Wide Hollow Creek Temperature, Dissolved Oxygen, and pH Water Quality Study for Aquatic Life, 2013 – 2014

August 2020

Publication No. 20-03-007

DEPARTMENT OF
ECOLOGY
State of Washington

Publication and information

This report is available on the Department of Ecology's website at
https://apps.ecology.wa.gov/publications/SummaryPages/2003007.html

Data for this project are available at Ecology's Environmental Information Management (EIM) website www.ecy.wa.gov/eim/index.htm. Search Study IDs: JICA0002 and WHM_WHB.

The Activity Tracker Code for this study is 13-051.

Contact information

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600, Olympia, WA 98504-7600
Phone: (360) 407-6764

Washington State Department of Ecology - www.ecy.wa.gov

- Headquarters, Olympia (360) 407-6000
- Northwest Regional Office, Bellevue (425) 649-7000
- Southwest Regional Office, Olympia (360) 407-6300
- Central Regional Office, Yakima (509) 575-2490
- Eastern Regional Office, Spokane (509) 329-3400

Cover photo: Wide Hollow Creek near 80th Ave.
Photo by Eiko Urmos-Berry, Department of Ecology.

Wide Hollow Creek Temperature, Dissolved Oxygen, and pH Water Quality Study for Aquatic Life, 2013-2014

by

Jim Carroll and Evan Newell

Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area: WRIA: 37; HUC number: 17030003.

This page is purposely left blank

Table of Contents

Page

List of Figures **6**

List of Tables **10**

Abstract **11**

Acknowledgements **12**

Background **13**
- Introduction 13
- Why is Ecology conducting this water quality study? 14
  - Water Quality Assessment (WQA) and the 303(d) List 14
  - Study overview 15
- Historical data review 15

Watershed Description **16**
- Climate 16
- Geology 16
- Soils and vegetation 19
  - Soils 19
  - Current vegetation 19
  - Historical vegetation 20
- Land use 20
- Hydrology 21
  - Pre-development and early diversions (pre-1880s) 21
  - Development of large irrigation projects 22
  - Current (mid-1980s to present) 25
- Fisheries 31
- Potential pollutant sources 32
  - Permitted point sources 32
  - Nonpoint sources 33
- Impairments addressed by this water quality study 35
- How will the results of this water quality study be used? 36

Water Quality Standards and Numeric Targets **37**
- Temperature 37
- Dissolved oxygen 37
- pH 38

Study Goals and Objectives **39**
- Study goals 39
- Study objectives 39

Water Quality Study......40
Ecology data collection......40
Types of monitoring activities......44
Non-Ecology data sources......47
Meteorological data......47
City of Yakima Water Treatment Plant (on Naches River)......47
Data quality (usability assessment)......47
Study data usability......47
Usability of results from modeling or other analysis......48
Location of data for availability and archiving......48
Study year results......48
Meteorological data......48
Hydrology (streamflow)......49
Vegetation shade measurements......54
Water temperature data......54
Field measurements and water sample results from synoptic surveys......57
Continuous dissolved oxygen data......63
Continuous pH data......66
Time-of-travel dye studies......76
Light extinction surveys......77
Groundwater measurement and water quality results......78
Biological and habitat assessment......81
Field study summary......84
Assessment of 303(d) listings based on observed field measurements from study......85
Streamflow and Water Quality Simulation......91
Overview......91
Modeling framework......91
Ttools......91
Shade.xls......91
QUAL2Kw......92
QUAL2Kw model setup......93
Spatial layout......93
Model schematic......93
QUAL2Kw model calibration......105
Model performance evaluation......105
QUAL2Kw hydro-geometry and water velocity calibration......106
Rating curves......106
Time-of-travel dye studies......107
QUAL2Kw streamflow simulation......108
Streamflow calibration......108
Summary of flow input and loss (withdrawals)......108
Specific conductivity and chloride calibration......111
QUAL2Kw water temperature simulation......116
Meteorology......116

Vegetation and effective shade calculations 116
Temperature calibration 119
QUAL2Kw suspended solids and solutes simulation 126
Summary of suspended solids and solutes mass balances 127
QUAL2Kw dissolved oxygen and pH simulation 132
QUAL2Kw calibrated model summary 137
QUAL2Kw model scenarios 137
QUAL2Kw model scenarios set up 137
QUAL2Kw model scenarios results 139
Model scenario results summary 146
Pre-development representation 147
Conclusions 149
Discussion 151
Recommendations 153
For managing Wide Hollow Creek "As is" 153
For restoring Wide Hollow Creek to a "Pre-development condition" 154
For the intermittent reaches in upper Wide Hollow Creek (above 101st Ave) 154
References 156
Appendices 159
Appendix A. Groundwater Study 159
Appendix B. Bioassessment Study 159
Appendix C. Water Quality Study Data Summary 159
Appendix D. Water Quality Study Data Quality 159
Appendix E. Stream Heating Mechanisms 159
Appendix F. QUAL2Kw Model Inputs 159
Appendix G. QUAL2Kw Model Calibration 159
Appendix H. QUAL2Kw Model Sensitivity Analysis 159
Appendix I. Flow Spikes Fall 2013 - Wide Hollow Creek 159
Glossary, Acronyms, and Abbreviations 160

List of Figures

Page

Figure 1. Study area for the Wide Hollow Water Quality Study. 14

Figure 2. Map of Wide Hollow Creek watershed with precipitation isopleths in inches per year. 17

Figure 3. Surface lithology of the study area. 18

Figure 4. Early diversions to Wide Hollow Creek (1860s to 1870s). Early irrigation development importing Naches River water to Wide Hollow Creek (1880s to 1905). 24

Figure 5. Later irrigation development in the upper Wide Hollow Creek watershed (1909-1985). Current irrigation configuration after conversion of the Tieton Division to pressurized pipe (1986-present). 26

Figure 6. Historical daily average streamflow illustrating the seasonal hydrologic characteristics and reduced flow over time in Wide Hollow Creek (gaged near Union Gap). 28

Figure 7. Picture showing debris/diversion dam at Fines Ditch. Fines Ditch flows to the right in the photo while Wide Hollow Creek flows to the left below the diversion dam. 30

Figure 8. Wide Hollow Creek at the gravity drop located at the historical grist mill in Union Gap. 30

Figure 9. Sampling location and type (mainstem creek, sources, and diversions). 41

Figure 10. Monthly statistics of air temperature and precipitation, comparing study year to long term average and range. 49

Figure 11. Monitoring locations for streamflow and temperature along Wide Hollow Creek. 51

Figure 12. Gaged streamflow and specific conductivity at three locations on Wide Hollow Creek (mid-May 2013 to July 2014). 52

Figure 13. Longitudinal flow measured during two synoptic surveys (irrigation season versus non-irrigation season). 53

Figure 14. Temperature statistics (Daily 7-DADMax and daily average) over the study year in Wide Hollow Creek. 55

Figure 15. Boxplots of field measurements grouped by source water type. 58

Figure 16. Water chemistry samples collected in Wide Hollow Creek. 60

Figure 17. Boxplot of water chemistry for several types of water sources, over the entire study year. 61

Figure 18. Comparison of water temperature between the Naches-Cowiche canal diversion versus outfall at 32nd Avenue (July 1 to October 15, 2013). 62

Figure 19. Comparison of canal diversion versus outfall water quality. 64

Figure 20. Detail of continuous flow and dissolved oxygen measurements at 101st Ave stream and water quality gage....68
Figure 21. Study year dissolved oxygen time series at 101st Ave. 70
Figure 22. Study year dissolved oxygen time series at 40th Ave. 71
Figure 23. Study year dissolved oxygen time series at White St (Union Gap). 72
Figure 24. Study year pH time series at 101st Ave. 73
Figure 25. Study year pH time series at 40th Ave. 74
Figure 26. Study year pH time series at White St (Union Gap). 75
Figure 27. Light extinction survey results on Wide Hollow Creek. 77
Figure 28. Relationship between measured slopes and detritus and inorganic suspended solids....78
Figure 29. Average and range of nine parameters during two synoptic surveys of Wide Hollow Creek, comparing groundwater, tributary sources to the creek, and water in the creek. 80
Figure 30. Current (2019) 303(d) Category 5 listings and associated assessment units....87
Figure 31. Summary of daily observation of 7-DADMax water temperature, dissolved oxygen, and pH measurements in Wide Hollow Creek during Ecology study year compared to respective water quality criteria....88
Figure 32. Summary of daily observation of water temperature, dissolved oxygen, and pH measurements in East Spring Creek during Ecology study year compared to respective water quality criteria. 89
Figure 33. Model segmentation and temperature logger locations (top). Model headwater detail (bottom). 95
Figure 34. Schematic of QUAL2KW model set up of Wide Hollow Creek. 96
Figure 35. Year-round point sources and diversions. 99
Figure 36. Full study year flow rates (cfs) for all point sources to Wide Hollow Creek.101
Figure 37. Measured range (max/avg/min) of vertical hydraulic gradient, interpolated for model. 103
Figure 38. Comparison of model simulated vs. observed travel times from two dye studies. 107
Figure 39. Model simulated flow (blue) vs measurements (orange), showing statistics of fit for the full year....109
Figure 40. Summary of the sources and losses of water to Wide Hollow Creek during irrigation and non-irrigation seasons. 111
Figure 41. Comparison between simulated and observed specific conductance during the non-irrigation season....112
Figure 42. Comparison between simulated and observed specific conductance during the irrigation season. 113
Figure 43. Comparison of simulated and observed chloride concentrations. 114

Figure 44. Summary of the seasonal loads of chloride to Wide Hollow Creek by category. 115
Figure 45. Summary of the seasonal loads of conductivity to Wide Hollow Creek by category. 115
Figure 46. Example of digitized vegetation polygons which were used for calculating effective shade. 117
Figure 47. Example of a hemispherical vegetation photograph taken at the center of Wide Hollow Creek. 118
Figure 48. Effective shade calculated by the shade model compared to hemispherical photograph calculations. 119
Figure 49. Hourly simulated (predicted) versus observed temperatures in Wide Hollow Creek during the 2013 portion of the study year. 122
Figure 50. Hourly simulated (predicted) versus observed temperatures in Wide Hollow Creek during the 2014 portion of the study year. 123
Figure 51. Daily 7-DADMax simulated (predicted) versus observed daily 7-DADMax temperatures in Wide Hollow Creek during the 2013 portion of the study year. 124
Figure 52. Daily 7-DADMax simulated (predicted) versus observed daily 7-DADMax temperatures in Wide Hollow Creek during the 2014 portion of the study year. 125
Figure 53. Summary of the seasonal loads of inorganic suspended solids to Wide Hollow Creek. 127
Figure 54. Summary of the seasonal loads of detritus to Wide Hollow Creek. 128
Figure 55. Summary of the seasonal loads of nitrate to Wide Hollow Creek by category. 129
Figure 56. Summary of the seasonal loads of organic nitrogen to Wide Hollow Creek. 129
Figure 57. Summary of the seasonal loads of ammonia to Wide Hollow Creek. 130
Figure 58. Summary of the seasonal loads of organic phosphorus to Wide Hollow Creek. 131
Figure 59. Summary of the seasonal loads of inorganic phosphorus to Wide Hollow Creek. 131
Figure 60. Summary of the seasonal loads of carbonaceous biochemical oxygen demand to Wide Hollow Creek. 132
Figure 61. Hourly simulated (predicted) versus observed dissolved oxygen in Wide Hollow Creek during the study year. 135
Figure 62. Hourly simulated (predicted) versus observed pH in Wide Hollow Creek during the study year. 136
Figure 63. Scenario #1 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen. 139
Figure 64. Scenario #2 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen. 141

Figure 65. Scenario #3 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen. 142
Figure 66. Scenario #4 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen. 143
Figure 67. Travel time, daily average flow, and maximum reach velocity comparison between the baseline and scenario simulations (from 64th Ave to the mouth). 145

List of Tables

Page

Table 1. Municipal stormwater NPDES permit holders in the study area. 32

Table 2. Stormwater and industrial wastewater NPDES permit holders in the study area. 33

Table 3. Current (2019) 303(d) Category 5 listings for temperature, dissolved oxygen, and pH for Wide Hollow Creek and tributaries. 35

Table 4. Current (2019) 303(d) Category 5 listings for bacteria and toxics for Wide Hollow Creek and tributaries (parameters not addressed by this study). 36

Table 5. Washington State water quality criteria for temperature, dissolved oxygen, and pH in Wide Hollow Creek...37

Table 6. Survey dates for synoptic surveys and other field measurements. 40

Table 7. List of surface sampling sites and monitoring activities.....................................42

Table 8. List of sites which were dry during all field survey dates (July 2013 - June 2014). 44

Table 9. Summary of weather stations, location, and available data. 47

Table 10. Highest daily maximum temperatures in Wide Hollow Creek and its tributaries during the 2013-14 study year. 56

Table 11. Time of travel - dye study results on Wide Hollow Creek. 76

Table 12. Tabulation of minimum dissolved oxygen, minimum and maximum pH, and 7-DADMax or maximum temperature from measurements of Wide Hollow Creek sources during the Ecology study period. 90

Table 13. Year-round point sources and diversions to Wide Hollow Creek. 98

Table 14. Irrigation season only point sources and diversions to Wide Hollow Creek...100

Table 15. Net gains/losses of groundwater used in the QUAL2Kw model. 104

Table 16. Goodness-of-fit statistics between simulated and measured flow. 110

Table 17. Vegetation classification used in the Shade.xls model. 117

Table 18. Root mean squared error (RMSE) and overall bias of differences between QUAL2Kw predicted and observed daily maximum and average temperatures (°C) in Wide Hollow Creek...121

Table 19. Root mean squared error (RMSE) and overall bias of differences between QUAL2Kw simulated and observed daily average, minimum, and maximum dissolved oxygen (mg/L) and pH (standard units) in Wide Hollow Creek. 133

Abstract

Located in Yakima County of central Washington State, the Wide Hollow Creek watershed originates in the upland areas to the west of the City of Yakima about 17 miles above its confluence with the Yakima River near the city of Union Gap. During the irrigation season, streamflow in the creek is dominated by irrigation water.

The aquatic life use category for Wide Hollow Creek is designated as salmonid spawning, rearing, and migration. Previous monitoring data have shown that Wide Hollow Creek does not meet the temperature, dissolved oxygen, or pH criteria needed to support its aquatic life use category and is therefore on Washington State′s list of impaired waters (303(d) list).

To understand the causes of the impairments, the Washington State Department of Ecology (Ecology) conducted a yearlong water quality study from July 2013 to June 2014. Ecology collected data to develop and calibrate a numerical water quality model of the perennial portion of the creek in order to simulate continuous temperature, dissolved oxygen, pH, and other water quality parameters. Additionally, Ecology conducted a biological and habitat assessment of selected reaches of Wide Hollow Creek.

This report examines water quality in Wide Hollow Creek for the 2013-2014 study year. In addition, water quality model simulations were used to predict water quality changes in temperature, dissolved oxygen, and pH levels in Wide Hollow Creek under different hydrologic and shade conditions.

Acknowledgements

The authors of this report thank the following people for their contributions to this study:

- Washington Department of Fish and Wildlife staff:
  - Jonathan Kohr and Robert Granger for assistance in measuring streamflow and sampling fish.
  - Jonathan Kohr, Eric Bartrand, and Perry Harvester for historical data and review of the draft report.
- Joel Freudenthal of Yakima County Water Resources for historical information, site selection, and review of the draft report.
- Irrigation districts for access to their canals to measure flow and sample water quality parameters: Robert Smoot (Yakima Valley Canal), Dan Butler (Naches-Cowiche Canal)
- Congdon Orchards (Dick Woodin) for access to their discharge for sampling.
- Colonial Lawn and Garden (Lance Forsee) for access to the creek.
- Perry Tech (Russ Warner) for recording pump data.
- Ray Lara, Earl Wickersham, John Steenbergen, Taisoo Choi, Mark Martin, Clifford Plath, Trent Marquis, John Hodkinson, and Pat McDonald for access to the creek.
- Washington State Department of Ecology staff:
  - Water Quality Program, Central Regional Office: Laine Young and Chris Coffin for assistance in field studies.
  - Environmental Assessment Program: Chris Hartman, Jill Lemmon, Chad Larson, Dan Dugger, Eiko Urmos-Berry, and Tom Mackie.

Background

Introduction

Wide Hollow Creek (Figure 1) is located in Yakima County and traverses parts of the cities of Yakima and Union Gap. The watershed drains the south slope of Cowiche Mountain and a portion of the east slope of Pine Mountain. The drainage area is about 70 square miles (CFHMP, 2012). Several of the smaller sub-drainages are:

- Cottonwood Creek
- Shaw Creek
- East Spring Creek

The Wide Hollow Creek watershed is arid and requires irrigation for agriculture. The watershed is intensely farmed, although the cities of Yakima and Union Gap urban areas increasingly expand into the lower watershed. Many irrigation ditches and drainage channels have been constructed since the late 1800s to promote agriculture. The current configuration of the watershed was constructed and modified to function as part of the irrigation system in the valley. Waters imported from the Naches and Tieton Rivers irrigate most of the middle and lower watershed.

The hydrology, geometry, and locations of the creek has been greatly altered to support irrigation in the watershed. Some portions of the creek are incised, channelized and diked. The watershed is subject to infrequent flooding, exceeding the hydraulic capacity of the creek channel. The flooding has been attributed to rain-on-snow events in the upper watershed (CFHMP, 2012).

Flow in the creek is higher during the irrigation season than in the non-irrigation season (not including winter/spring runoff events from the upper watershed). This occurs due to irrigation water which is discharged directly into the creek. Irrigation season typically goes from mid-March to mid-October. During the study year, direct discharge of irrigation to the creek only affected Wide Hollow Creek from 101st Ave downstream.

During the non-irrigation season, some of the upper creek is intermittently dry; below 64th Ave perennial flow in the creek is supported year-round by groundwater inflow. The groundwater inflow is from localized areas where the creek intercepts the groundwater table, and where drainage improvement district (DID) pipes direct collected groundwater to the creek. Further upstream of 64th Ave, the creek generally dries up except for localized areas where the incised channel intercepts the water table but then goes subsurface again, and when runoff events take place.

Former studies reported Wide Hollow Creek is limited for aquatic life by habitat and water quality issues (Kendra, 1988; Haring, 2001). Some parties are interested in supporting and sustaining fish use in the creek. This report will contribute by presenting findings about sources of water to the creek and an assessment of the water quality impairment.

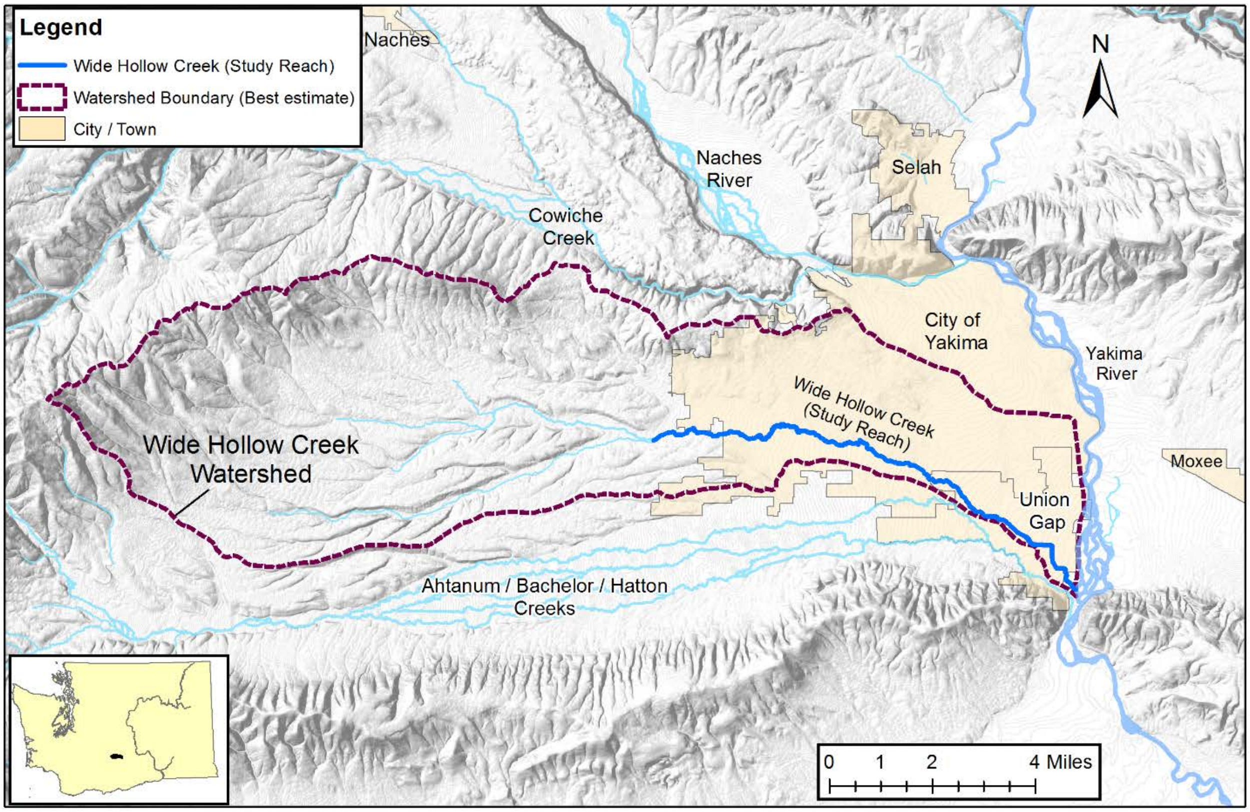


Figure 1. Study area for the Wide Hollow Water Quality Study.

Maps in this report (such as Figure 1) were prepared by Ecology using geographic information system (GIS) datasets and ArcMap software (version 10.2.2). More information is available at *https://ecology.wa.gov/Research-Data/Data-resources/Geographic-Information-Systems-GIS*.

Why is Ecology conducting this water quality study?

The aquatic life use category designated for Wide Hollow Creek is salmonid spawning, rearing, and migration. Because areas in the creek do not meet the criteria for water temperature, dissolved oxygen (DO), or pH needed to support this aquatic life use category, it is considered impaired. It is included on a list of Washington State′s impaired surface waters, called the 303(d) list. This study was conducted to: (1) understand what is causing the impairments to this creek, (2) determine what improvements may be feasible for this creek, and (3) provide technical support for a possible future TMDL (see next section).

Water Quality Assessment (WQA) and the 303(d) List

Every two years states are required to prepare a list of water bodies that do not meet water quality standards. This list is called the Clean Water Act Section 303(d) list. In Washington State, this list is part of the Water Quality Assessment (WQA) process.

To develop the WQA, the Washington State Department of Ecology (Ecology) compiles its own water quality data along with data from local, state, and federal governments, tribes, industries, and stakeholder monitoring groups. All data used in the WQA are reviewed to ensure that they were collected using appropriate scientific methods before they are used in the assessment. The list of waters that do not meet standards [the 303(d) list] is the Category 5 part of the larger assessment.

The WQA divides water bodies into five categories. Those not meeting standards are given a Category 5 designation, which collectively becomes the 303(d) list.

Category 1 – Waters that meet standards for parameter(s) for which they have been tested.

Category 2 – Waters of concern.

Category 3 – Waters with no data or insufficient data available.

Category 4 – Polluted waters that do not require a clean-up plan because they:

- 4a. – Have an approved water clean-up plan being implemented.
- 4b. – Have a pollution-control program in place that should solve the problem.
- 4c. – Are impaired by a non-pollutant such as low water flow, dams, and culverts.

Category 5 – Polluted waters that require a water clean-up plan – the 303(d) list.

Further information is available at Ecology's Water Quality Assessment website.

The Clean Water Act requires that a clean-up plan called a Total Maximum Daily Load (TMDL) be developed for each of the water bodies on the 303(d) list. A TMDL is numerical value representing the highest pollutant load a surface water body can receive and still meet water quality standards. Any amount of pollution over the TMDL level needs to be reduced or eliminated to achieve clean water.

Study overview

Ecology conducted a year-long water quality study beginning in July 2013 and ending in June of 2014. As part of this study, Ecology collected data to develop and calibrate a numerical water quality model of the creek to simulate continuous temperature, DO, pH, and other water quality parameters. This model can be used to understand the causes of impairments to this creek and predict stream response to potential future improvements. Additionally, Ecology conducted a biological and habitat assessment of Wide Hollow Creek.

