.or.us/Watermaster/SurfaceWater/upload/FlowReport-2000.pdf accessed July 10, 2011.

USEPA (U.S. Environmental Protection Agency), 1996. Watershed Approach Framework. EPA 840-S-96-001.http://water.epa.gov/type/watersheds/framework.cfm accessed July 14, 2011.

USEPA, 2002. A Review of Statewide Watershed Management Approaches Final Report. http://www.epa.gov/owow/watershed/approaches_fr.pdf accessed July 14, 2011.

USEPA, 2001. Protecting and Restoring America's Watersheds: Status, Trends and Initiatives in Watershed Management. EPA 840-R-00-001. http://water.epa.gov/type/watersheds/outreach /protecting_index.cfm accessed July 14, 2011.

VanRheenen, Nathan T., Richard N. Palmer, and Margaret A Hahn, 2011. Evaluating Potential Climate Change Impacts on Water Resource Systems Operations: Case Studies of Portland, Oregon and Central Valley, California. Journal of Contemporary Water Research and Education: Vol. 124: Iss. 1, Article 6.

Wehr, John and Robert Sheath, eds. 2003. Freshwater Algae of North America: Ecology and Classification. San Diego, California: Academic Press.

Wehr, John and Robert Sheath, eds. 2003. Use of Algae in Environmental Assessments. San Diego, California: Academic Press.

Wilson, Doyle, 1997. Post-Middle Miocene Geologic History of the Tualatin Basin, Oregon with Hydrologic Implications. (Unpublished Doctoral Dissertation). Portland State University, Portland Oregon.

Yagow G., B. Wilson, P. Srivastava and C.C. Obropta, 2006. Use of biological indicators in TMDL assessment and implementation. Transactions of the SABE 2006, vol. 49, n°4, pp. 1023-1032.