Historical data review

Past studies providing details regarding Wide Hollow Creek water quality were summarized in the QAPP (Carroll, 2013). A list of the summarized studies include:

- 2012 Comprehensive Flood Management Plan – Yakima County
- 2007-08 Yakima River Pesticides and PCBs TMDL Study – Ecology
- 2005-06 and 2010 Yakima Area Creeks Bacteria TMDL Study – Ecology
- 2002-03 Water Quality BMP Implementation– North Yakima Conservation District
- 2001 Habitat Limiting Factors Yakima River Watershed – Washington State Conservation Commission
- 1987 Quality of Water, Sediment, and Biota in Wide Hollow Creek– Ecology

Watershed Description

Climate

The Wide Hollow Creek watershed is located in an arid region. Average annual precipitation ranges from as little as 5 inches per year at its mouth to about 20 inches in the upper watershed. The watershed lies in the rain shadow of the Cascades, largely protected from rain and snow accumulation. Most of the precipitation falls as snow during winter in the upper watershed (Figure 2). Agriculture in the valley is dependent on irrigation water imported from the Naches and Tieton Rivers.

The climate is dominated by warm and dry summers with relatively mild winters. Air temperatures in Yakima reach an average daily high of 87°F (30.5°C) in July dropping to an average daily high of 37°F (2.7°C) in January.

Geology

The Wide Hollow Creek watershed is located on the western boundary of the Yakima Fold Belt. Elevations range from almost 4000 feet at the top of Pine Mountain to about 1000 feet at the mouth near Union Gap. The Yakima Fold Belt is characterized by east west trending ridges and valleys formed by the folding of basalt flows of the Miocene aged Columbia River Basalt Group (CRB). The CRB is composed of a sequence of basaltic lava flows several thousand feet thick. It is the basal or bedrock unit in the valley.

Surface lithology for the study area is shown in Figure 3. The most important units for the Wide Hollow Creek watershed are:

- Basalt - Columbia River Basalt Group (CRB), bedrock unit described above.
- Ellensburg Formation - Overlying and interbedded with the CRBs are the sandstones and volcanoclastic sediments of the Miocene Ellensburg Formation. The Ellensburg Formation consists of several hundred feet of semi-consolidated clay, silt, sand and gravel. It is mostly indurated and tough, but some sand and gravel strata are weakly cemented and are moderately permeable (Foxworthy, 1962). This unit contains a water-bearing aquifer.
- Thorp Gravel - Above the CRB and Ellensburg Formations are the Pliocene-aged consolidated gravels of the Thorp Formation. These gravels are predominantly derived from basalt and include moderately to well-rounded cobbles. They are generally well cemented but also contain sand, silt, and clay lenses. They are more than 400 feet thick in some places.
- Alluvium - consists of a thin layer of unconsolidated and semi-consolidated stream deposits over the gravel. Alluvium thickness ranges from a few to about 30 feet.
- Terraced deposits - consists of older alluvium deposits terraced above the more current alluvial deposits.

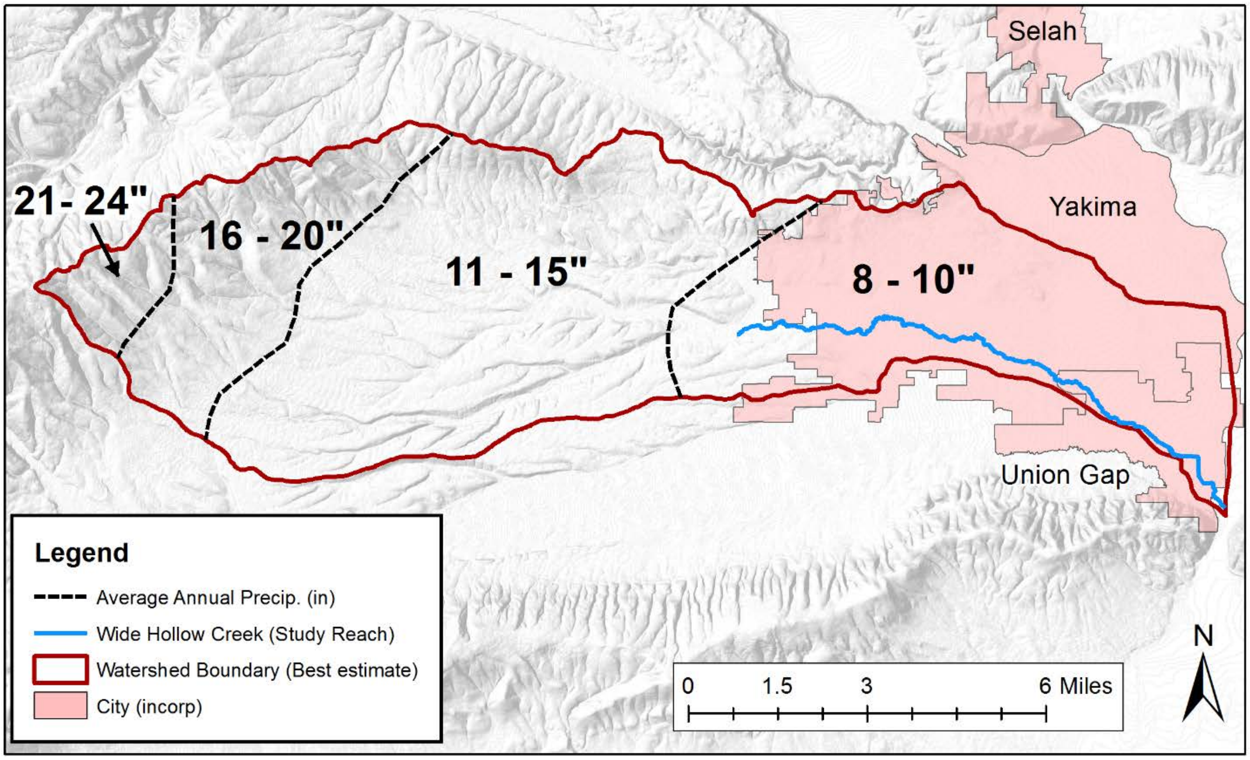


Figure 2. Map of Wide Hollow Creek watershed with precipitation isopleths in inches per year. *Isopleths drawn based on average annual precipitation data 1981-2010 from PRISM Climate Group at Oregon State University.*

Shallow groundwater in the unconsolidated alluvium beneath the creek may alternately rise to or sink below the land surface several times along the eastward course (Foxworthy 1962), although in general, surface water recharges the alluvial aquifer in the upper valley and the alluvial aquifer recharges surface water streams in the lower valley.

Where the stream channels are cut or incised deep enough, groundwater enters the creek at localized areas where the creek bottom intercepts the alluvial aquifer. In some places the aquifer naturally surfaces as springs in topographic depressions.

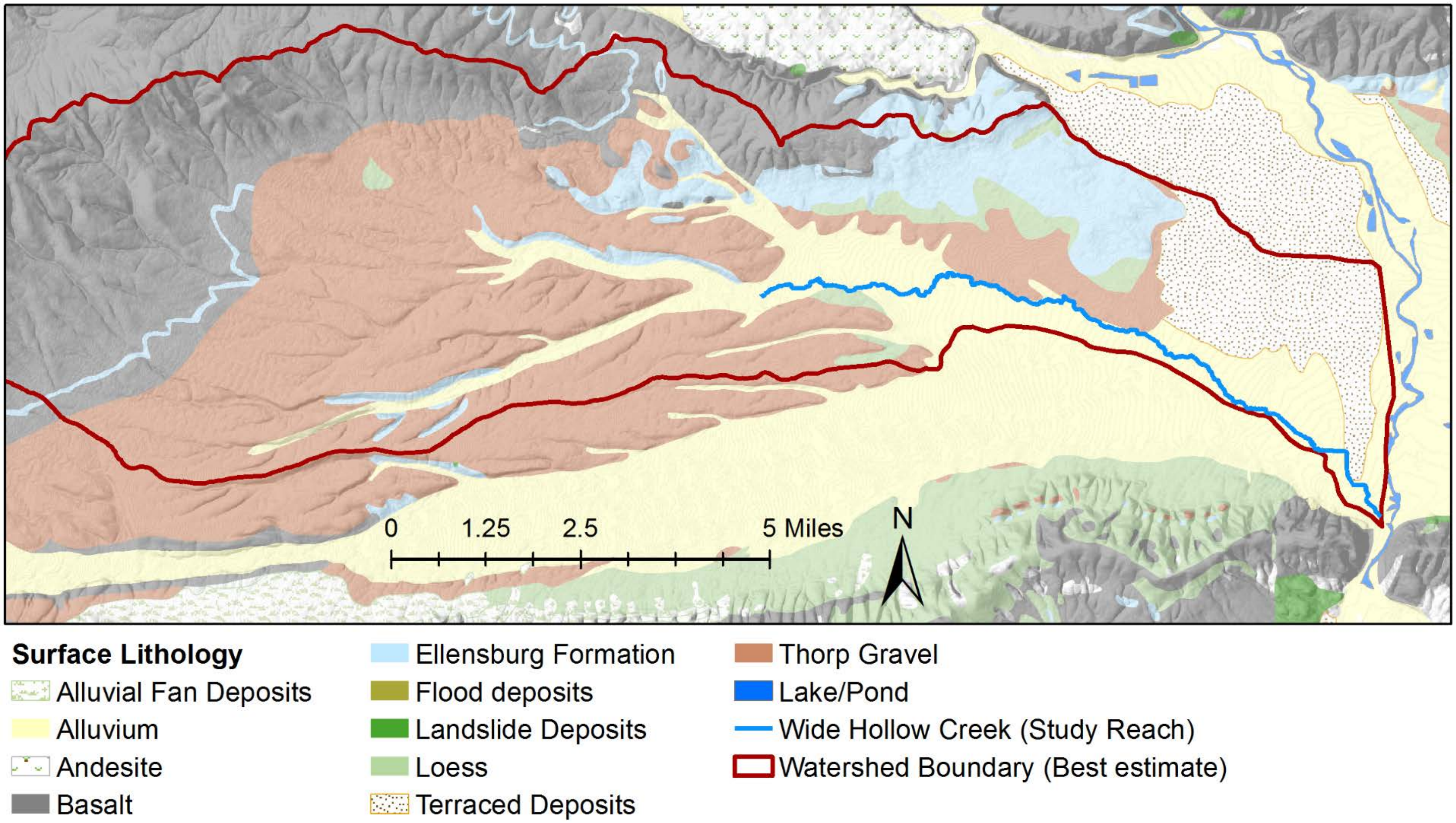


Figure 3. Surface lithology of the study area.

Modified from Washington State Department of Natural Resources geologic unit polygons.

Soils and vegetation

Soils

The lower portion of the watershed is formed on low terraces and a flood plain of the Yakima River. The soils are Umapine, Esquatzel, and Warden silt loams (NRCS 2016). These areas were generally artificially drained to reduce alkali effects, and create drier conditions for farming and ranching. The native vegetation would possibly have been alkali-tolerant grasses, forbs, and shrubs.

The middle of the watershed is formed on terraces with a variety of loams and silt loams (Harwood, Selah, Cowiche, Gorst), some of unique and important agricultural significance (NRCS, 2016). Many of the soils of these dissected terraces were formed from Pleistocene-aged loess deposits. The potential native vegetation on this unit is mainly bluebunch wheatgrass, big sagebrush, and Sandberg bluegrass. The terraces are generally used for irrigated field and orchard crops, rangeland, and home sites. Grasses and legumes are grown for hay, pasture, or seed.

The upper watershed, which drains Cowiche and Pine Mountains, are predominately stony, silt loam soils (Rock Creek and Kiona) (NRCS, 2016). Pre-development, there were areas with sparser vegetation on the rocky, steeper declines of the very upper watershed elevation maxima, but also a healthy shrub-steppe climax vegetation association watered by the highest precipitation in the watershed.

Current vegetation

Most of the upper watershed above irrigated lands is in private ownership. Much of that land has been rangeland for over a century and is dominated by cheat grass (*Bromus tectorum*). Heavy grazing over many decades has produced a more vulnerable soil and vegetation profile with higher erosion and precipitation runoff than the original native vegetation cover.

Parts of the upper watershed are within the irrigated lands, and has been turned into agricultural land such as tree orchards and pasture. The lower watershed is primarily urban usage, with vegetation consisting of irrigated lawns, gardens, trees, and shrubs.

Riparian vegetation along the creek consists of willow and associated water-loving plants (phreatophytes or "well-plants"). These generally grow in belts and clumps along the perennial portions of the creek that carry irrigation water along the lower valley floor. These plants are supported by imported irrigation water during the hot and dry summers.

One of the dominant, invasive riparian plants is (*Salix fragilis*) “crack willows”. Yakima County has been working to replace these trees because they damage stream function. Crack willows were introduced in the early 20th century to stabilize stream banks in rapidly cultivating and developing Yakima County. In wet conditions, the tree is highly invasive and forms an extensive over-story that prevents native understory growth. The result is stream banks that lack many normal ecosystem functions, such as healthy recruitment of replacement shrubs and trees, support for wildlife, and normal sediment transport and deposition. In addition, crack willows presents risks to roads, structures, bridges and stream banks. They can grow to moderate height, but often sag and cast off fragile branches, forming log jams in streams, particularly around bridge abutments. For this reason, cities and counties are actively working to eliminate these hazard trees.

Plans to replace the trees with more stable vegetation are currently in progress in the Wide Hollow Creek watershed. Yakima County has conducted a survey of crack willow presence and found that a majority of Wide Hollow Creek's banks are dominated by crack willow canopy. Replacement of crack willow requires complete removal of the canopy while new stable vegetation is established, which may affect water quality issues, like stream temperature. Though removal might have short term effects on creek functions, eventual replacement with a distribution of self-recruiting shrubs and trees that also form stream canopies is desirable.

Historical vegetation

As described by Farnsworth (1872) and Richardson (1867), prior to development, the whole watershed of Wide Hollow Creek (particularly the upper watershed), other than areas with alkali soils, was covered in a mature, shrub-steppe climax vegetation association of big sagebrush and blue-bunch wheatgrass (*Artemisia tridentate* - *Agropyron spicatum*). As described by Daubenmire (1970), the sagebrush would have been scattered ($\approx$ 33 plants per 100 m^2), occupying about 15% of the coverage with perennial bluebunch wheatgrass averaging about 50% of the coverage. The balance of coverage would have partially dominated by perennial Sandberg bluegrass (*Poa secunda*), Antelope bitterbrush (*Purshia tridentate*), and minor amounts of annual forbs.

The surface of the soil would have been broken into hexagonal pieces separated by soil cracks a few centimeters deep due to alternate freezing/thawing or wetting/drying. The annuals would be briefly confined to the soil cracks. Daubenmire (1970) makes note that the soil was never bare in this climax vegetation association. Where open and not covered by vasculars, a delicate but continuous cryptogamic soil crust made up of lichens, mosses, and occasionally, liverworts covered the soil and protected it from wind erosion and aided infiltration and soil stability.

Any stream channels or sloughs that had enough water supported a thorny riparian thicket (Richardson, 1867).

Land use

Most of the watershed above irrigation supply is privately-owned rangeland, with a small portion managed by the Washington Department of Fish and Wildlife. The transition to pasture, orchards, and cropland occurs down valley, starting abruptly where irrigation systems convey water from the Tieton and Naches Rivers.

Wide Hollow Creek is bordered by agricultural orchards and livestock pasture. However, the West Valley area is experiencing rapid urbanization from Yakima, with residential, commercial, and light industrial land usage all the way to Union Gap. Urban land use comprises about a third of the Wide Hollow Creek watershed.

Hydrology

The hydrology of the Wide Hollow Creek watershed has changed over time due to the development of irrigation in the Yakima Valley. Prior to irrigation development, Wide Hollow Creek did not receive enough precipitation to produce perennial streamflow in most years. Today, irrigation water from the Tieton and Naches Rivers is imported to the Wide Hollow Creek watershed via canals and pipelines, profoundly impacting the hydrology of the basin. To understand the complex changes in hydrology over time, the hydrology and irrigation development during several time periods are described below. This is a generalized description based on historical references, as well as interpretations based on the conclusions and the work conducted during this study (see below).

Pre-development and early diversions (pre-1880s)

Pre-development (before irrigation) streamflow in the creek originated from the upper basin and ranged from very little to occasional seasonal runoff events (intermittent) usually in late winter/early spring. Most rain and snowmelt in the upper basin infiltrated to groundwater or was used by vegetation. Rain-on-snow flood events also shaped the lower valley from time to time. The basin was described as a giant sage-flat expanse (Farnsworth, 1872; Richardson, 1867).

Intermittent upper watershed streamflow:

- *Sometimes dry*
  Prior to development, some years yielded no runoff from the upper basin (as seen in winter and spring of the study year 2013-14), with all precipitation and snow-melt infiltrating to ground, or intercepted by vegetation. The upper watershed, where most of the precipitation falls, was described as rolling to gently rolling prairie with 3rd and 4th rate soils, generally covered in a mature, climax zonal vegetation of bunchgrass and sagebrush (Farnsworth, 1872), except for the upper steeper sections which were stony and bare. The entire watershed would have had greater infiltration capacity and less erosion in its unaltered state than it does today (see above section on Vegetation and Soils).

- *Seasonal run-off*
  In years that precipitation or snowmelt exceeded the infiltration rate or if the ground was frozen, water ran down many intermittent channels into the lower watershed (Figure 4) as shown in the 1899 USGS quadrangle map. The surface flow extended downstream until the volume was either infiltrated in more alluvial portions of Wide Hollow, or eventually routed to perennial channels (Spring Creek, Bachelor Creek, and ultimately Ahtanum Creek). Seasonal runoff events would not have supported perennial flow.

- *Intermittent flooding*
  Large runoff events also occurred in the Wide Hollow watershed. When these runoff events were large enough in volume, they converged from the upper watershed drainages to form sheet floods that, overtime, scoured and carved out a mile-wide hollow (flood channel) from 101st Ave to 48th Ave, giving the land a morphological surface form for which it is named.

Groundwater

Infiltrating water in the upper watershed moved down-slope as groundwater through the alluvium, sometimes surfacing in the lower watershed, like Spring Creek (near the airport), but mostly converging and discharging to the Yakima River above Union Gap, which is the natural restricted discharge outlet for the Yakima-Moxee groundwater basin.

Other perennial lower watershed streamflow (not Wide Hollow Creek)

While not showing Wide Hollow Creek, the GLO surveys from the 1860s (Figure 4) showed perennial tributaries to Ahtanum Creek, including Bachelor Creek which included flow from Spring Creek. There was also a “spring branch” tributary to Ahtanum Creek near Fulbright Park. East Spring (Chambers) Creek was shown as a tributary to the Yakima River, down on the Yakima River alluvial plain, and did not receive water from the Wide Hollow Creek watershed.

Early diversions from Bachelor Creek and Ahtanum Creek

The first irrigation ditch of substantial size to be constructed in the Wide Hollow Creek area was that of the Shanno brothers (Pfaff, 2002). They settled on a sagebrush flat at what is now the town of Union Gap (then called Yakima City) and, in 1871, dug a ditch to divert water from Bachelor Creek before its confluence with Ahtanum Creek near the Carpenter property (currently the Youth Activities Park). Bachelor Creek likely included intermittent flow from Wide Hollow too. The irrigation ditch routed water directly east to irrigate the sage-flat just west of Union Gap (Figure 4, top). The ditch was only productive during spring runoff, and not through the summer. A Metsker’s county map showed the Shanno ditch diversion of Bachelor Creek as late as 1932.

At some point, Ahtanum Creek was diverted just before today’s Fulbright Park into a flume running northeasterly called the “Barker’s Raceway” (Figure 4, top) to drive the flour grist millworks at Main Street in Union Gap. Again, insufficient flow in the summer and fall limited the use of the flume diversion year-round.

A ditch to divert water from Ahtanum Creek was constructed in 1879. Called the Ahtanum and Wide Hollow Ditch, it headed on the north side of the creek and carried water for 10 miles toward the town of North Yakima, irrigating about 250 acres (Pfaff, 2002).

Development of large irrigation projects

Early irrigation-development (1880s to 1905)

Larger scale irrigation was brought into the Wide Hollow watershed in the late 1880s and 1890s by importing water from the Naches River watershed. Two early irrigation projects diverted water from the Naches River to irrigate lands in present-day west Yakima and West Valley:

- Naches and Cowiche Canal
  The Naches and Cowiche Canal, originally built in 1882, diverted <35 cfs of water from the Naches River (Jensen and Olshausen, 1901), and routed water through the terraced deposits where the “North” Yakima City was established. It could only deliver water up-valley to present day 32nd Ave. Excess water in the canal was delivered to the Wide Hollow alluvial plane near the present day airport.

- <u>Yakima Valley Canal</u>
  The Yakima Valley Canal (also called Congdon Ditch), built in 1894, originally diverted 37 cfs of water from the Naches River (Jensen and Olshausen, 1901), near present-day Eschbach Park. In July-August of 1903, it diverted an average of 58 cfs (Jayne, 1907).

After clearing the rock outcroppings above Chesterley Park, Yakima Valley Canal turned west and snaked into West Valley, maintaining a high line until intercepting an intermittent channel of the Wide Hollow drainage (Shaw Creek) near present-day 91st Ave and Wide Hollow Rd. Excess water in the canal was discharged into the Wide Hollow Creek channel.

Jensen and Olshausen (1901) found that the Yakima Valley Canal lost 30-33% of its flow "by actual determination" due to leakage and infiltration to ground from the unlined canal.

Figure 4 (bottom) shows the configuration of these irrigation projects based on the mapping shown on the 1899 USGS quadrangle map (USGS, 1899). The map shows that the natural intermittent channels of Wide Hollow were used to distribute and move the out-of-basin irrigation water.

The 1899 USGS quad map shows intermittent channels, one from Cottonwood Canyon, one from the upper Wide Hollow, and one from Shaw Creek joining near present-day 96th Ave. The map shows the Yakima Valley Canal flowing to this intersection of intermittent channels (via Shaw Creek) from where it was apparently routed down the continuing channel of Wide Hollow Creek.

The 1899 USGS map shows the creek channel splitting just below present-day 80th Ave. One channel routed water directly east and connected into the Spring Creek drainage. Another channel routed the canal northward toward the western toe of Nob Hill at 64th Ave. This part of the canal generally followed the southern margin of the Nob Hill rise, past the Congdon properties to present-day 16th Avenue. Below 16th Ave, Wide Hollow Creek was apparently re-routed easterly by digging a ditch across terraced deposits to connect with the alluvial sage flats near Union Gap ("old Yakima City"). This ditch would provide irrigation to the sage flats and consistent water to power the flour grist millworks in Union Gap. Locally, this ditch was referred to on maps as the "Congdon Canal" or "Congdon Ditch".

The eastern extent of the 1899 USGS quad map ends before Union Gap, but a US Department of Agriculture map from a 1901 soils report show Wide Hollow Creek (Congdon Ditch) continuing to Main Street in Union Gap and entering the East Spring Creek drainage (Jensen and Olshausen, 1901). The soils report refers to Wide Hollow Creek (Congdon Ditch) as the "Wide Hollow waste slough" and commended its ability, due to its dug depth of at least 5 feet below the soil surface, to artificially drain the surrounding alkali soils of excess saturating groundwater in the lower watershed.

Irrigation canal water diverted into the Wide Hollow Creek basin apparently caused problems with soil alkalinity (Figure 4, bottom) because it raised the groundwater level close to the surface. The 1901 soil survey notes that many of the agricultural lands "formerly among the best" in the Wide Hollow and Ahtanum Valley had been abandoned to salt-grass and greasewood, due to alkali in the soil. The survey notes, "The alkali in the Wide Hollow and Ahtanum areas has originated from the seepage water brought down from the lands above" (Jensen and Olshausen, 1901).

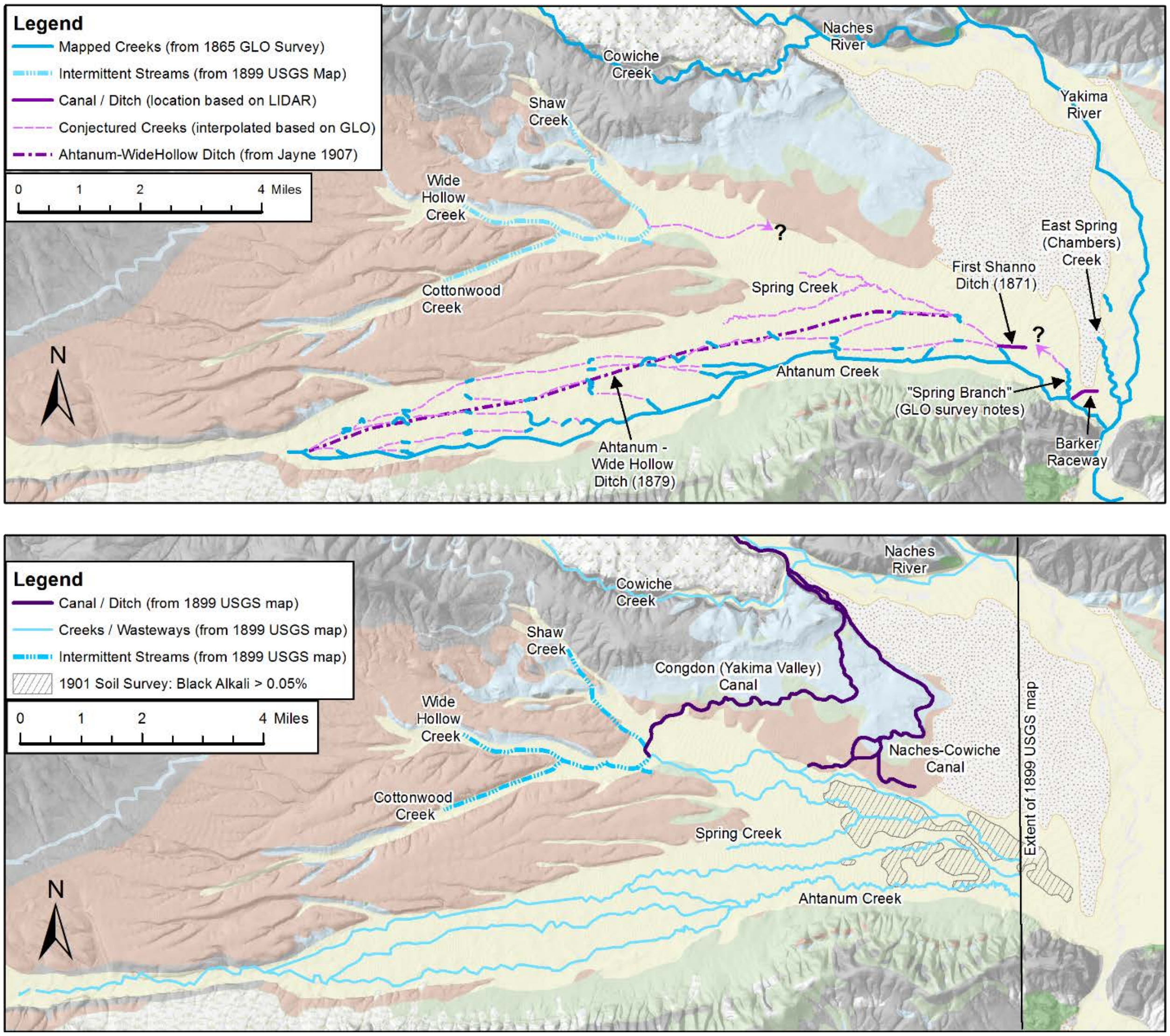


Figure 4. *Top*: early diversions to Wide Hollow Creek (1860s to 1870s). *Bottom*: early irrigation development importing Naches River water to Wide Hollow Creek (1880s to 1905).

Drainage improvement districts (DIDs) were established to control rising groundwater tables due to the increased irrigation in the lower watershed. Field drains and sub-surface drain tile collection systems were also encouraged to lower the groundwater table to improve soils for agriculture (Jensen and Olshausen, 1901). Sub-surface drain tile collection systems routed groundwater to the Wide Hollow Creek "waste slough" (Jensen and Olshausen, 1901).

All of the out-of-basin water increased the flow in Wide Hollow Creek during the irrigation season, creating higher flow during the normally dry summer season.

Later irrigation-development (1909 to 1980s)

The upper Wide Hollow Creek watershed (above 101st Ave) was opened to irrigation beginning in October 1909, when the Tieton Main Canal was completed (Pfaff, 2002). The West Valley Division distribution system (Figure 5, top), was built between 1909 and 1911. After emerging from the North Fork Tunnel, the Tieton Main Canal emptied into the North Fork of Cowiche Creek. From there, water was diverted at five points by low diversion dams into eight main laterals (Pfaff, 2002).

Formerly intermittent channels in the upper watershed were used to convey water, collect irrigation runoff, intercept newly elevated groundwater tables, and move excess water out of the upper basin. Intermittent channels were altered for irrigation purposes and sometimes moved to new locations, interrupting their natural function (CFHMP, 2012).

Like all unlined canals in the valley, the Yakima-Tieton Canal lost water to leakage and infiltration to groundwater, artificially raising groundwater levels in the upper watershed. Perennial streamflow in Wide Hollow Creek probably began from rising groundwater levels during this time period.

Current (mid-1980s to present)

Since the mid-1980s, the Yakima-Tieton Irrigation District converted from an open gravity feed ditch to a pressurized pipe delivery for irrigation (Figure 5, bottom). This piping eliminated the infiltration loss of water from the canal, as well as end-of-canal water flow to the creek. Figure 6 shows that recent flow measurements in Wide Hollow Creek, after conversion of the Yakima-Tieton to pressurized lines, (2004-14) are lower than flow from the earlier period (1911 to 1982), including decreased winter baseflow. However, the overall pattern of high summer irrigation flow and low winter baseflow continued (Figure 6).

During the study year (July 2013 through June 2014), frequent site visits by Ecology consistently found no surface water flow from the upper basin (above 101st Ave), although a small flow was evident in the spring of 2013. Conversely, wet winters in 2015 and 2016 produced short, sustained spring run-off from the upper watershed.

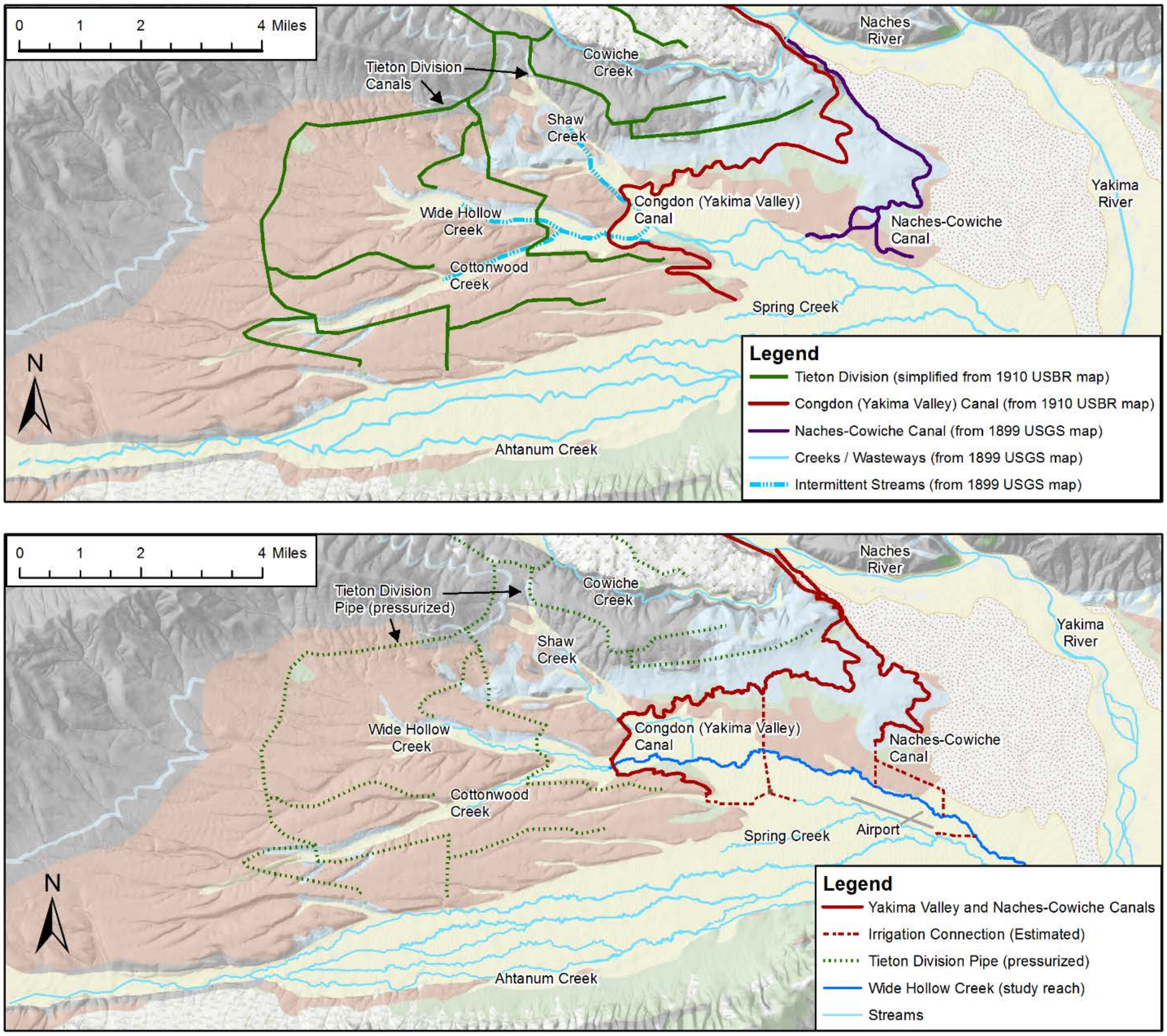


Figure 5. *Top*: later irrigation development in the upper Wide Hollow Creek watershed (1909-1985). *Bottom*: current irrigation configuration after conversion of the Tieton Division to pressurized pipe (1986-present).

Intermittent upper watershed streamflow

The current upper watershed hydrology (above 101st Ave) probably represents something closer to pre-development hydrology and hydrogeology compared to the time before the Yakima Tieton Canal was piped and pressurized.

- Sometimes dry
  Similar to the time period prior to development of the Yakima-Tieton irrigation, some years yield no runoff from the upper basin (as seen in winter and spring of the study year 2013-14), with all precipitation and snow-melt infiltrating to ground, or intercepted by vegetation. However, disturbed vegetation in the upper watershed permits flashy runoff from precipitation and snowmelt events in some years.

- Seasonal run-off
  In years that precipitation exceeds the infiltration rate (reduced from historical rates by current vegetation) or if the ground is frozen, water runs down many intermittent channels into the lower watershed. The surface flow extends downstream until the volume is either infiltrated in more alluvial portions of Wide Hollow, or eventually routed to perennial channels (Ahtanum Creek and Yakima River). These are generally short, seasonal runoff events and do not support perennial flow.

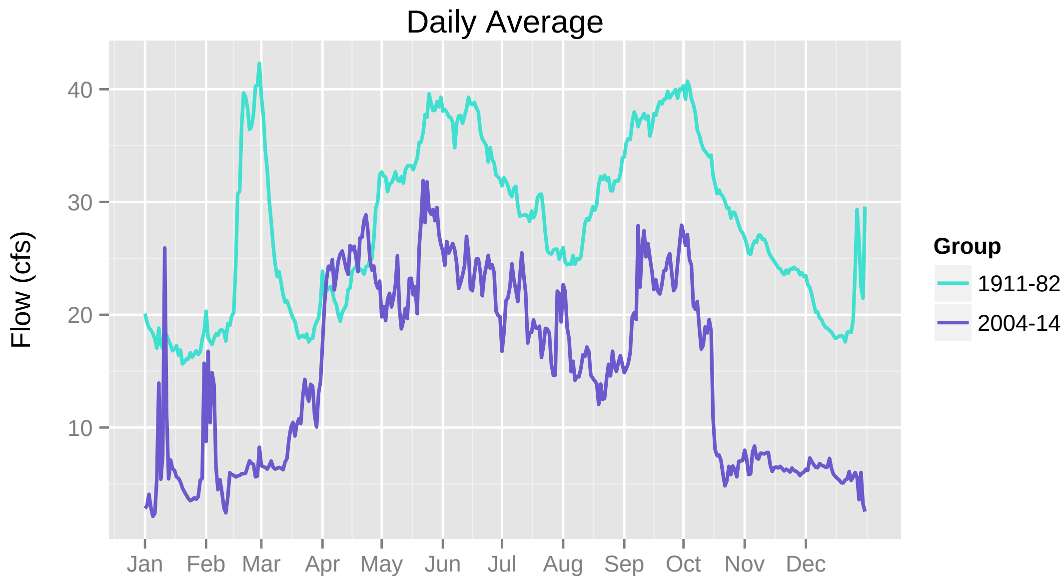
- Intermittent flooding
  Large runoff events and floods still occur in the Wide Hollow watershed. When these runoff events are large enough in volume, they converge from the upper watershed drainages to form sheet floods that exceed the channel capacity of Wide Hollow Creek. The floods of 1976 (a 20-year flood) and 1993 (a 15-year flood), small by any measure to the historical past, exhibited that no channel can contain the flood waters of Wide Hollow basin.

Mid to lower watershed streamflow / continued irrigation conveyance:

Irrigation begins in mid-March and ends in mid-October every year. Imported irrigation water is still transferred to Wide Hollow Creek by the Yakima Valley and the Naches-Cowiche end-of-canal discharges. Congdon Orchards also has operational discharges of irrigation water to the creek during the irrigation season. Irrigation return to the creek is variable mainly due to changing water demand, with the greatest demand for irrigation water in July and August when hot weather requires more irrigation. Cooler weather requires less irrigation and increases more end-of-canal operational discharge into Wide Hollow Creek.

Groundwater and perennial lower watershed streamflow:

Infiltrating water in the upper watershed moves down-slope as groundwater through the alluvium, and generally begins recharging Wide Hollow Creek near 64th Ave. and other reaches downstream where the Wide Hollow Creek channel is deep enough to intercept the alluvial groundwater table, or where groundwater drainage (DIDs) is directed to the creek. Groundwater provides a perennial baseflow in Wide Hollow Creek beginning at 64th Ave. More recently, around 5 cfs of sustained baseflow reaches Union Gap in the winter (Figure 6).



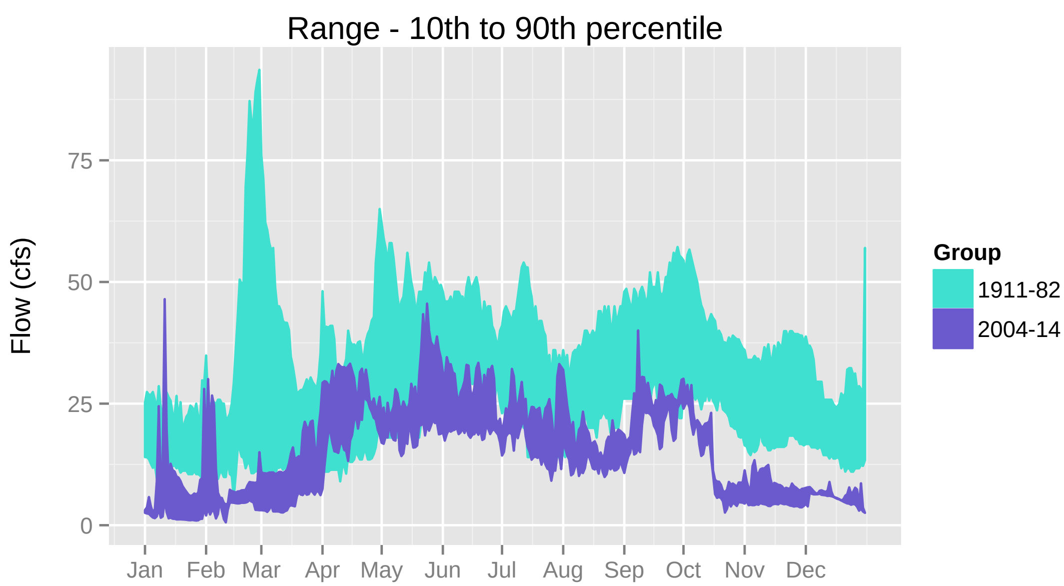


Figure 6. Historical daily average streamflow illustrating the seasonal hydrologic characteristics and reduced flow over time in Wide Hollow Creek (gaged near Union Gap).

Top figure shows daily average flow for the years 1911-82 versus 2004-14. Bottom figure shows the range of flow during associated time periods. (Historical data courtesy of USBR Yakima Field Office)

Continued diversion to sage-flat west of Union Gap and old grist mill:

Wide Hollow Creek is partially diverted near the Ahtanum Business Park to the south (Fines Ditch) to irrigate land west of Union Gap. The water not used from Fines Ditch is discharged to Ahtanum Creek near Fulbright Park. Flow in Wide Hollow Creek is diverted to the Fines Ditch by a simple barrier dam in the Wide Hollow Creek (Figure 7).

The rest of Wide Hollow Creek flow is still routed through the town of Union Gap past the historical millworks on Main Street. Wide Hollow Creek enters the historical East Spring (Chambers) Creek watershed after cascading through a gravity drop at the mill (Figure 8).

East Spring Creek is a natural spring creek that shows up on the 1860s GLO maps as a historical tributary to the Yakima River. East Spring Creek flows along the eastern edge of the City of Union Gap, and is now considered a tributary of Wide Hollow Creek. East Spring Creek currently derives water from groundwater recharge (springs), irrigation returns, and groundwater/stormwater drainage networks.

Today, Wide Hollow Creek's terminus is considered the confluence with the Yakima River and East Spring Creek is considered a tributary of Wide Hollow Creek, entering the creek about a kilometer above its confluence. However, because East Spring Creek existed prior to the diversion of Wide Hollow Creek to Union Gap, it may be more appropriate to consider Wide Hollow Creek as a man-made tributary to East Spring Creek.

Within the former East Spring Creek watershed is another tributary to Wide Hollow Creek called "Un-named Creek" in this study. Un-named Creek runs parallel east of Main Street from Washington Street to Wide Hollow Creek below the old mill and is apparently a groundwater and stormwater drain from under Main Street.

Floodplain and channel modifications

The Wide Hollow Creek that we know today is a modified drainage system developed as part of the irrigation supply to west Yakima valley. Irrigation has impacted the size and location of the creek channel over time. The creek no longer follows the pre-development course which originally flowed south to Ahtanum Creek but now flows east through Union Gap and into the Yakima River. Today many areas of the creek are incised, channelized and diked. A narrow gallery of riparian vegetation, mostly non-indigenous (particularly crack willow), is supported by the introduction of irrigation water, and has contributed to large debris dams affecting the channel geometry and stream function.

Figure 7. Picture showing debris/diversion dam at Fines Ditch. Fines Ditch flows to the right in the photo while Wide Hollow Creek flows to the left below the diversion dam.

Figure 8. Wide Hollow Creek at the gravity drop located at the historical grist mill in Union Gap. *The Alaska steep-pass fish ladder is to the left of the waterfall.*

At this point, Wide Hollow Creek is entering the former East Spring Creek watershed.

Fisheries

The Washington Department of Fish and Wildlife (WDFW) has a collection of notes documenting fish surveys, kills, sightings, and plantings in Wide Hollow Creek (Harvester, 2013).

The Yakima Fish Hatchery operated on Spring Creek (by the airport) from the mid-1930s to 1992 by WDFW; Yakama Nation used it for two additional years (1992-94) for steelhead production. The hatchery primarily raised catchable-size rainbow trout, but also cutthroat, eastern brook, steelhead and kokanee. The 1985-88 average annual production was around 50,000 pounds (Easterbrooks, 2016).

Rainbow trout were released into Wide Hollow Creek for youth fishing. WDFW said the rainbow trout found at 3rd Ave and near Kissel Park during this study may be remnants from these hatchery releases (Easterbrooks, 2016).

Flow records no longer exist, but the WDFW had water rights for 1000 gpm (2.2 cfs) from Spring Creek, 500 gpm (1.1 cfs) from other springs, and 300 gpm (0.6 cfs) of groundwater from wells (Easterbrooks, 2016).

The hatchery closed down after suffering a decline in water supply (quantity) and water quality. Spring Creek surface water quality became poorer, with elevated temperature, turbidity and pollutants. Well water quantity was adequate but water temperatures were near the upper-range limit for salmonid production (Easterbrooks, 2016). This was coincident with the Yakima-Tieton Irrigation District pressurizing their irrigation lines in the mid-1980s, which may have led to a decrease in Spring Creek flow which is part of the Wide Hollow Creek watershed (see Figure 6).

The hatchery also closed to accommodate the Yakima Airport. Yakima County needed to acquire the property to comply with Federal Aviation Administration safety buffer requirements. The hatchery property was sold and infrastructure demolished in early 2000s (Easterbrooks, 2016).

An Alaskan steep-pass fishway was installed at the gravity drop by the historical Union Gap mill in October 1989. WDFW has documented adult coho salmon using the fishway. Sightings of adult steelhead in Wide Hollow Creek near Perry Technical School are presumably entering the creek via the fishway too.

In general, WDFW has information that show portions of Wide Hollow Creek contain habitat currently supports limited cold-water aquatic life including rainbow trout and coho salmon. Additionally, WDFW believes that brown trout, which were planted in the 1980s, may have persisted as a resident fish.

Overall though, Wide Hollow primarily supports numerous native cyprinids; speckled dace, redside shiner, chiselmouth, and northern pike minnow. WDFW has also documented stickleback, largescale suckers, and mountain suckers.

Potential pollutant sources

Pollutants that can result in impairments to water temperature are those that increase heat in the stream. Heat in water is increased by solar radiation entering the water, and by heated source water entering the stream. The amount of shade cover is usually an important factor in controlling the water temperature of a stream.

Pollutants that can result in impairments to DO and pH are usually those that increase primary productivity (algal productivity) in the water to excessive levels. Algal productivity is increased by warmer water temperatures, more light availability and increased dissolved nutrients (nitrogen and phosphorus) in the water.

Algae exchange DO and carbon dioxide with the surrounding water. If reaeration processes cannot keep up with algal gas exchange in the water, then DO and pH levels will "swing" throughout the course of the day. DO and pH levels go up during daylight hours from algal photosynthesis and go down during nighttime hours from algal respiration.

In addition, DO can be reduced by addition of low oxygenated water, addition of organic carbon or nitrogen sources that exhibit a biochemical oxygen demand (BOD), and sediment oxygen demand (SOD) of the overlying water.

Permitted point sources

Municipal wastewater

There are no municipal wastewater treatment plant discharges to Wide Hollow Creek.

Municipal stormwater

Within the study area, three municipal entities maintain stormwater infrastructure covered under the general NPDES Phase 2 municipal stormwater permits for eastern Washington, including Yakima County, as well as the cities of Yakima and Union Gap (Table 1).

Table 1. Municipal stormwater NPDES permit holders in the study area.

Permit Holder	Receiving Water	Permit Number	Permit Type
Yakima County	All creeks and drains in urbanized areas	WAR046014	Phase II SW
City of Yakima	Wide Hollow Creek	WAR046013	Phase II SW
City of Union Gap	Wide Hollow Creek	WAR046010	Phase II SW
Yakima Valley Community College	Wide Hollow Creek	WAR046201	Phase II SW
Washington Dept. of Transportation	Wide Hollow Creek	WAR043000	Phase II SW

Phase II SW = Municipal NPDES Stormwater Permit

Other permitted facilities

Other permitted facilities operate under a variety of different permit types including state individual industrial wastewater permits and general permits for industrial stormwater (Table 2).

Table 2. Stormwater and industrial wastewater NPDES permit holders in the study area.

Permit Holder	Receiving Water	Permit Number	Permit Type
Clasen Fruit and Cold Storage	Wide Hollow Creek	WAG435176B	Fruit
Borton and Sons	Wide Hollow Cr. via Lateral T	WAG435131B	Fruit
Eakin Fruit Company	Wide Hollow Cr. via Stormwater Pipe	WAG435031B	Fruit
Del Monte Foods 125	Wide Hollow Creek	SO3000215D	Industrial SW
Western Recreational Vehicles	Wide Hollow Creek	SO3004527B	Industrial SW

Fruit = Fresh Fruit Packer General Permit
Industrial SW = Industrial Stormwater Permit

There may be other active permits within the study area covered under the Construction Stormwater General Permit.

Nonpoint sources

Nonpoint sources are sources not covered by an NPDES permit.

Nonpoint sources affecting water temperature

Contributing nonpoint factors to stream heating could include:

1. Heat (or cold) from water nonpoint sources (non-permitted) entering the creek:
   - Irrigation water
   - Drainage improvement districts (DIDs)
   - Diffuse groundwater inflow
2. Riparian vegetation disturbance and loss of shade due to:
   - Removal of trees and shrubs for pasture, crops, timber harvest, roads, or buildings.
   - Grazing by livestock and wild animals.
   - Alteration of the local hydrograph or lowering the water table to such an extent that riparian vegetation cannot complete its life history requirements.
   - Competition from aggressive non-native plant species.
3. Channel morphology changes (depth and width) resulting from:
   - Increased sediment loading.
   - Constraining, straightening of channel for agriculture or development.
   - Increased bank instability, erosion, and sedimentation from removal of established riparian vegetation and high stream velocities from altered streamflow.

4. Hydrologic changes influenced by:
   - Extraction and return of groundwater or surface water.
   - Altered streamflow patterns resulting in altered seasonal hydrographs, like irrigation.
   - Global climate change and its regional effects on overall water quantity (snow pack), as well as the timing and magnitude of the spring freshet.
   - Altered sediment/energy regimes that result in channel incision or aggradation.

The role of riparian vegetation in maintaining a healthy stream condition and water quality is well documented and accepted in the scientific literature (Appendix E). Summer stream temperature generally decreases when riparian vegetation is allowed to develop, and generally increases when riparian vegetation is removed. Water temperature in streams without riparian vegetation have larger daily temperature variations because of the effect of diurnal fluctuation in solar heat flux.

Nonpoint sources affecting DO and pH

In addition to the nonpoint sources listed above that affect the amount of light and temperature in Wide Hollow Creek, potential nonpoint sources of nutrients within the watershed could include:

- Irrigation water return flows
- DID flows
- Stormwater runoff
- On-site septic systems, particularly those that are failing, poorly constructed, or poorly maintained
- Range and pastured livestock with direct access to water bodies
- Improperly stored or applied manure or fertilizers
- Impervious surface runoff and overland flooding
- Sediment from erosion and overland flooding
- Pet manure
- Wildlife

There are many on-site septic systems near Wide Hollow Creek in the rural areas of unincorporated Yakima County. Failing and improperly maintained on-site septic systems can be sources of nutrients to surface or groundwater through leaching or ponding. Even properly functioning systems may leach nutrients to groundwater, depending on site-specific factors such as soil types, depth to water, etc.

A wide variety of perching birds, upland game birds, raptors, and waterfowl are found within the study area. Beaver and other mammalian wildlife species are also present. Open fields are attractive feeding grounds for some birds and wildlife whose presence can increase nutrient loading to streams. Usually these sources are dispersed and do not constitute a significant nutrient source, but sometimes animals are locally concentrated and may result in water quality degradation.

Background sources of nutrients, both within and upstream of the study area, include:

- Atmospheric deposition (rainfall, snow, particulates)
- Geologic weathering
- Decomposing plant, invertebrate, and animal material

Some nonpoint sources were monitored directly in this Wide Hollow study, including return flow from irrigation canals, groundwater inflows, DIDs and baseflow in stormwater pipes.

Impairments addressed by this water quality study

As discussed in the QAPP (Carroll, 2013), this study addressed Wide Hollow's temperature, DO, and pH impairments listed on the 2012 303(d) list (Table 3). Each category 5 listing has documentation (Listing ID) that shows the creek is not meeting the water quality standard for listed parameter. Each listing refers to a specific location (Reach Code) in Wide Hollow Creek where the impairment was measured by previous monitoring. This study examined the watershed more thoroughly to understand the spatial and temporal extent of the temperature, DO, and pH impairments. Some individual listings in Table 3 have been consolidated into larger NHD assessment units as described in a section below (Assessment of the 303(d) listing based on study year observations – page 85).

Table 3. Current (2019) 303(d) Category 5 listings for temperature, dissolved oxygen, and pH for Wide Hollow Creek and tributaries.

Water body	Parameter	Listing ID	Category	National Hydrography Dataset Reach Code
Wide Hollow Creek	Temperature	8307	5	17030003000812
Wide Hollow Creek	Dissolved oxygen	47370	5	17030003007003
Wide Hollow Creek	Dissolved oxygen	11173	5	17030003000812
Wide Hollow Creek	pH	11174	5	17030003000812
East Spring Creek	Temperature	73587	5	17030003007802
East Spring Creek	Temperature	66747	5	17030003007831
Cottonwood Creek	Dissolved Oxygen	47395	5	17030003013826

There are other 303(d) listed parameters in Wide Hollow Creek that this study did not address (Table 4). Water quality technical studies have already been completed to address the bacteria listings (Bohn, 2015 and Tarbutton, 2012) and toxic listings (Johnson et al., 2010).

Table 4. Current (2019) 303(d) Category 5 listings for bacteria and toxics for Wide Hollow Creek and tributaries (parameters not addressed by this study).

Water body	Parameter	Listing ID	Category	NHD Reach Code
Wide Hollow Creek	4,4'-DDE	8848	5	17030003000812
Wide Hollow Creek	4,4'-DDD	8849	5	17030003000812
Wide Hollow Creek	DDT (and metabolites)	8855	5	17030003000812
Wide Hollow Creek	Bacteria	6717	5	17030003000812
Wide Hollow Creek	Bacteria	45161	5	17030003007003
Congdon Canal	Bacteria	45875	5	17030003003299
Cottonwood Creek	Bacteria	45210	5	17030003013826
DID #24	Bacteria	74270	5	None
DID #40	Bacteria	47271	5	None
DID #48	Bacteria	45081	5	None
East Spring Creek	Bacteria	45541	5	17030003007802
Randall Park Pond Outlet	Bacteria	45753	5	17030003015930
Shaw Creek	Bacteria	45869	5	17030003007184

How will the results of this water quality study be used?

This study assessed current water quality conditions in Wide Hollow Creek with regards to water temperature, DO, and pH. A water quality model was developed for the creek. The model was used to identify what kind of water quality might be attained in Wide Hollow Creek under different management plans. Ecology and local partners can use the model as a tool to assess future water quality improvement activities.

Water Quality Standards and Numeric Targets

Washington's Administrative Code outlines water quality standards for the state of Washington (WAC 173-201A). In the state water quality standards, fresh water aquatic life use categories are described using key species (salmonid versus warm-water species) and life-stage conditions (spawning versus rearing). Wide Hollow Creek was never given a specific aquatic life use designation, and therefore, a default aquatic life use category is applied by the standards, which is "Salmonid spawning, rearing, and migration". The criteria used to protect this aquatic life use are outlined in Table 5 and described in further detail below.

Table 5. Washington State water quality criteria for temperature, dissolved oxygen, and pH in Wide Hollow Creek.

Parameter	Criteria
Temper-ature	To protect the designated aquatic life uses of "Salmonid Spawning, Rearing, and Migration," the highest 7-DADMax temperature must not exceed 17.5°C (63.5°F) more than once every ten years on average. When a water body's 7-DADMax temperature is warmer than 17.5°C and that condition is due to natural conditions, then human actions considered cumulatively may not cause the 7-DADMax temperature of that water body to increase more than 0.3°C (0.54°F).
Dissolved Oxygen	To protect the designated aquatic life use of "Salmonid Spawning, Rearing, and Migration," the lowest 1-day minimum oxygen level must not fall below 8.0 mg/L more than once every ten years on average. When a water body's dissolved oxygen is lower than 8.0 mg/L and that condition is due to natural conditions, then human actions considered cumulatively may not cause the oxygen level of that water body to decrease more than 0.2 mg/L.
pH	To protect the designated aquatic life uses of "Salmonid Spawning, Rearing, and Migration," pH must be kept within the range of 6.5 to 8.5, with a human-caused variation within the above range of less than 0.5 units.

Temperature

Temperature affects the physiology and behavior of fish and other aquatic life. Temperature may be one of the most influential factors limiting the distribution and health of aquatic life and can be greatly influenced by human activities.

Temperature levels fluctuate over the day and night in response to changes in climatic conditions and river flow. Since the health of many aquatic species is tied predominantly to the pattern of maximum temperatures, the criteria are expressed as the highest seven-day average of the daily maximum temperatures (7-DADMax) occurring in a water body.

Dissolved oxygen

Aquatic organisms are sensitive to reductions in the level of DO in the water. The health of fish and other aquatic species depends on maintaining an adequate supply of DO in the water.

DO levels affect growth rates, swimming ability, susceptibility to disease, as well as the ability to endure environmental stressors and pollutants. Washington State designed the DO criteria to maintain conditions that support healthy populations of fish and other aquatic life. Direct mortality due to inadequate DO levels can occur.

DO levels fluctuate over the day and night in response to changes in climatic conditions as well as the respiratory effects of aquatic plants and algae. Since the health of aquatic species is tied predominantly to the pattern of daily minimum oxygen concentrations, the criterion is based on the lowest 1-day minimum oxygen concentration that occurs in a water body.

pH

The pH of natural waters both directly and indirectly affects the ability of waters to have healthy populations of fish and other aquatic species. The pH is a measure of acid-base equilibrium achieved by the various dissolved compounds, salts, and gases. It is an important factor in the chemical and biological systems of natural waters.

Changes in pH affect the degree of dissociation of weak acids or bases. This effect is important because the toxicity of many compounds is affected by the degree of dissociation. For example, ammonia increases in toxicity at higher pH.

Study Goals and Objectives

Study goals

The goal of this water quality study is to provide a better understanding of the current and potential water quality conditions in Wide Hollow Creek, particularly for water temperature, dissolved oxygen (DO), and pH (Carroll, 2013). Additionally, provide a better understanding of the current biological and habitat function in Wide Hollow Creek.

Study objectives

Objectives for the study are to:

- Collect a dataset of sufficient quality and quantity to calibrate a water quality model of Wide Hollow Creek for streamflow, water temperature, DO and pH.
- Develop a water quality model capable of simulating continuous streamflow, temperature, DO, and pH in Wide Hollow Creek.
- Characterize current processes governing water temperature, DO, and pH in Wide Hollow Creek including the influence of flow from tributaries, nonpoint sources, point sources, and groundwater.
- Collect and analyze biological and habitat data in Wide Hollow Creek.

Water Quality Study

Ecology data collection

Study field data collection started in July 2013 and continued until the end of June 2014, covering the latter and beginning of two irrigation seasons and the non-irrigation season during the winter of 2013-14. The irrigation season in Wide Hollow Creek watershed generally runs from mid-March to mid-October. Field survey dates are listed in Table 6. Synoptic surveys sampled all sites and included nutrient samples.

Table 6. Survey dates for synoptic surveys and other field measurements.

Date	Season	Synoptic?
June 17-19, 2013	Irrigation (2013)	
July 8-9, 2013		Yes
July 31- Aug 1, 2013		
August 6-7, 2013		Yes
August 27, 2013		
September 9-10, 2013		Yes
September 24, 2013		
October 8-9, 2013		Yes
October 31, 2013	Non-Irrigation	
November 12-13, 2013		Yes
November 26, 2013		
December 10-11, 2013		Yes
March 3-4, 2014		
March 25-26, 2014	Irrigation (2014)	Yes
April 29-30, 2014		Yes
June 3-4, 2014		Yes

Figure 9 shows the sampling locations where these different types of data were collected. The types of data collected at these sampling locations are listed in Table 7. The "short name" in this table corresponds to site labels on Figure 9. Piezometer locations are not included on the figure and table below, but are presented in Appendix A. Surface sampling locations at canal diversions on the Naches River are also not shown below.

Figure 9. Sampling location and type (mainstem creek, sources, and diversions).

Table 7. List of surface sampling sites and monitoring activities.

Short Name	EIM Location ID	Station Description	Continuous temperature	Continuous flow	Continuous water quality	Synoptic nutrients	Synoptic flow	Biological monitoring	Latitude	Longitude
Yak Valley Canal	37-IS-16	Yakima Valley Canal discharge to Wide Hollow Creek near 101st Ave		(+)		X			46.5824	-120.6417
GW at 101st	37-IS-16D	Wide Hollow Creek groundwater seepage upstream of Yakima Valley Canal					X		46.5800	-120.6421
WHC at 101st	37-IS-16B	Wide Hollow Creek below Yakima Valley Canal	X	X	X	X	X		46.5805	-120.6412
WHC at 80th	37-FW-8	Wide Hollow Creek upstream of 80th Ave	X			X	X	X	46.5813	-120.6146
WHC at 64th	37-SS-12	Wide Hollow Creek at 64th Ave	X			X	X		46.5834	-120.5940
DID #48	37-SS-48	DID #48 outfall at 64th Ave	X			X	X		46.5833	-120.5939
DID #38	37-SS-38	DID #38 outfall at 64th Ave	X			X	X		46.5833	-120.5939
Congdon	37-IS-33	Congdon Orchards discharge to Wide Hollow Creek		(+)		X			46.584	-120.5901
WHC at 48th	37-SS-11	Wide Hollow Creek at 48th Ave/Randall Park				X	X	X	46.5791	-120.5723
Randall Pipe	37-SS-11B	Pipe discharge to Wide Hollow Creek 300 ft downstream of 48th Ave				X	X		46.5790	-120.5709
Randall Pond	37-IS-17.5	Randall Park Pond outlet on 44th Ave	X			X	X		46.5800	-120.5673
WHC at 40th	37-FW-6B	Wide Hollow Creek upstream of 40th Ave behind Bergren Screen Printing	X	X	X	X	X		46.5786	-120.5656
DID #40	37-IS-17	DID #40 outfall at 38th Ave and Logan Ave	X			X	X		46.5799	-120.5592
NC Canal at 32nd	37-IS-20B	Naches and Cowiche Canal discharge near 32nd Ave	X	(+)		X			46.5753	-120.5515
WHC at 24th	37-FW-5B	Wide Hollow Creek upstream of 24th Ave behind Texaco gas station	X	X		X	X	X	46.5739	-120.5477
Perry divert	37-IS-32	JM Perry Technical Institute water right use		(*)					46.5720	-120.5354
Broadway divert	37-IS-29	Broadway Irrigation water right use					X		46.5710	-120.5331
WHC at 16th	37-FW-4	Wide Hollow Creek at 16th Ave	X			X	X		46.5685	-120.5305
NC Canal at 12th	37-IS-20A	Naches and Cowiche Canal discharge near 12th Ave	X			X	X		46.5681	-120.5287
SW Yakima 12th	37-IS-26	City of Yakima stormwater outfall at 12th Ave bridge (NE corner)				X	X		46.5681	-120.5252

Short Name	EIM Location ID	Station Description	Continuous temperature	Continuous flow	Continuous water quality	Synoptic nutrients	Synoptic flow	Biological monitoring	Latitude	Longitude
DID #4	37-IS-15	DID #4 outfall at Colonial Nursery				X	X		46.5677	-120.5228
Spring Ck Irrig	37-IS-23	Spring Creek Irrigation District inflow				X	X		46.5635	-120.5202
DID #24 L2	37-IS-13	DID #24 outfall L2 near Pioneer Ln and Cornell Ave				X	X		46.5639	-120.5159
WHC at 3rd	37-FW-3B	Wide Hollow Creek upstream of 3rd Ave	X			X	X	X	46.5595	-120.5099
SW Yakima 3rd	37-SS-6	City of Yakima stormwater outfall at 12th Ave bridge (NE corner)				X	X		46.5589	-120.5097
DID #24 at 3rd	37-IS-12	DID #24 outfall L1 at 3rd Ave	X			X	X		46.5593	-120.5094
SW Union Gap	37-IS-22	Union Gap stormwater outfall (E5-41) under Ahtanum bridge				X	X		46.5578	-120.5031
Fines Ditch	37-FW-1C	Fines Ditch diversion	X	(+)		X	X		46.5524	-120.4916
WHC blw Fines	37-FW-1E	Wide Hollow Creek below Fines Ditch diversion					X		46.5524	-120.4909
SW Yakima RR	37-IS-21	City of Yakima stormwater outfall at RR tracks				X	X		46.5501	-120.484
Hodkinson divert	37-FW-1D	Hodkinson diversion below RR tracks					X		46.5500	-120.4829
WHC at White St	37-FW-1B	Wide Hollow Creek at White St. in Union Gap	X	X	X	X	X		46.5496	-120.4806
Un-named Creek	37-FW-2B	Un-named creek behind Union Gap Mill	X			X	X		46.5436	-120.4752
East Spring Creek	37-FW-2	East Spring (Chambers) Creek behind Union Gap Public Works				X	X		46.5427	-120.4715
WHC mouth	37-FW-0B	Wide Hollow Creek below East Spring (Chambers) Creek	X			X	X	X	46.5440	-120.4739

Site IDs consist of the WRIA number (37), and a unique identifier for each location. The first two letters of the identifier refer to (“FW” for Wide Hollow Creek site), (“IS” for Intensive Study site) and (“SS” for Stormwater Site).
(+) flow at this location was inferred during simulation (described in the simulation section below).
(*) flow data at this location was provided to Ecology by Perry Institute.

Table 8 lists locations where samples could not be collected due to the site being dry during all survey dates. These sites are not shown on Figure 9. Note that Cottonwood Creek is listed as being dry, even though a small amount of groundwater seepage was sampled at this site during March 3-4, 2014. It is listed as dry because the creek was dry immediately upstream of this seepage.

Table 8. List of sites which were dry during all field survey dates (July 2013 - June 2014).

Location_ ID	Station Description	Comment	Latitude	Longitude
37-FW-13	Cottonwood Creek at Dazet Rd	not sampled (always dry)	46.5792	-120.6464
37-FW-12	Wide Hollow Creek at Dazet Rd	not sampled (always dry)	46.5798	-120.6464
37-SS-13	Shaw Creek at 80th Ave	not sampled (always dry)	46.5868	-120.6150
37-SS-8	City of Yakima stormwater outfall at end of 34th Ave	not sampled (always dry)	46.5769	-120.5542
37-IS-31	City of Yakima stormwater outfall at Washington Ave bridge (NE corner)	not sampled (always dry)	46.5712	-120.5335
37-IS-30	City of Yakima stormwater outfall at Washington Ave bridge (SW corner)	not sampled (always dry)	46.5707	-120.5332
37-IS-28	City of Yakima stormwater outfall SW diagonal from Wash and 16th	not sampled (always dry)	46.5702	-120.5325
37-IS-27	City of Yakima stormwater outfall at 12th Ave bridge (NW corner)	not sampled (always dry)	46.5681	-120.5254
37-IS-24	City of Yakima stormwater outfall at 10th Ave bridge (NW corner)	not sampled (always dry)	46.5666	-120.5200

Types of monitoring activities

Methods for data collection, compilation, and assessment were developed to meet the data requirements of the water quality model and are described in the Quality Assurance Project Plan (Carroll, 2013). A number of different types of data were collected at the sampling locations shown in Figure 9 and are described briefly in the following section:

Continuous temperature

Ecology installed a network of continuous temperature dataloggers in the Wide Hollow Creek watershed as part of a temperature study in the Yakima River watershed (Dugger, 2013). Dataloggers were located at most sampling locations along the Wide Hollow Creek and in major point and tributary sources, such as irrigation discharges. Loggers were deployed from May 2013 through July 2014 and logged temperature at 30-minute intervals.

Continuous flow

Ecology's Freshwater Monitoring Unit installed five continuous flow measurement stations in the study area during 2013-14. These stations recorded stage height continuously from June to December 2013 and February to July 2014. Instantaneous flow measurements were also taken at these five continuous flow-monitoring stations to develop stage-discharge rating curves.

Continuous water quality

Ecology's Freshwater Monitoring Unit installed 3 continuous water quality stations in Wide Hollow Creek, using Hydrolab® dataloggers set to log at 15-minute intervals for most of the study, except the winter months when freezing temperatures threatened the electronic equipment. Continuous records of temperature, DO, conductivity and pH were collected.

Synoptic water chemistry

Ecology collected water samples of major nutrients (ammonia, nitrate, total nitrogen, total phosphorous, orthophosphate, dissolved organic carbon, total organic carbon, alkalinity, total suspended solids, and total non-volatile suspended solids). All water samples were analyzed by Ecology's Manchester Environmental Laboratory as described in the QAPP (Carroll, 2013).

Synoptic flow

During the synoptic sampling surveys, flow measurements were taken concurrently with synoptic nutrient sampling at all stations whenever possible. Diversions from the creek were also measured, but no nutrient samples were collected at these locations.

Water quality

Additionally, water quality measurements (pH, specific conductance, DO) were collected using a Hydrolab® minisonde at time of sampling. These measurements were taken at all sampling locations during synoptic surveys. Turbidity was also measured at some sites.

Light extinction

Light extinction surveys were taken during most synoptic surveys to capture a range of light attenuation through the water column with respect to changing water turbidity.

Air temperature and relative humidity

Ecology installed a network of data loggers to monitor continuous near-stream air temperature and relative humidity in the study area (Dugger, 2013).

Time-of-travel dye study

A time-of-travel dye study using rhodamine, a fluorescent, non-toxic dye, was conducted on Wide Hollow Creek to estimate reach velocities. Dye studies estimate travel times by measuring the time it takes for a slug of dye to reach specific downstream locations.

The irrigation season dye study (IRR 2013) was conducted Oct 1-3, 2013 and the non-irrigation season dye study (non-IRR 2013) was conducted Oct 24-25, 2013. A slight difference in dye release locations between these two studies occurred at 64th Ave: the non-irrigation study released dye at the bridge at 64th Ave while the irrigation study released dye from a point slightly downstream of this bridge (at the Congdon Orchards discharge). During non-irrigation season, the dye study was conducted from 64th Ave because a portion of the creek was dry between 80th Ave and 67th Ave.

Stormwater monitoring

This study assessed typical water quality conditions in Wide Hollow Creek during irrigation and non-irrigation seasons from July 2013 through June 2014. During the synoptic surveys, samples and measurements were taken from any storm drain with a measurable flow. Ecology did not find discharges from most stormwater pipes; none of Ecology's synoptic samplings occurred during precipitation events and Ecology did not attempt to target stormwater related events during the study year.

There were several stormwater outfalls that had year-round groundwater discharge to Wide Hollow Creek. The collection pipes of those stormwater drainage networks intercept the groundwater table and effectively act like a DID for that collection area. In some cases, the mapped stormwater drainage networks and mapped DID networks intercept each other, indicating they share infrastructure with each other.

Groundwater monitoring

Ecology assessed groundwater and surface-water interactions via a network of instream piezometers installed from 101st Ave down to the mouth from June 2013 to July 2014. The piezometers were used to monitor surface-water and groundwater interaction and groundwater water quality (see Appendix A).

Quarterly, Ecology collected water quality samples from piezometers. Water samples were submitted to the laboratory for analysis of alkalinity, chloride, orthophosphate, total phosphorus, nitrate/nitrite, ammonia, total persulfate nitrogen, iron, and dissolved organic carbon analysis. Groundwater temperature, conductivity, pH, and DO were also measured in a continuous flow cell.

Biological and habitat data – periphyton

Periphyton consists of a community of algae, fungi, microbes and microscopic plants and animals that grow in shallow water habitats and attach to submerged surfaces. Periphyton (algal productivity) is often one of the most important drivers of DO and pH in shallow streams and rivers.

Periphyton biomass data were collected in the summer/fall of 2013. Biomass data were collected at five sampling sites. Periphyton was scraped from the rocks and vegetation into the sample container along with deionized water. The surface area from which periphyton was collected was measured.

Periphyton samples were analyzed for Chlorophyll a and Ash-Free Dry Weight. Laboratory results and the surface areas from which samples were collected were then used to calculate periphyton areal biomass estimates per square meter of streambed.

Non-Ecology data sources

Meteorological data

Meteorological data was obtained from the NWS station at Yakima Airport and the AgWeatherNet station at Cowiche (Table 9).

Table 9. Summary of weather stations, location, and available data.

Station ID	Location	Network/ Origin	Air Temperature	Dew Point	Relative Humidity	Precipitation	Wind Direction	Wind Speed	Cloud Cover	Solar Radiation
KYKM	Yakima Airport	NCDC – National Weather Service	x	x	x	x	x	x	x	
Cowiche	Cowiche	Washington State University AgWeatherNet								x

City of Yakima Water Treatment Plant (on Naches River)

A daily time series of turbidity data from the Naches River was obtained from the Yakima Water Treatment Plant (WTP) on the Naches River. Daily data was available from June 1 – October 11, 2013 and April 30 – June 30, 2014. The turbidity of the Naches River is measured by instrumentation at the intake (prior to treatment) by the Yakima Water Plant. These data were used to determine the suspended solids and turbidity in the irrigation water imported to Wide Hollow Creek.

Data quality (usability assessment)

Study data usability

All data collected by Ecology or gathered from external sources were checked to see if they conformed to Ecology's credible data policy: https://ecology.wa.gov/DOE/files/3b/3bf2eaab-090b-49d1-8ff4-fd8c82960f7a.pdf.

Ecology also verified that the study data met the data quality objectives established for this study in the QAPP (Carroll, 2013). This final report has a companion appendices (linked to this report online) that includes a section (Appendix D) on data quality assessment and certification that the data met a level of quality acceptable for use in this study.

Overall, Ecology's quality assurance review showed that the data met the data quality objectives for this water quality study and were found to be of good quality and appropriate for its intended use.

Usability of results from modeling or other analysis

The usability of the results in the QUAL2KW model is assessed by Ecology by comparison of predicted model results to observed values, comparison of calibrated model parameters and rates to those from other studies, and other techniques. A summary of model inputs and model calibration for Wide Hollow Creek is presented in Appendix G.

Overall, Ecology's quality assurance review showed the model fit was acceptable and the model outputs were usable for this water quality study and was found to be of good quality and appropriate for its intended use.

Location of data for availability and archiving

An EIM user study (JICA0002) was created for this study and all monitoring data is available via the internet. The URL address for this geospatial database is: www.ecy.wa.gov/eim/. All data was uploaded to EIM after the data was reviewed for quality assurance.

Study year results

Meteorological data

The study period (July 2013 - June 2014) had warmer air temperatures (more solar) and less precipitation than normal (Figure 10). The warmest months of the study year were July and August 2013. The winter of 2013-14 was very dry which led to no runoff from the upper watershed of Wide Hollow (above 101st Ave) in the late winter and spring of 2014.

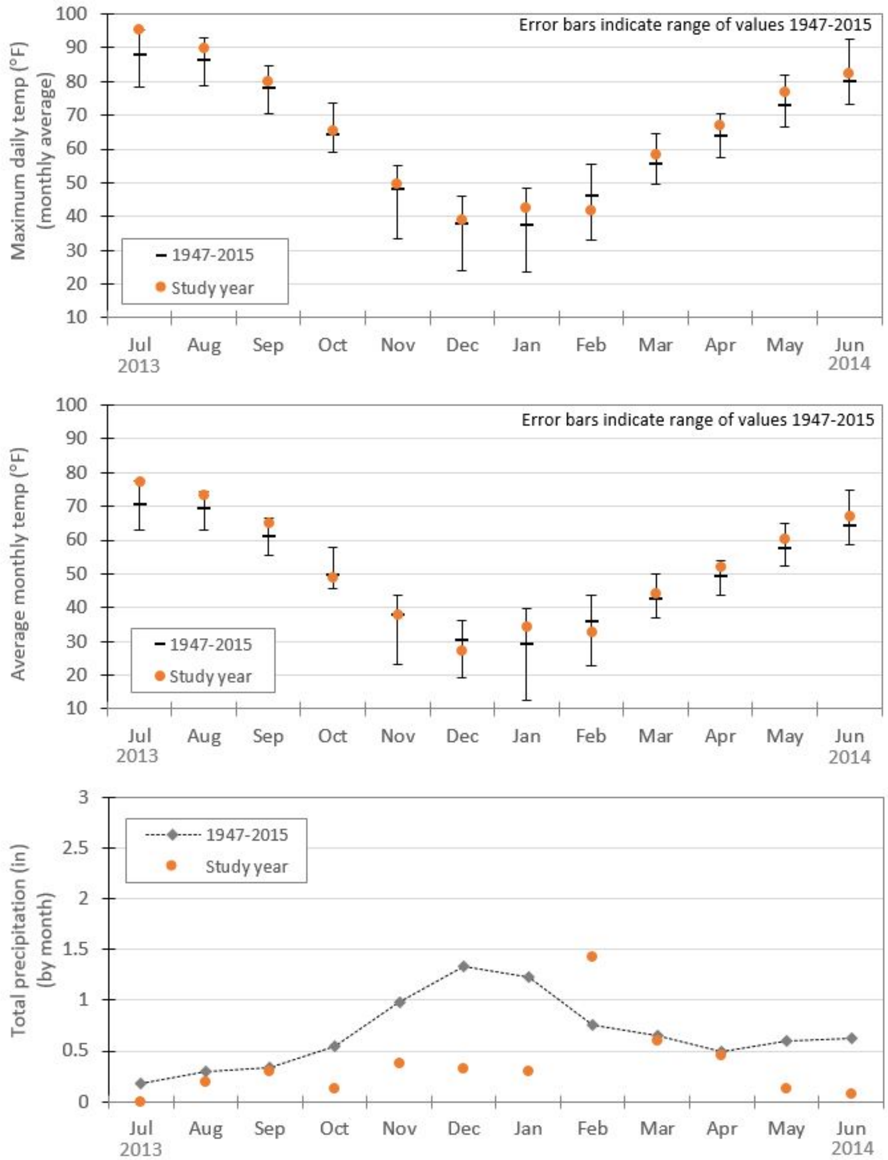


Figure 10. Monthly statistics of air temperature and precipitation, comparing study year to long term average and range.

Top: daily maximum temperature averaged by month. Middle: overall average monthly temperature. Bottom: precipitation totals by month. (Yakima airport data 1947-2015).

Hydrology (streamflow)

During the study year, streamflow in Wide Hollow Creek was monitored continuously at 4 streamflow gage locations and measured instantaneously at a large number of locations during synoptic surveys. This was done to understand:

- short-term and long-term temporal fluctuations in streamflow due to several large and highly variable irrigation sources to the creek
- spatial changes in streamflow due to a many smaller sources and diversions to the creek

Continuous streamflow monitoring

Streamflow was continuously monitored at WHC at 101st, WHC at 40th, WHC at 24th, and WHC at White St. (Figure 11). Specific conductance was also continuously monitored at all of these locations, except WHC at 24th Ave. A gage was installed to monitor streamflow in Fines Ditch, but data from this gage was rejected due to the poor relationship between stage and streamflow at this site, likely related to irrigation controls downstream in the ditch.

Continuous monitoring of streamflow occurred from mid-May 2013 through June 2014, except for a winter hiatus (mid-December 2013 to February 2014), when gages were inactivated to avoid damage to equipment from ice and freezing temperatures. During the winter, streamflow was observed to be low due to below average precipitation, with no evidence of winter runoff.

Continuous monitoring indicated streamflow was higher and more variable during the irrigation season than during the non-irrigation season (top portion of Figure 12). This figure shows continuous streamflow and conductivity gaging in Wide Hollow Creek for the study year at three gage stations:

- 101st Ave – almost all streamflow during the irrigation season is due to the Yakima Valley Canal, flow is close to zero during the non-irrigation season. Streamflow was less than 10 cfs, with daily fluctuations approximately 1-4 cfs.
- 40th Ave - the large increase in flow and variability at 40th Ave was primarily due to the irrigation water entering the creek at Congdon Orchards. Streamflow was often higher than 20 cfs and highly variable on an hourly basis with daily fluctuations sometimes exceeding 10 cfs.
- White St – similar streamflow to 40th Ave, due to a balance of water entering the creek from irrigation (Naches-Cowiche) and a large diversion of water out of the creek at Fines Ditch. Less variable than 40th Ave, with fluctuations approximately 2-4 cfs.

The largest irrigation sources (Yakima Valley Canal, Congdon and Naches-Cowiche Canal) could not be directly measured on a continuous basis. These are highly variable sources which dominate streamflow in Wide Hollow Creek. Flow from these sources was calculated using the QUAL2Kw model simulation, and are presented in the simulation section below. Continuous streamflow into Fines Ditch also was also calculated using the model simulation, because the gage in Fines Ditch did not have a reliable rating curve.

Conductivity was lower during the irrigation season (bottom portion of Figure 12) than during the non-irrigation season because most of the water in the creek during irrigation season comes from surface water sources with relatively low conductivity.

During the non-irrigation season, spikes in flow were seen at the continuous streamflow gage at 40th Ave apparently related to periodic discharges into the creek from some unknown source upstream. These spikes are analyzed further in Appendix I.

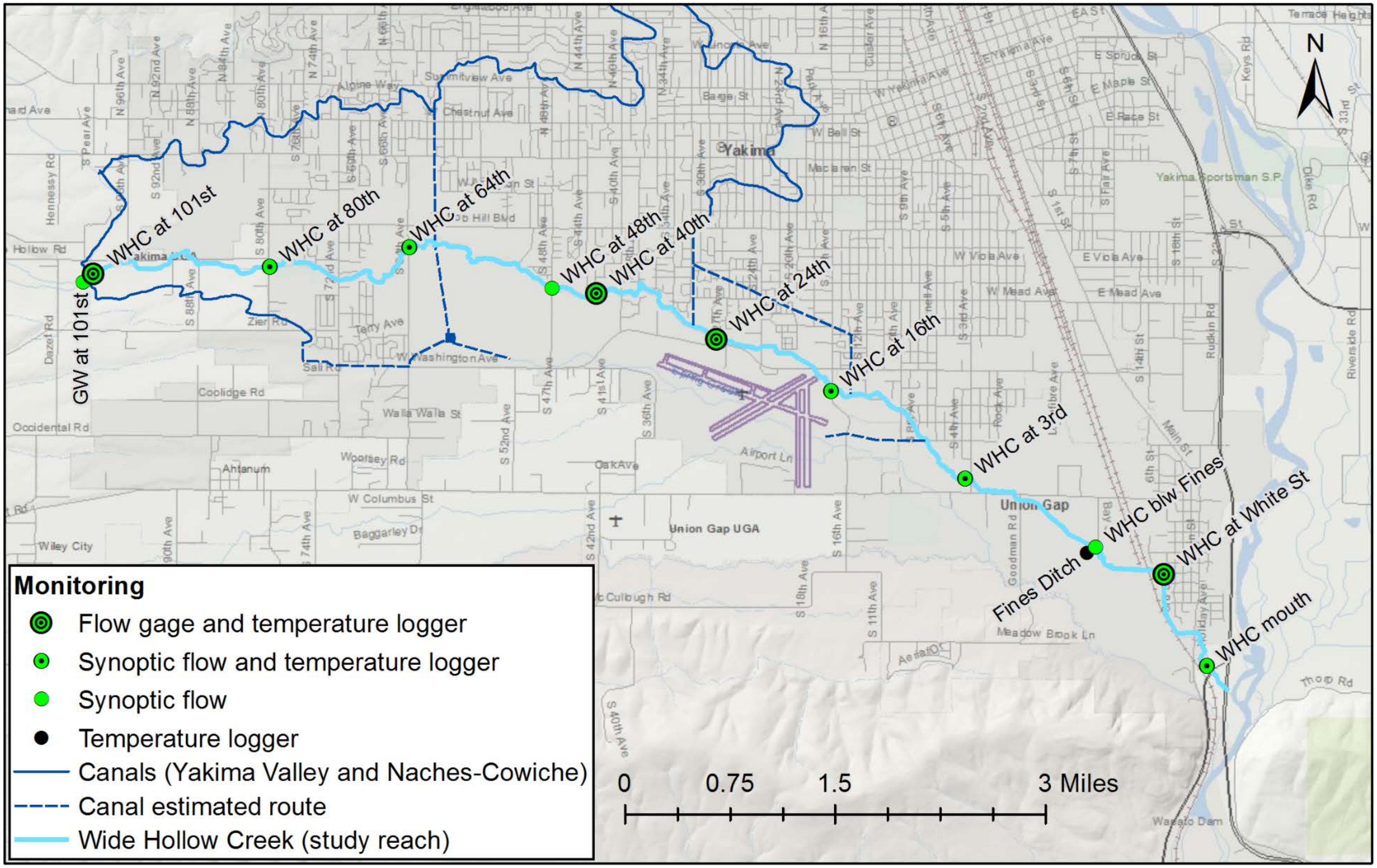


Figure 11. Monitoring locations for streamflow and temperature along Wide Hollow Creek.

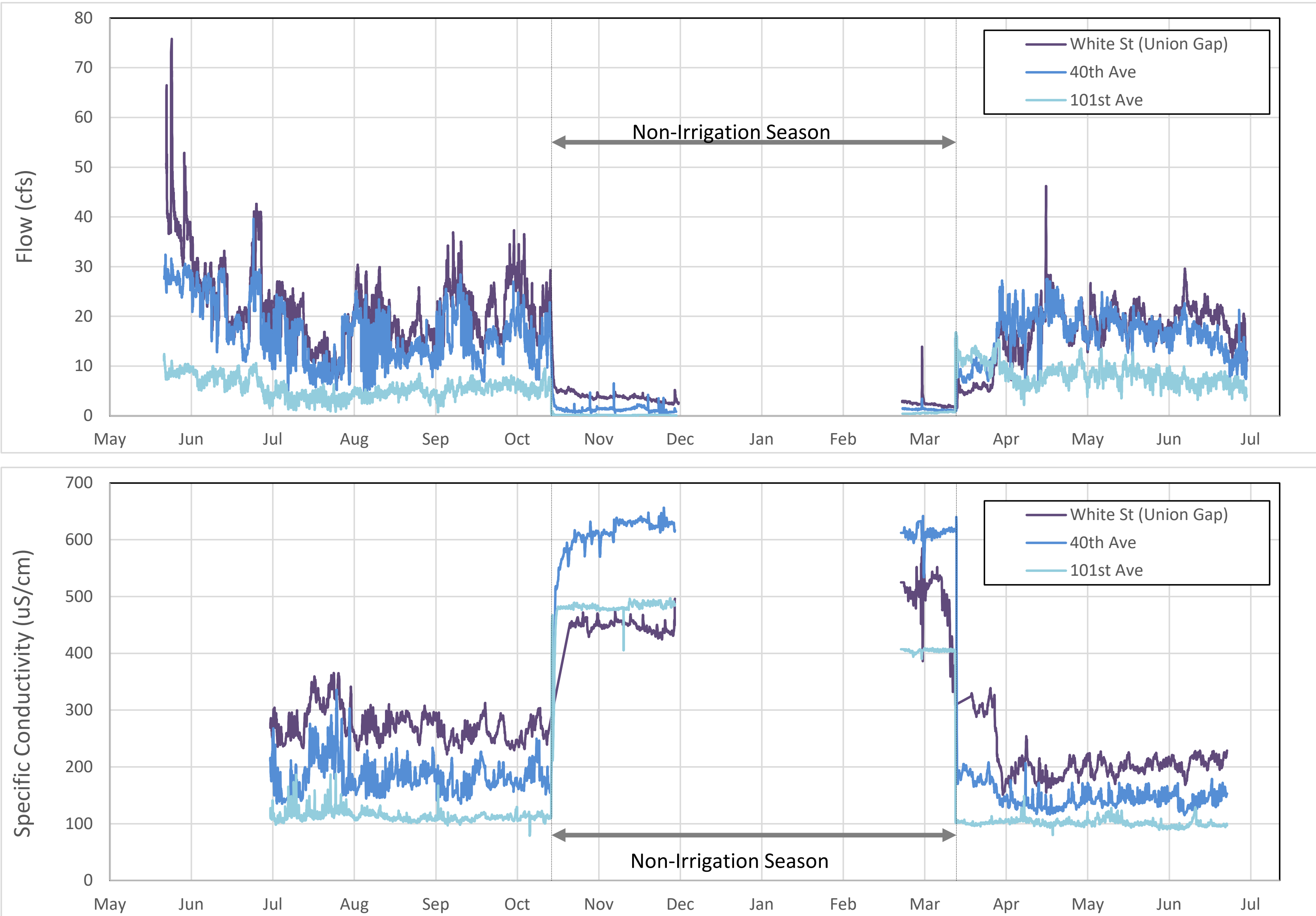


Figure 12. Gaged streamflow and specific conductivity at three locations on Wide Hollow Creek (mid-May 2013 to July 2014).

Instantaneous streamflow measurements

Instantaneous streamflow was measured at 12 locations along Wide Hollow Creek during the synoptic surveys (see Figure 11 above): GW at 101st, WHC at 101st, WHC at 80th, WHC at 64th, WHC at 48th, WHC at 40th, WHC at 24th, WHC at 16th, WHC at 3rd, WHC blw Fines, WHC at White St, and WHC mouth. Instantaneous streamflow was measured once or twice a month during the study period, except during the winter hiatus. In addition to streamflow in the creek, instantaneous flow was also measured at all known sources and diversions to the creek, where possible.

Instantaneous streamflow measurements provide a longitudinal snapshot of flow in the creek (Figure 13). This figure shows longitudinal flow measured during two synoptic surveys: one during irrigation season (Apr 29-30, 2014) and another during non-irrigation season (Mar 3-4, 2014).

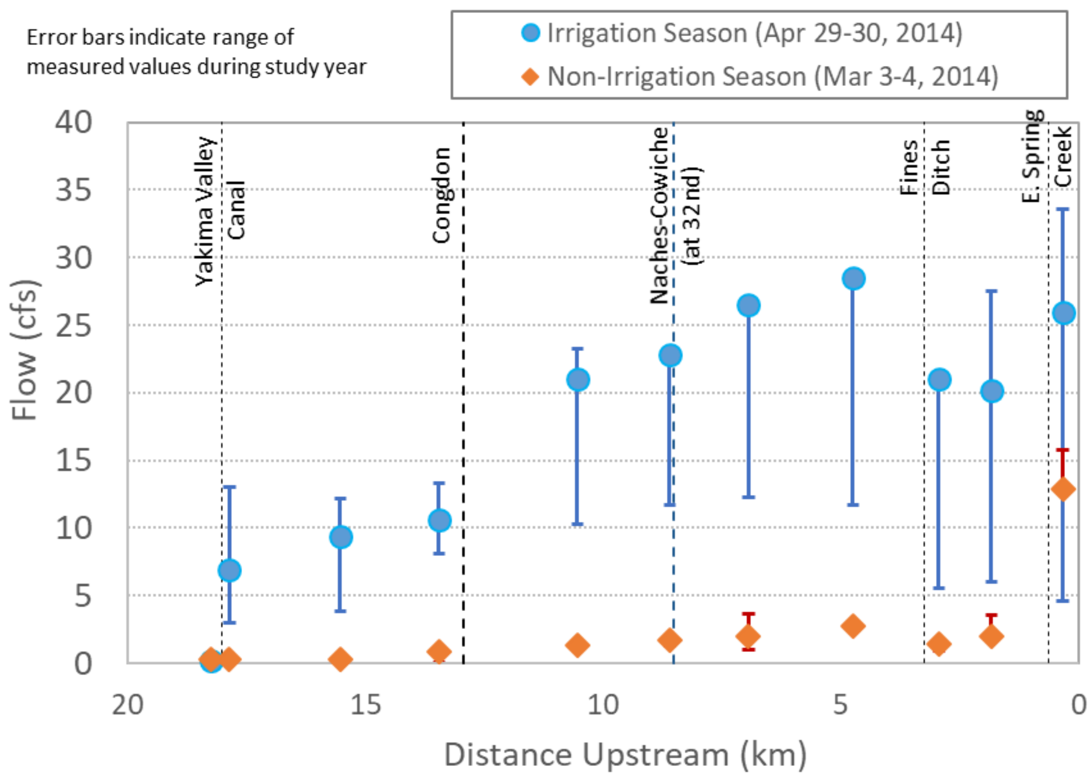


Figure 13. Longitudinal flow measured during two synoptic surveys (irrigation season versus non-irrigation season).

The location of major sources/diversions to Wide Hollow Creek are indicated by vertical dashed lines.

During both irrigation and non-irrigation seasons, streamflow in Wide Hollow Creek increases in the downstream direction, except where Fines ditch diverts water near km 3.

- Irrigation season: water from three irrigation sources (Yakima Valley Canal, Congdon Orchards and Naches-Cowiche Canal near 32th Ave.) dominated the streamflow during the irrigation season. Fines ditch and East Spring Creek also impacted streamflow.

- Year-round: Groundwater, DIDs, and stormwater pipes contribute perennial flow, mostly below 64th Avenue. When irrigation was turned off in October, Wide Hollow Creek was dry from just above 80th Ave to just above 64th Ave for the rest of 2013.

In addition to the measurements of flow in the creek, instantaneous flow measurements were made at all known point sources and diversions to the creek. These sources are described and measurements presented in the model simulation section below.

Vegetation shade measurements

Hemispherical photos were taken on October 1, 2013 (before leaf fall) that measured the sky opening through the riparian above the surface of the creek at five locations (see below in shade simulation section - Figures 47 and 48). Wide Hollow Creek had measurements ranging from 30 to 90% shade, with an average shade of value of 75% for all the photo measurements taken from 80th Ave to the mouth. Overall, Ecology observed that most of Wide Hollow Creek was highly shaded during the growing season by deciduous trees and shrubs.

Water temperature data

Temperature was continuously recorded by data loggers at 10 locations in Wide Hollow Creek (see Figure 11 above): WHC at 101st, WHC at 80th, WHC at 64th, WHC at 40th, WHC at 24th, WHC at 16th, WHC at 3rd, Fines Ditch, WHC at White St, and WHC mouth. Temperature in tributaries to the creek was also recorded where possible.

Data from the 2013-14 study show water temperature in excess of the applicable 17.5°C highest 7-DADMax water quality criterion throughout Wide Hollow Creek from when the study started in July to mid-September 2013 and in the upper and lower part of the creek during part of June 2014 (Figure 14, Table 10). Based on the criteria exceedance, Wide Hollow Creek did not support aquatic life uses during these time periods.

Additionally, 1-DMax water temperature approached or exceeded 23°C, particularly in the upper part of Wide Hollow Creek (Table 10). Ecology acknowledges a 1-DMax of 23°C as an acute lethality threshold for salmonids. Table 10 shows that summer-time maximum temperatures in the creek are higher upstream than downstream.

Temperatures of point sources to Wide Hollow Creek were also quite warm, most recording a daily 7-DADMax in excess of 20°C for the hottest time periods.

Wide Hollow Creek did not have temperature limitation for algal productivity in the summer. Diatoms, the dominant algae type in streams of the Pacific Northwest, have a critical temperature at which photosynthesis occurs of about 5°C (Wetzel, 1983), with an optimal temperature range for maximum growth between 20 to 30°C (EPA, 1985). Wide Hollow Creek water temperature was generally around 20°C in July and August of 2013.

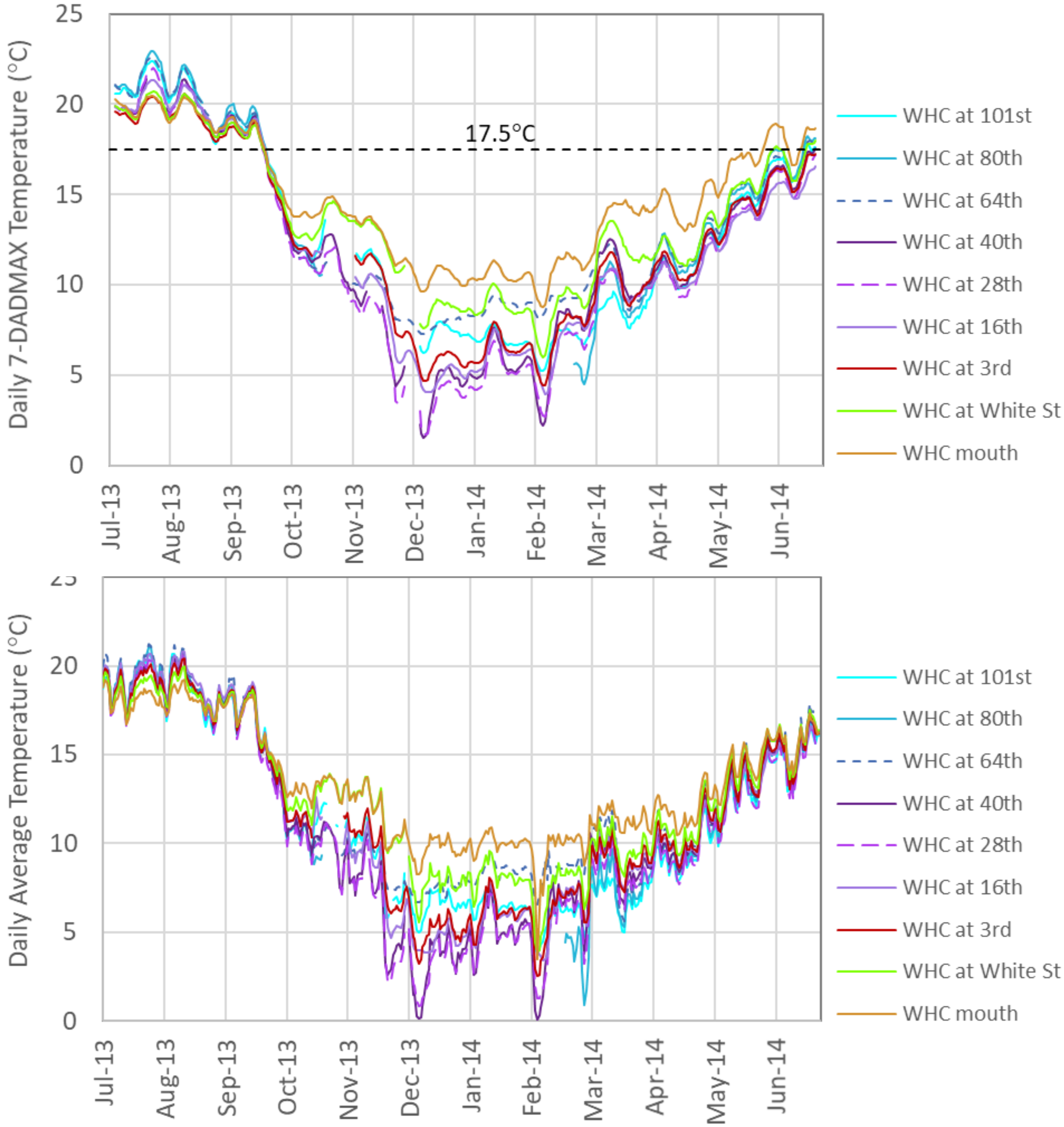


Figure 14. Temperature statistics (Daily 7-DADMax and daily average) over the study year in Wide Hollow Creek.

The daily 7-DADMax water temperature is the average of the maximum temperatures from 3 days prior to 3 days after each day. The maximum of these values is termed the "highest 7-DADMax".

Table 10. Highest daily maximum temperatures in Wide Hollow Creek and its tributaries during the 2013-14 study year.

Sites are listed in downstream order.

Station ID	Station description	Highest 1-D Max[1] (ºC)	Highest 7-DAD Max[2] (ºC)
Wide Hollow Creek			
37-IS-16B	WHC at 101st	22.78	22.37
37-FW-8	WHC at 80th	23.38	22.91
37-SS-12	WHC at 64th	23.16	22.62
37-FW-6B	WHC at 40th	22.15	21.76
37-FW-5	WHC at 24th	22.50	22.01
37-FW-4	WHC at 16th	21.72	21.35
37-FW-3	WHC at 3rd	20.98	20.59
37-FW-1C	WHC blw Fines	21.08	20.73
37-FW-1B	WHC at White St	20.82	20.48
37-FW-0B	WHC mouth	21.34	20.49
Tributaries			
37-IS-16	Yak Valley Canal	20.86	20.39
37-SS-38	DID #38	20.60	20.23
37-SS-48	DID #48	22.40	21.43
37-IS-17	DID #40	20.90	20.24
37-IS-17.5	Randall Pond	33.60	31.16
37-IS-20B	NC Canal at 32nd	22.60	22.24
37-IS-20A	NC Canal at 12th	22.50	22.16
37-IS-23	Spring Ck Irrig	22.20	20.23
37-IS-12	DID #24 at 3rd	15.50	15.50
37-FW-2B	Un-named Creek	17.50	17.40
37-FW-2	East Spring Creek	22.30	21.26

[1] Highest 1-DMax = highest value of daily maximum temperature during study year 2013-14.
[2] Highest 7-DADMax = highest value of the 7-day average of daily maximum temperatures during study year 2013-14.

Field measurements and water sample results from synoptic surveys

Appendix C lists all of the instantaneous field measurements and water chemistry results.

Instantaneous field measurements

Instantaneous field measurements of specific conductivity (SpCond), dissolved oxygen (DO), and pH are summarized in Figure 15 below. Measurements are categorized into the following list of source types:

- DID and stormwater outfalls (DID #38, DID #40, DID #24, all stormwater outfall. Spring / Un-named Creeks
- Irrigation canal outfalls (Yakima Valley, Naches Cowiche, Congdon Orchards)
- Wide Hollow Creek

It should be noted that these measurements are instantaneous measurements, usually taken from mid-morning to mid-afternoon, potentially missing the temporal diel extremes of DO and pH seen in productive waters. Continuous measurements of DO and pH were made in Wide Hollow Creek at 3 locations to capture the full diel range and are presented later in this report.

Specific conductivity field measurements in Wide Hollow Creek were higher during non-irrigation season. Sources of high conductivity are primarily from the DID and stormwater outfalls, which drain groundwater. Irrigation canal outfalls had lower specific conductivity, because these come from the Naches River water which is primarily snowmelt or reservoir released water.

Groundwater contributions to the creek also had higher specific conductivity and are presented later in the groundwater section.

Instantaneous DO field measurements in Wide Hollow Creek were typically above 8 mg/L during the irrigation season, with a few samples below this during non-irrigation season. The DID and stormwater outfalls had lower DO during the non-irrigation season. Again, instantaneous DO samples in the creek do not represent the temporal diel range. DO minimums were likely lower than the instantaneous measurements made during the synoptic surveys.

Almost all instantaneous field measurements of pH were within the water quality criteria range of 6.5-8.5, but again may not reflect the temporal diel range.

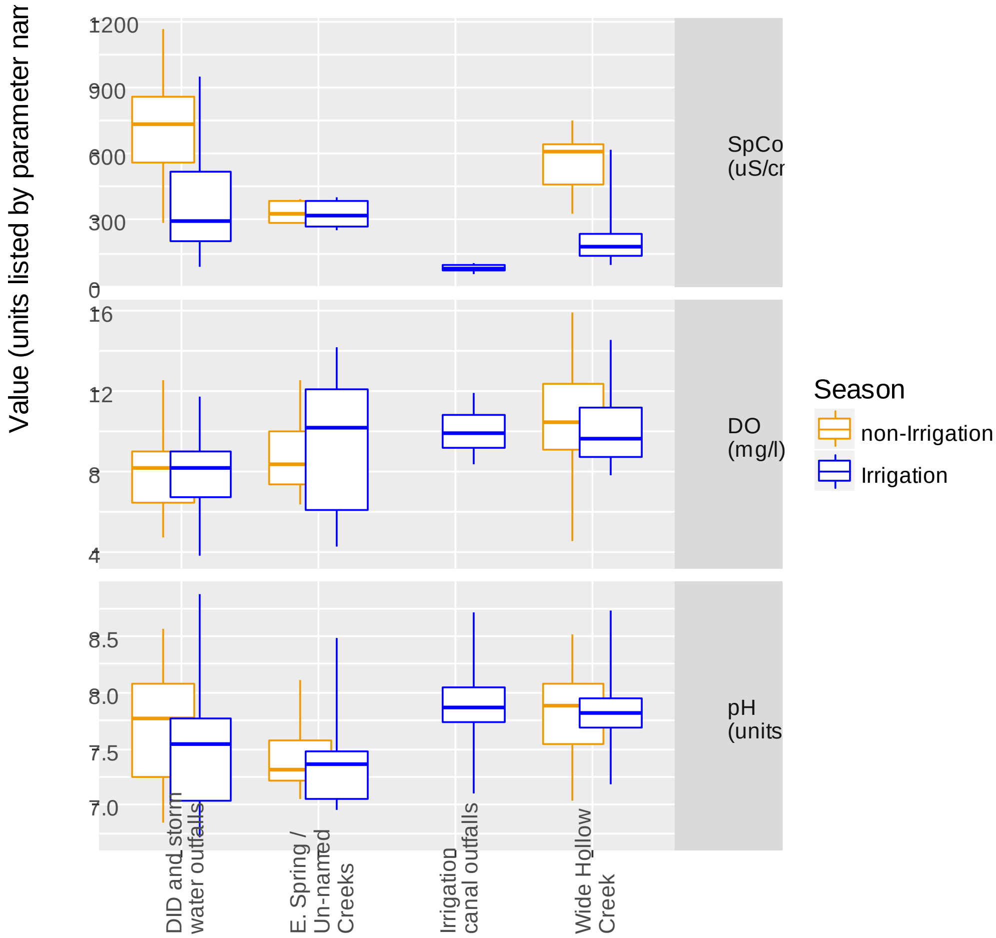


Figure 15. Boxplots of field measurements grouped by source water type.

Boxplot colors indicate season (irrigation versus non-irrigation). Whiskers extend to the maximum and minimum measured values. Boxes are drawn between the 25th and 75th percentiles, with a horizontal center line indicating the median value.

Water chemistry

Results of water chemistry samples collected in Wide Hollow Creek are plotted by river mile in Figure 16. Symbols are colored according to whether the sample was collected during irrigation or non-irrigation season. The following abbreviations are used for water chemistry parameters in the figure:

- TPN = total persulfate nitrogen
- NO_{23} = nitrate-nitrite
- TP = total phosphorous
- OP = orthophosphate
- Alk = alkalinity
- Hard = hardness
- TOC = total organic carbon
- DOC = dissolved organic carbon

- Cl = chloride
- NH_4 = ammonia
- TNVSS = total non-volatile suspended solids
- TSS = total suspended solids

An upstream to downstream trend is seen during irrigation season for some of the chemistry parameters. These parameters include the nutrients (TPN, NO_{23}, TP, OP) and also ionic strength (Alk, Hard, Cl). Concentrations of these parameters tend to be lower during the irrigation season than the non-irrigation season.

To help identify possible reasons for the observed trends, Figure 17 shows boxplots of water chemistry in both the creek as well as three different types of sources to the creek: irrigation canal outfalls, DID/stormwater outfalls, and East Spring/Un-named Creeks.

Figure 17 indicates that nutrients tend to be lower in irrigation canal outfalls, which originate in Naches River water. Nutrients tend to be higher in DID/stormwater and E. Spring/Un-named Creeks, which are fed at least in part by groundwater. The irrigation canal outfalls make up a large percentage of flow during the irrigation season (especially farther upstream), which helps explain why nutrients and ionic strength are lower during irrigation season. An increasing trend downstream during irrigation season is likely due to the other source types entering the creek as it flows downstream.

Nutrient levels in Wide Hollow Creek were high during the non-irrigation season, generally occurring at concentrations far above limiting concentrations for algal growth in the stream. Nutrient concentrations that limit growth saturation for diatoms start somewhere below 0.025 mg/L for orthophosphate (Hill et al., 2009; Rier and Stevenson, 2006; Bothwell, 1985) and 0.086 mg/L for dissolved inorganic nitrogen (Rier and Stevenson, 2006; Snouwaert and Stuart, 2015).

Nutrient levels in Wide Hollow Creek during the irrigation season were also above limiting concentration in the lower part of the creek, but may have had some potential limitation in the upper reaches, around 101st Ave where low-nutrient Naches River water additions dominated.

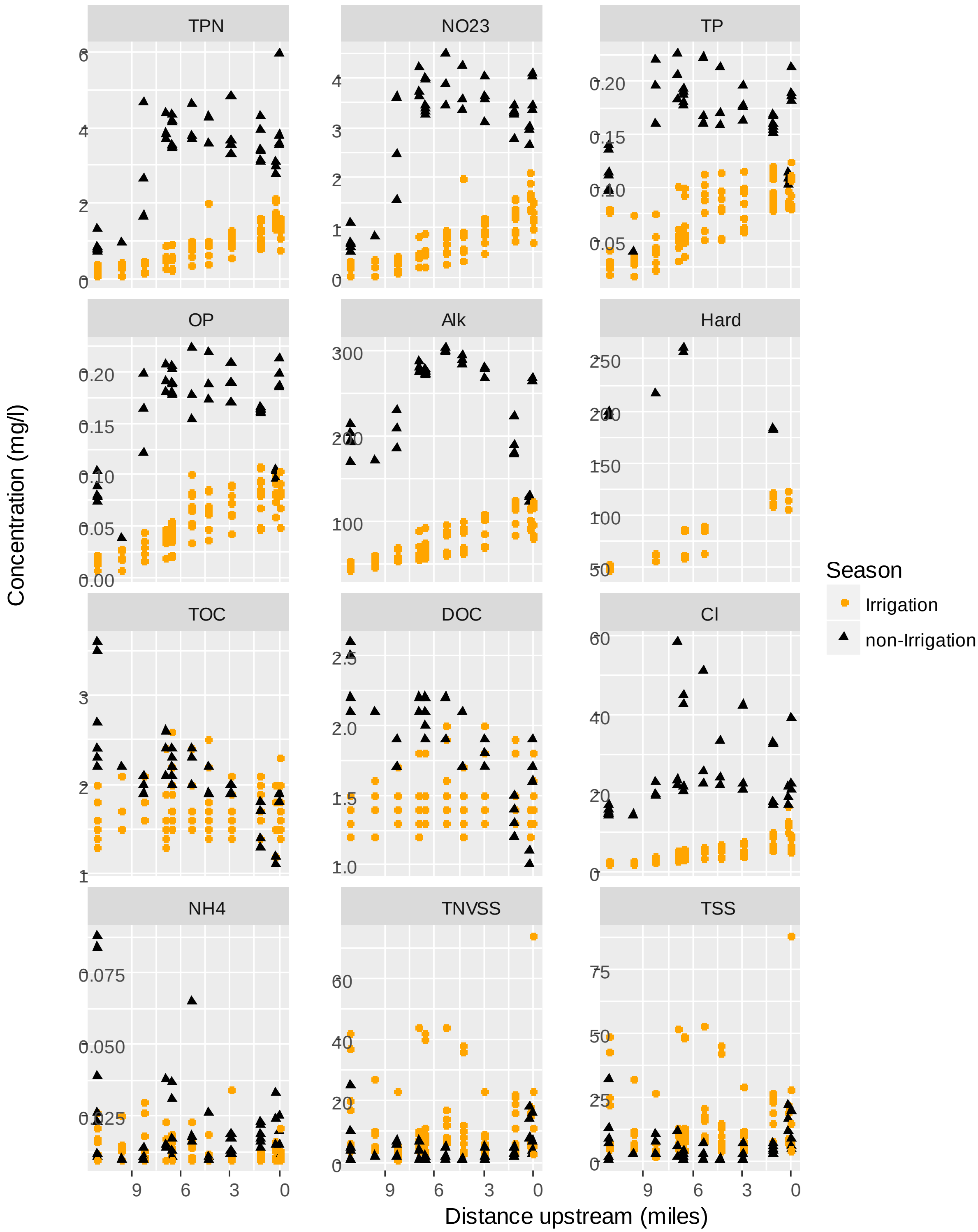


Figure 16. Water chemistry samples collected in Wide Hollow Creek.

See text for a list of abbreviations used in this figure.

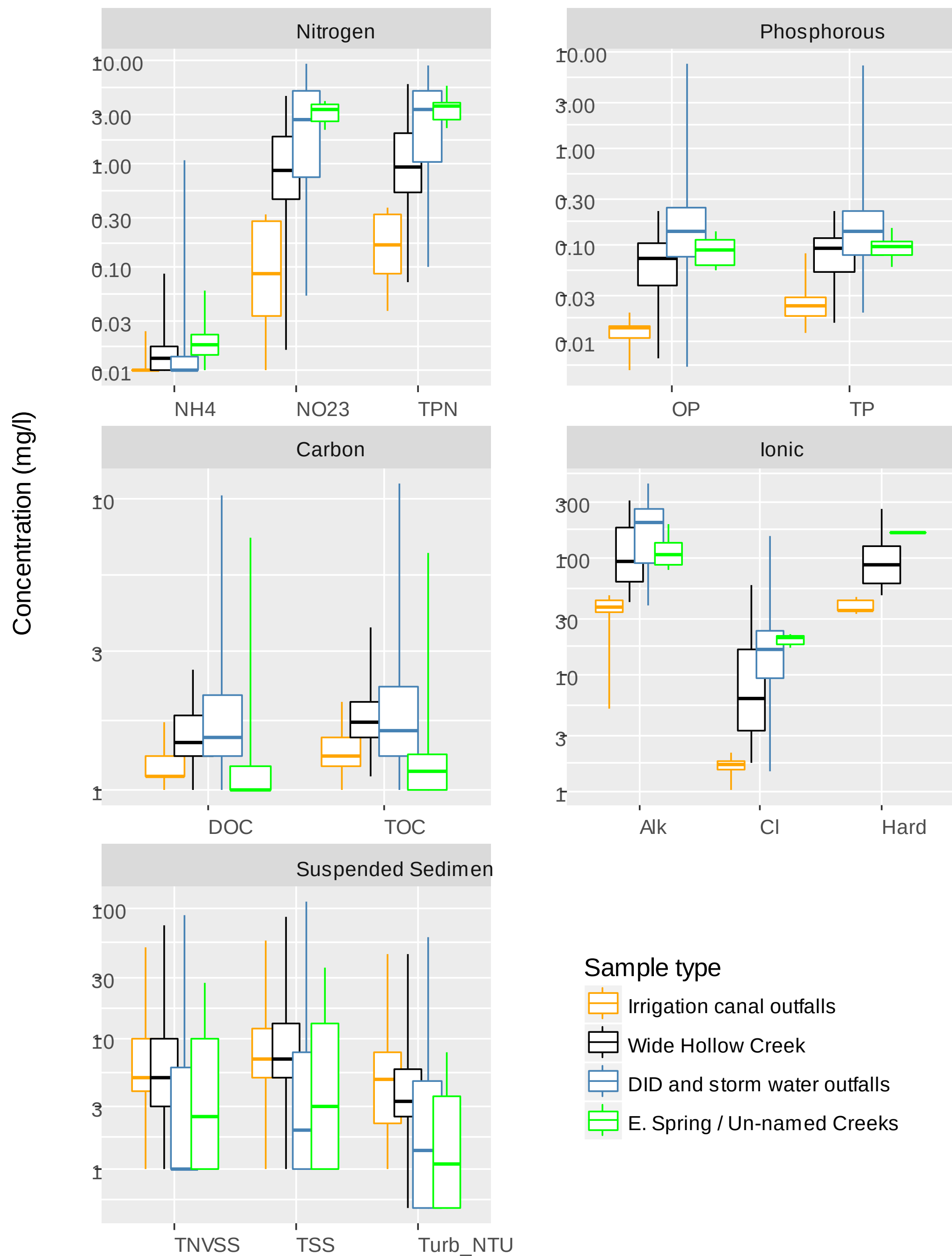


Figure 17. Boxplot of water chemistry for several types of water sources, over the entire study year.

Note the logarithmic scale (base 10). Boxplot colors indicate type of water source. Whiskers extend to the maximum and minimum measured values. Boxes are drawn between the 25th and 75th percentiles, with a horizontal center line indicating the median value.

Comparison of diversion and discharge water temperature and chemistry in irrigation canals

Both the Yakima Valley Canal and the Naches-Cowiche Canal divert streamflow from the lower Naches River. Both canals divert water from the Naches River and discharge a portion of that water into Wide Hollow Creek.

To investigate how passage through irrigation canals impacts water temperature and chemistry of the Naches River irrigation water, Ecology analyzed water samples and measured temperature and conductivity at both the diversions and outfalls for the two canals (Naches-Cowiche canal and Yakima Valley canal).

Ecology measured continuous water temperature at the diversion sites for each canal; however, the temperature datalogger was lost for the Yakima Valley Canal diversion on the Naches River, so data is not available for that location. Temperature measurements were collected from July 1 to Oct 15. Water quality samples were collected and measurements made during three synoptic events in 2013 (Aug 6, Sept 10 and Oct 8).

A reduced diel range in temperature was observed at the Naches-Cowiche outfall (NC Canal at 32nd) compared to the diversion (Figure 18).

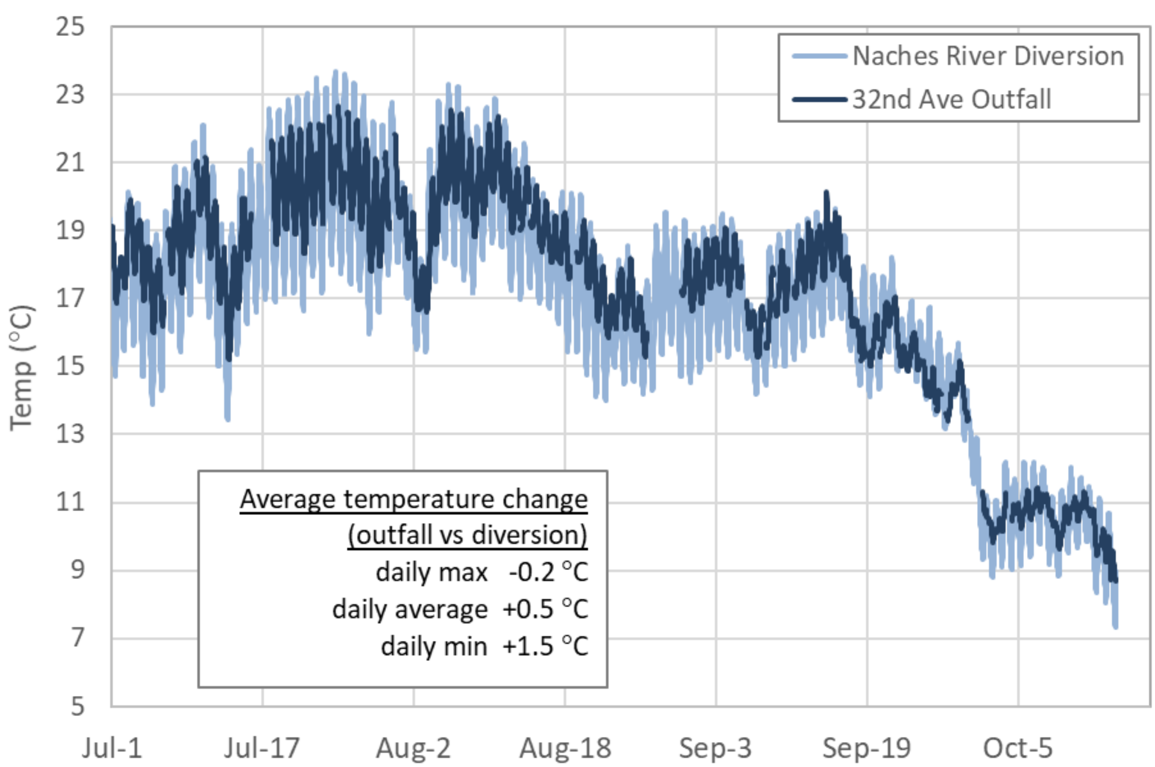


Figure 18. Comparison of water temperature between the Naches-Cowiche canal diversion versus outfall at 32nd Avenue (July 1 to October 15, 2013).

On average during July 1-Oct 15, daily maximum temperatures at the outfall were -0.2 °C lower, daily average temperatures were 0.5 °C higher and daily minimum temperatures were 1.5 °C higher compared to the diversion. No comparison of water temperature was made for the Yakima Valley canal, due to the loss of the data logger at the canal diversion.

Differences in water chemistry between the diversions and outfalls of the Naches-Cowiche and Yakima Valley canals are shown in Figure 19 and values are listed in Appendix C – Table C-2.

Overall, water quality differences are small. It is impossible to determine how much of the small differences are due to short term variability in the Naches River water, compared to changes happening during water passage through the canals. Naches River variability is considered less likely to cause consistent or large changes in both canals during all events.

- Nitrogen-phosphorous nutrients - small but consistent increases (8-35% RPD).
- Organic carbon - near the detection limit.
- Solids / turbidity - low during the Aug and Oct events. For the Sept event, the two canals show inconsistent results. The higher values in Sept are due to increased flow in the Naches River.
- Conductivity/alkalinity – small changes, possibly increasing.

Continuous dissolved oxygen data

Continuous dissolved oxygen (DO) data collected from three streamflow gaging stations are presented in Figure 21 to Figure 23. Appendix D describes the quality assessment of the observed continuous DO data. As described in this appendix, data were assessed as excellent, good, fair, and poor based on regular calibration checks. These figures depict excellent data as unqualified and good data as qualified (highlighted). Fair and poor data were not depicted in these figures.

In addition to the observed DO concentration, the saturated DO concentration is also plotted. DO saturation is temperature dependent with warmer water holding less DO than colder water.

Warmer water temperatures in the summer contributed to lower DO concentrations throughout Wide Hollow Creek. However, fully saturated DO concentrations never went below 8 mg/L at any of the three continuous water quality gage stations during the study period. DO concentrations were below the minimum criterion because of low DO concentration from inputs (e.g., groundwater inputs) or DO sinks (e.g., metabolic respiration or SOD).

Collecting continuous DO data is valuable for understanding the dynamic metabolic functioning of Wide Hollow Creek. Each of the three locations where continuous DO levels were recorded showed unique daily and seasonal patterns.

Continuous dissolved oxygen data at 101st Ave

The continuous DO time series at the 101st Ave gage showed the direct effect of the water quality of the irrigation water that was discharged to Wide Hollow Creek. The gage station was just a short way (≈ 250 feet) below the Yakima Valley Canal discharge to the creek. The water quality of the irrigation water was mostly dominated by the source water quality, which was the Naches River, but algal productivity in the canal may have affected the DO concentration as well.

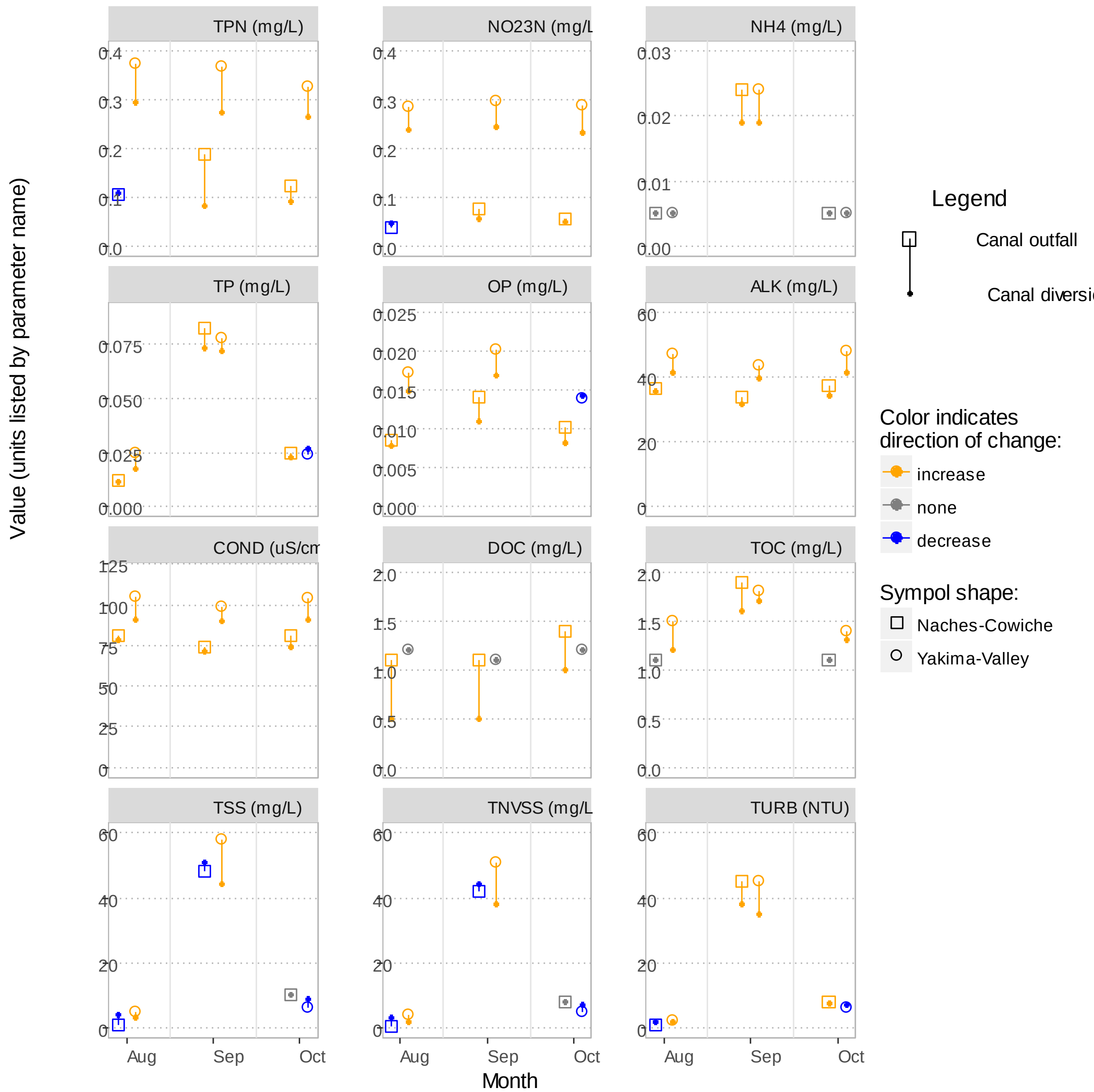


Figure 19. Comparison of canal diversion versus outfall water quality.

At the beginning of the record in July 2013, the DO of the irrigation water that was discharged from the Yakima Valley canal dominated the DO signal at the gage. Later that fall, after October 15th, the irrigation water was shut off and the low oxygenated groundwater seep that perennially waters this portion of the creek dominated. The pattern reversed in 2014, with the DO time series dominated by the groundwater seep until March 15 when irrigation commenced. Measurements of the DO in the groundwater seep at this location averaged about 2 mg/L over the course of the study (Appendix A).

Figure 20 details the dynamic interplay of flow mixing between the groundwater seep and irrigation water input on the DO concentration at the 101st Ave gage for the months of July, October, and March.

During July 2013, DO had a diel range of about 1 mg/L and despite warm water temperature, both the DO and saturated DO concentrations were usually above the DO water quality minimum standard of 8 mg/L for most hours of the day.

However, there were about 20 days in July when the daily minimum was below 8 mg/L, with at least 4 days briefly going below 7 mg/L for a daily minimum. Streamflow dropped to nearly 1 cfs at the gage on those days with the lowest DO concentrations. On those days, the low oxygenated groundwater seep dominated the mix of water at the gage and pulled down the DO concentrations to the seasonal lows.

In October 2013, after the irrigation water was shutoff after the 15th, the flow dropped to below 1 cfs and the low DO of the groundwater seep dominated the creek, resulting in DO levels well below saturation and below the minimum DO criterion. A little algal productivity in the creek at this time caused mid-day diel DO spikes, but the under-saturation still persisted.

In March 2014, the irrigation water was turned on about the 18th and the flow suddenly increased at 101st Ave. Prior to irrigation, DO in the creek varied widely through the day with a diel swing of about 6 mg/L. The day-time DO lows were under-saturated and often below the minimum criterion. Once irrigation water was discharged into the creek, the DO signal was dominated by the water quality of the water from the canal.

Overall, the irrigation water from the canal appeared to be well-aerated as the DO levels were generally around saturation throughout the irrigation seasons. The exception was in the spring of 2014, from April through May, when a spring bloom was taking place in the Naches River (and potentially in the irrigation canal) with super-saturated DO levels during the daytime, and under-saturated levels during the night and early morning. The peak of the bloom was early May and corresponded to the lowest measured nitrate and phosphate levels at 101st Ave. due to the uptake of these nutrients from the pronounced algal productivity.

Continuous dissolved oxygen data at 40th Ave

The continuous DO time series at the 40th Ave gage generally showed under-saturated conditions throughout the study year. Here, Wide Hollow Creek (downstream of 64th Ave) skirts the bottom edge of Nob Hill. The channel is generally highly incised, deep, and the bottom sediment silty in places. Sediment oxygen demand is expected to be higher in these conditions. Algal productivity was moderate but was probably light-limited by the heavy tree cover in the creek riparian.

The direct effect of the water quality of the irrigation water was still somewhat evident. After irrigation was ended in mid-October 2013, the DO levels at this gage were dominated by the groundwater seep at 64th Ave. The groundwater seep discharged into the creek over a mile upstream and had time to reaerate but DO levels were still below saturation most of the time. Cooling temperature generally kept the under-saturated DO levels above the minimum DO criterion during the fall.

During the irrigation season, there was lower algal productivity with a 1-2 mg/L daily swing in DO concentration, whereas the saturated DO concentration diel range was less than 0.5 mg/L. Shading from riparian vegetation in this reach limited the algal productivity. Even though the DO levels were under-saturated, the lowest daily DO concentrations stayed above the minimum

DO criterion most of the irrigation season except in July and early August 2013 when the saturated DO was the lowest due to warm water temperatures.

Continuous dissolved oxygen data at White St in Union Gap

The continuous DO time series at the White St. gage showed the least influence of irrigation water additions. The DO diel levels showed moderate algal productivity from July through August 2013, with a 3-4 mg/L daily swing in DO concentration, whereas the saturated DO concentration diel range was less than 0.5 mg/L. The saturated diel range was caused by the diel swing in water temperature.

The reach above the White Street gage was more exposed to light than the reaches above the 101st Ave and 40th Ave gages. The creek was routed (ditched) to Union Gap and much of this distance has less shade from riparian vegetation.

The DO levels in July 2013 were somewhat balanced between over-saturated and under-saturated conditions, but starting in August 2013, the DO levels moved more and more towards an under-saturated condition until finally in September, the DO levels remained under-saturated throughout the rest of 2013.

By September, the reed canary grass had grown up along the sides of the creek and bent over to shade the water surface, sometimes covering the entire surface. Also, around September 7, a slug of inorganic suspended sediment from the Naches River irrigation water blocked the light in the water column for most of the rest of the month.

When DO was measured again in March of 2014, the DO levels showed higher algal productivity with 5-6 mg/L daily swing in DO concentrations, and slightly favoring over-saturating conditions. After irrigation started, and certainly by May, the DO levels dropped to more moderate algal productivity, similar to where they were in July 2013. The lowest daily DO concentrations stayed above the minimum DO criterion of 8 mg/L until the water temperatures increased enough to drive saturated conditions lower in June 2014.

Continuous pH data

Continuous pH data collected from three streamflow gaging stations are presented in Figure 24 to Figure 26. Appendix D describes the quality assessment of the observed continuous pH data. There were gaps and qualified data in the records because of poor pH sensor performance. The pH criteria for Wide Hollow Creek calls for a pH level between 6.5 and 8.5 pH units.

In addition to the observed pH, Figures 24 to 26 show the calculated pH saturation. The pH saturation is dependent on the alkalinity, conductivity and temperature of the water as well as the CO_2 concentration in the atmosphere. The pH saturation represents what the pH in the creek would be if the CO_2 in the creek water was in equilibrium with the CO_2 in the atmosphere. The water in the creek continually reaerates with the atmosphere to try and achieve this equilibrium.

In general, the pH saturation for Wide Hollow Creek was above the 8.5 criterion during the non-irrigation season when groundwater sources dominated the creek. The higher conductivity and alkalinity levels in the groundwater lead to higher pH saturation. During the irrigation season, pH saturation met pH criteria because the irrigation water had lower conductivity and alkalinity levels, leading to lower pH saturation.

Similar to the continuous DO data, the continuous pH data is valuable for understanding the dynamic metabolic functioning of Wide Hollow Creek. Again, each reach showed unique daily and seasonal patterns.

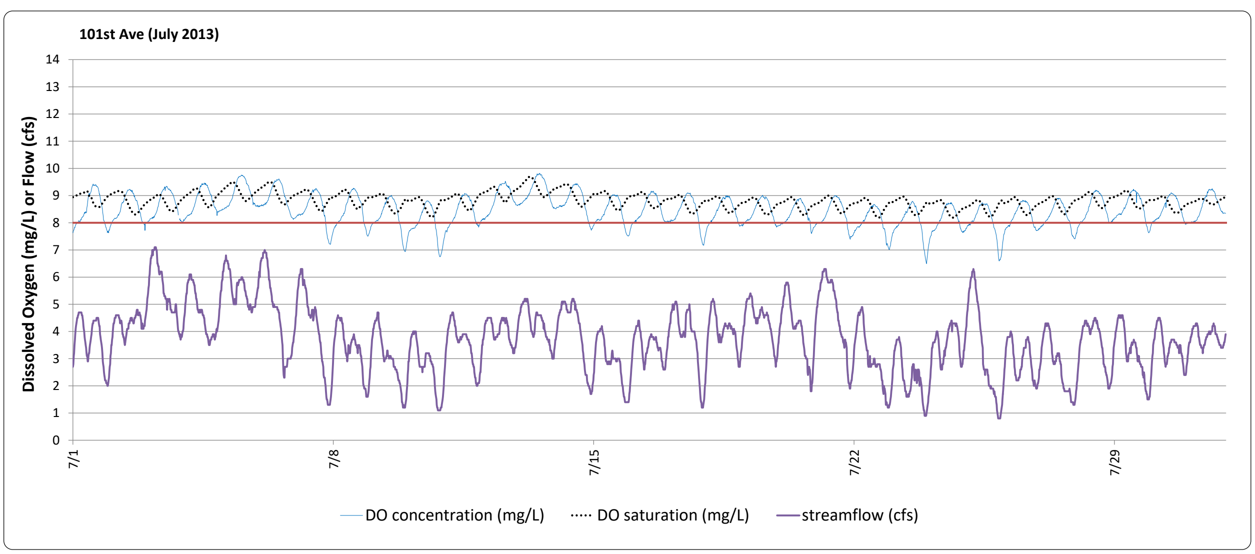
Continuous pH data at 101st Ave

Like the DO data, the continuous pH time series at 101st Ave reflected the pH of the Yakima Valley Canal irrigation water that was discharged to Wide Hollow Creek. The pH of the irrigation water was mostly determined by the pH in the Naches River (the out-of-basin source water), but algal productivity in the Yakima Valley Canal may have affected the pH as well.

During the irrigation season, the observed pH in Wide Hollow generally ranged between 7.5 and 8.5 pH units. While the pH saturation was relatively flat, the observed pH had a diel range of about 1 pH unit. The diel range is the difference between the highest and lowest pH during a single day. The diel change was caused by moderate algal productivity in the irrigation water.

During the spring, there was a distinct departure from moderate algal productivity. A spring algal bloom started in April and continued until turbid snowmelt runoff and higher flow in the Naches River caused algal productivity to drop in June. There was a corresponding increase in diel DO during this spring bloom (noted above) from the extra algal productivity. The diel pH range increased to about 2 pH units with daily maximums reaching almost 9.5 pH units from the increased photosynthesis.

During the non-irrigation season, the pH at 101st Ave was under-saturated, even though the groundwater, with its higher conductivity and alkalinity, had the potential to be higher. The groundwater was recently emerged from the seep and had not time to equilibrate with atmospheric CO_2. Measurements of pH in the groundwater from piezometers at this location averaged 6.81 pH units over the course of the study (Appendix A). Again, the potential pH saturation was over 8.5 pH units. As the groundwater moved downstream in the creek the pH was expected to increase as the gases in the creek reaerated with the atmosphere.



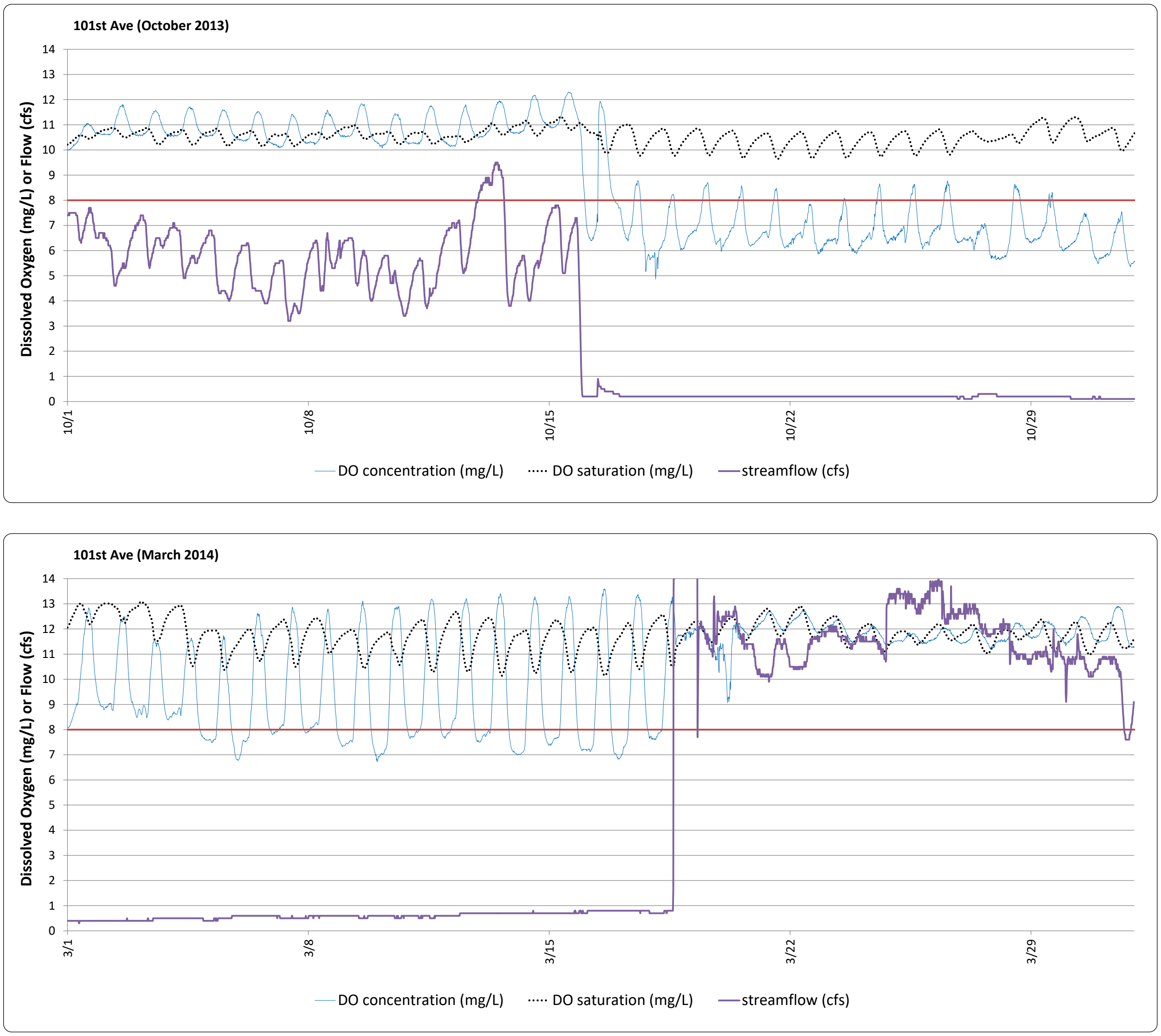


Figure 20. Detail of continuous flow and dissolved oxygen measurements at 101st Ave stream and water quality gage.

Continuous pH data at 40th Ave

Like the continuous DO, the pH at the 40th Ave gage generally showed under-saturated pH levels throughout the study year. The observed pH levels at the 40th Ave gage were never outside of the range for the pH criteria.

During the irrigation season, algal productivity was limited due to light-limitation from the heavy tree cover in the creek riparian. The diel range of pH was about 0.5 pH unit or less. The springtime high pH of the water observed at the 101st Ave gage did not persist to the 40th Ave gage.

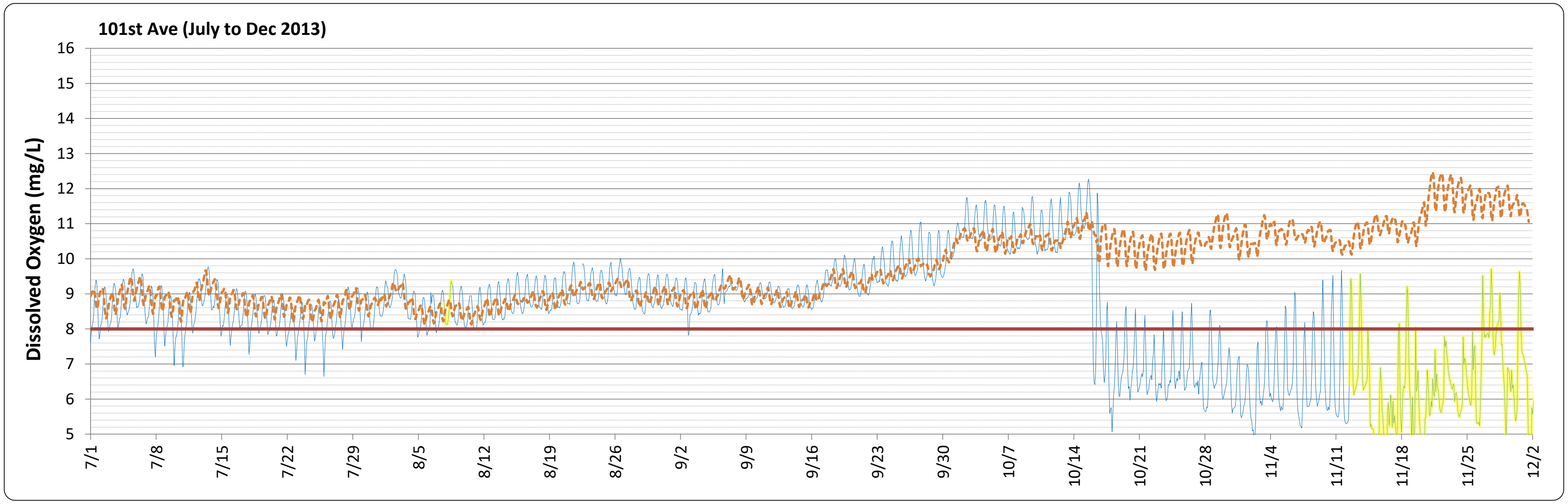
During the non-irrigation season, the pH saturation of the groundwater entering this reach was above 8.5, but the water in the creek had not reaerated enough to equilibrate to the atmospheric CO_2.

Continuous pH data at White St in Union Gap

The continuous pH at the White St. gage also showed generally under-saturated conditions throughout the study period. The diel range of pH was greatest in the spring (> 1 pH unit) and smallest in the fall (< 0.25 pH unit) with a gradual decline throughout the summer. This was most likely due to the increased shading throughout that period as streamside brush and trees leafed out and reed canary grass grew streamside to block out sunlight. The section of Wide Hollow Creek from the Fines Ditch to its confluence with East Spring Creek had the least amount of riparian trees, but the most reed canary grass and macrophytes.

The potential pH based on the pH saturation was slightly above the upper criterion of 8.5 during the non-irrigation season and either equal to or slightly below 8.5 during the irrigation season.

The observed pH only exceeded 8.5 pH units in the early part of May which was the height of the spring bloom as indicated from the DO time series data at both the 101st Ave and White St gages. The under-saturated conditions were likely influenced by the mixing of groundwater inputs (seepage and drains) in this reach. The average groundwater pH measured in a piezometer in this area was 6.97 pH (Appendix A).



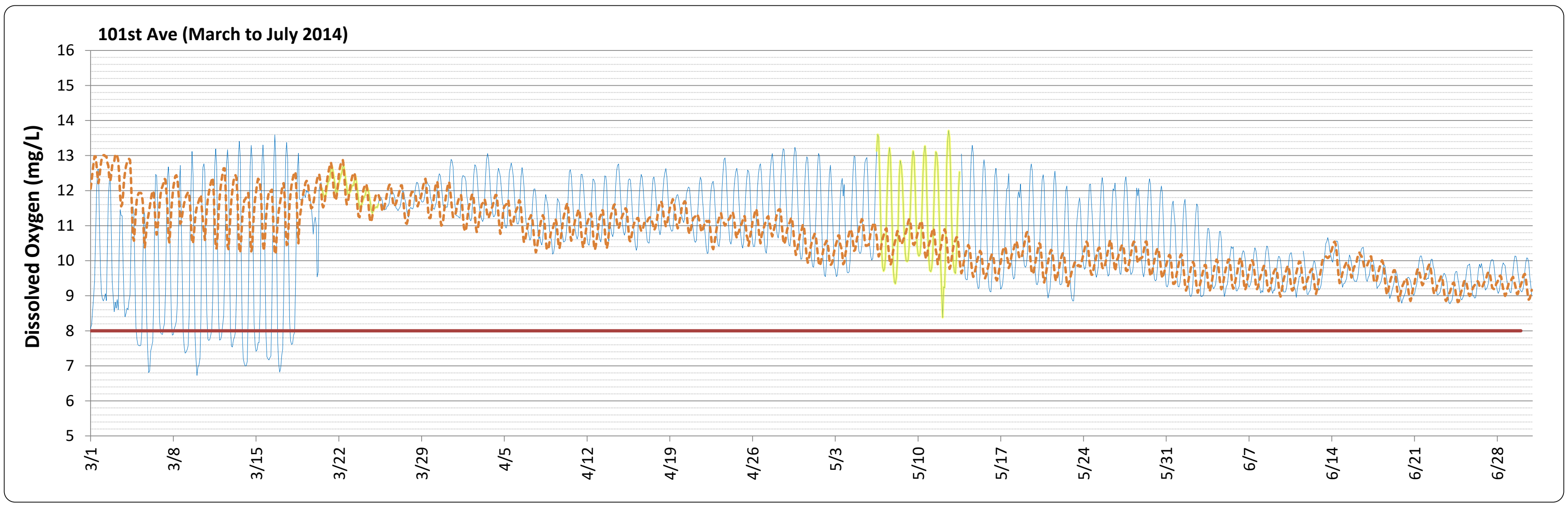


Figure 21. Study year dissolved oxygen time series at 101st Ave.
DO results in relation to the 8.0 mg/L minimum criterion and saturated DO concentration (dashed line). Time series data considered "excellent" are shown as blue and "good" as green (see Appendix D).

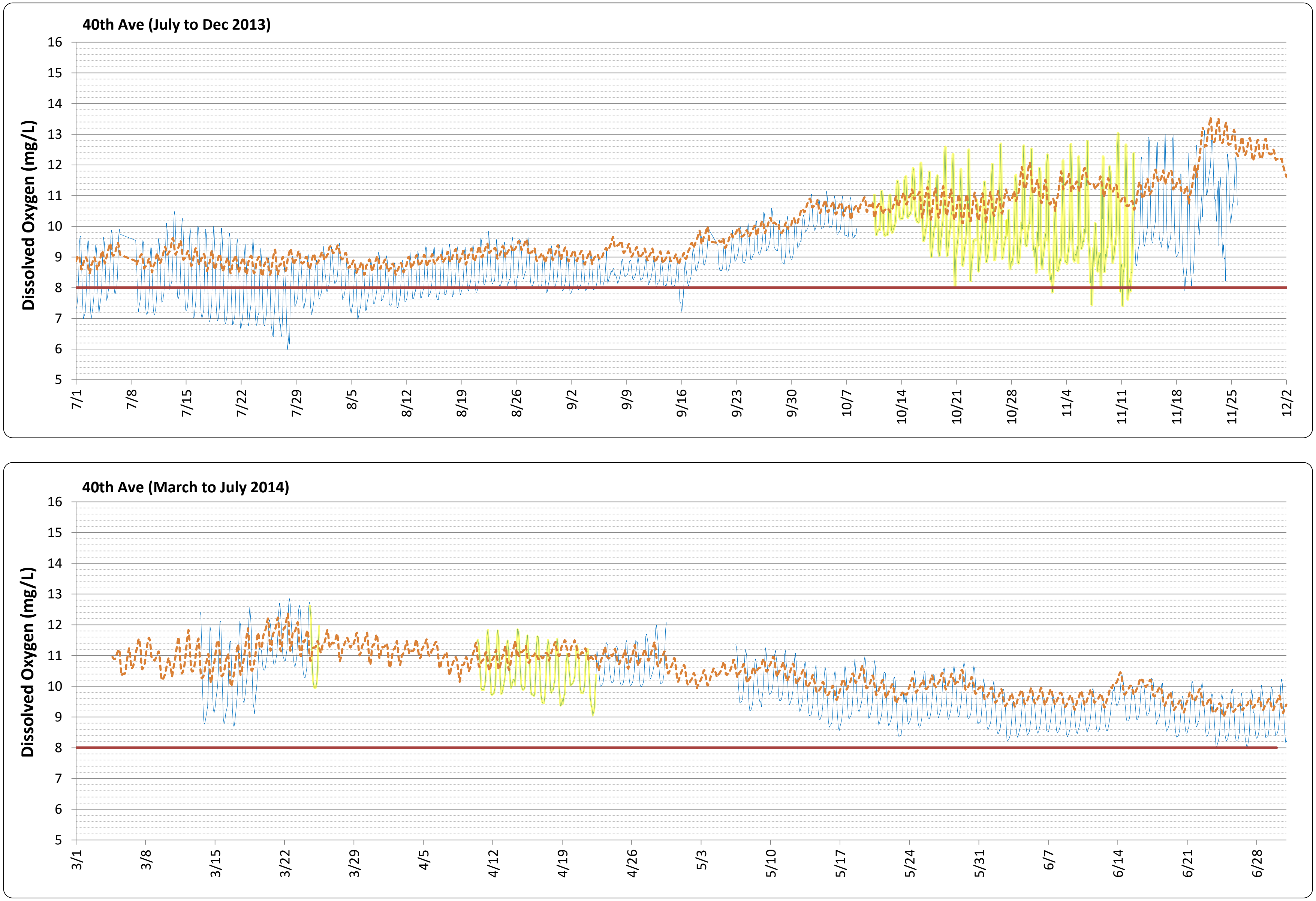
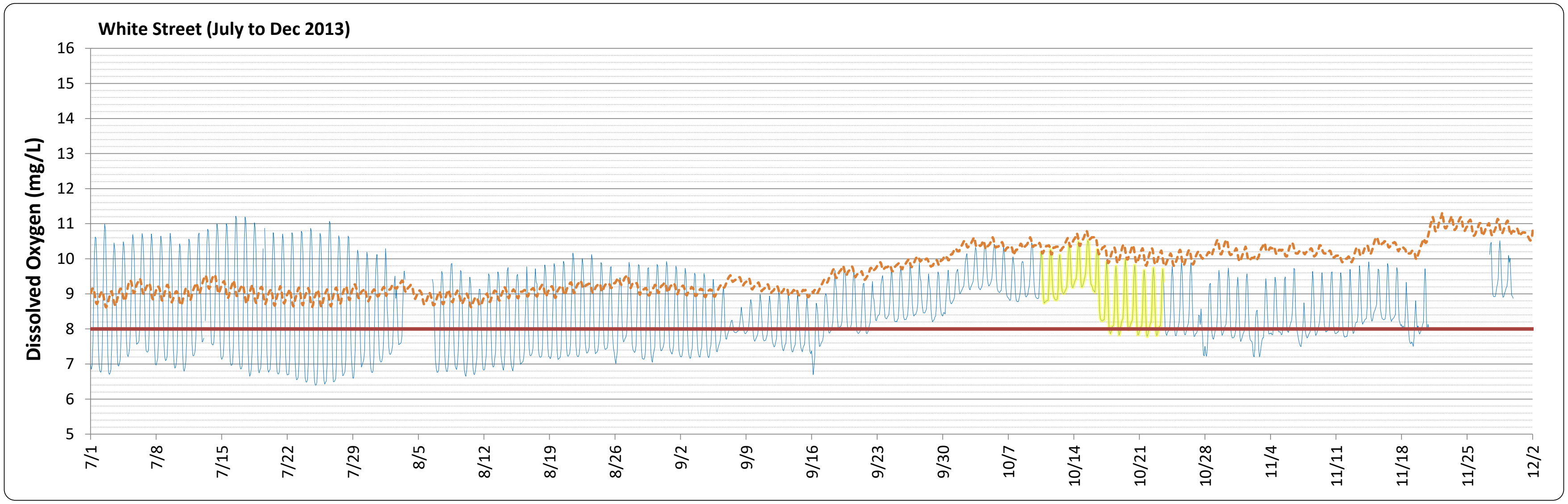


Figure 22. Study year dissolved oxygen time series at 40th Ave.

DO in relation to the 8.0 mg/L minimum criterion and saturated dissolved oxygen concentration (dashed line). Time series data considered "excellent" are shown as blue and "good" as green (see Appendix D).



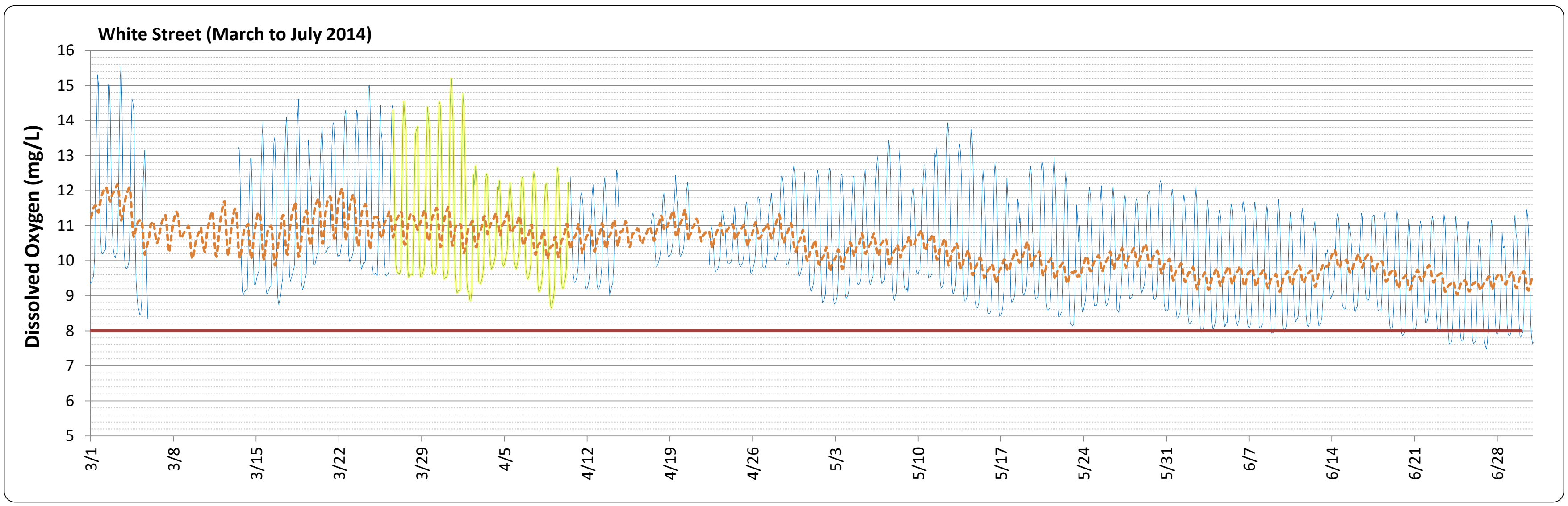


Figure 23. Study year dissolved oxygen time series at White St (Union Gap).

DO in relation to the 8.0 mg/L minimum criterion and saturated dissolved oxygen concentration (dashed line). Time series data considered "excellent" are shown as blue and "good" as green (see Appendix D).

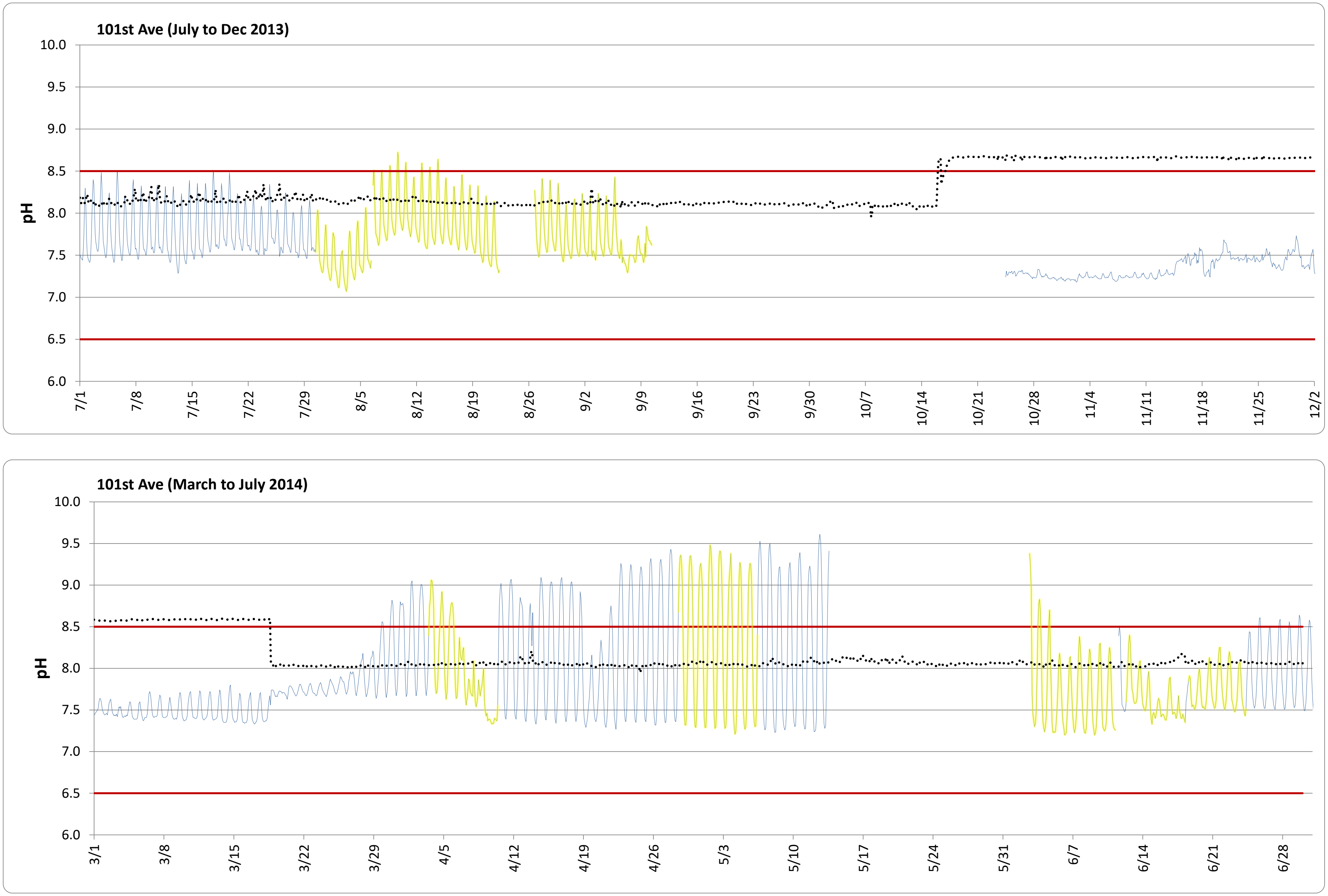


Figure 24. Study year pH time series at 101st Ave.

pH in relation to the pH criteria and saturated pH concentration (dashed line).
Time series data considered "excellent" are shown as blue and "good" as green (see Appendix D).

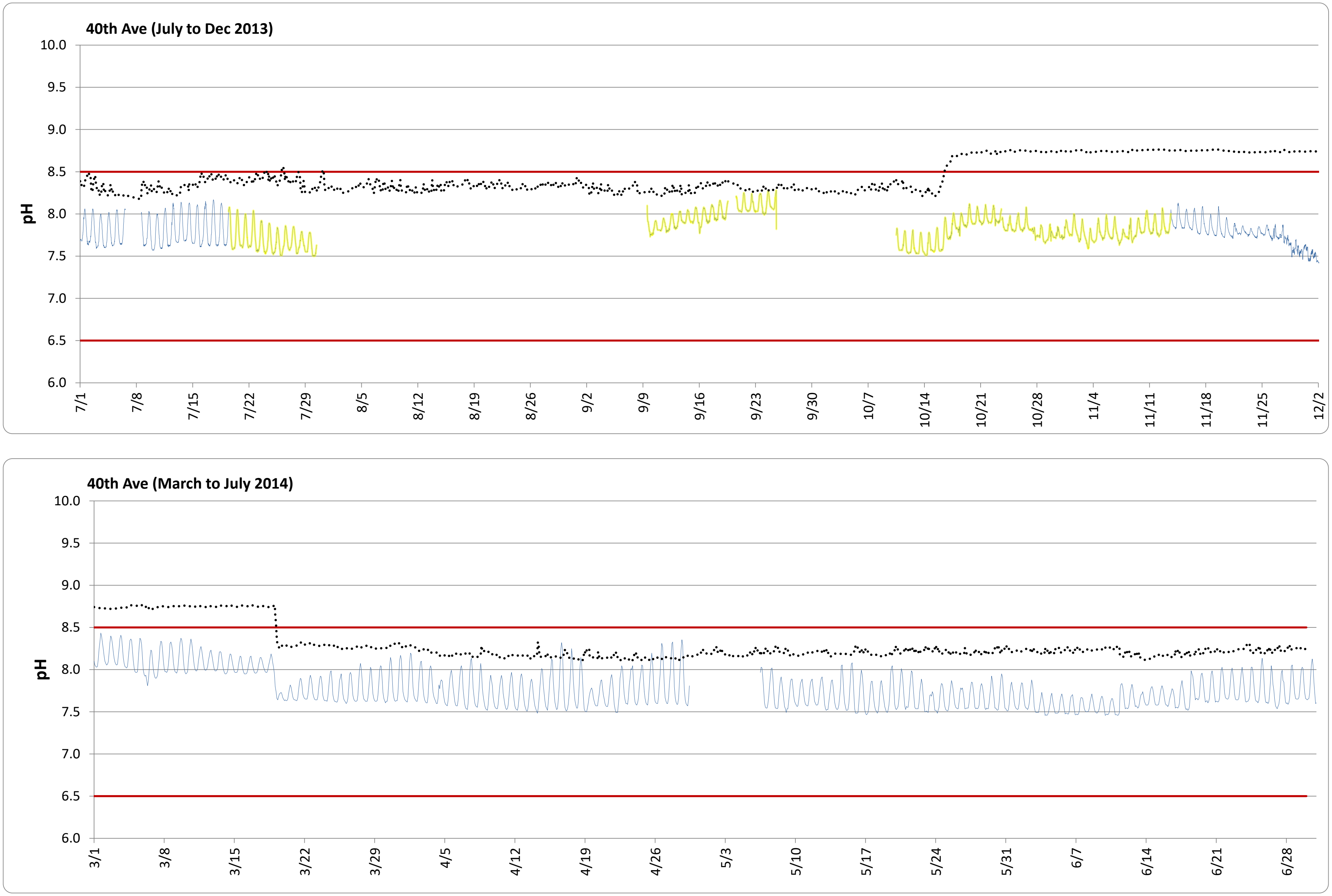
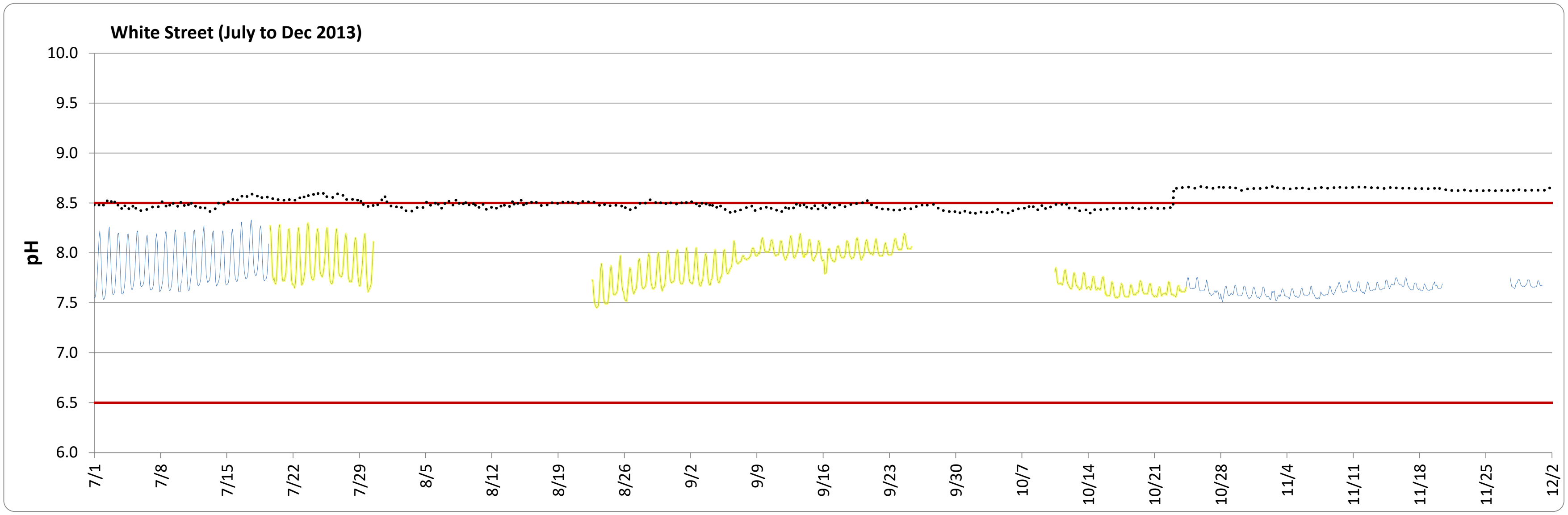


Figure 25. Study year pH time series at 40th Ave.

pH in relation to the pH criteria and saturated pH concentration (dashed line).
Time series data considered "excellent" are shown as blue and "good" as green (see Appendix D).



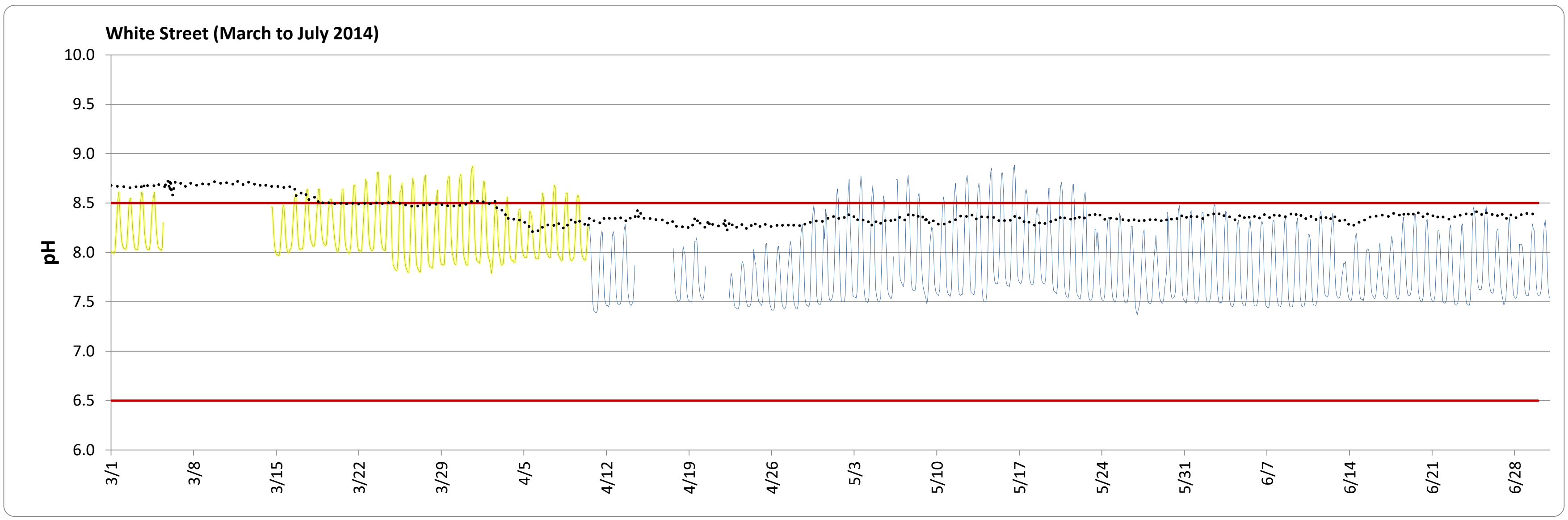


Figure 26. Study year pH time series at White St (Union Gap).
pH in relation to the pH criteria and saturated pH concentration (dashed line).
Time series data considered "excellent" are shown as blue and "good" as green (see Appendix D).

Time-of-travel dye studies

Two time-of-travel dye studies (representing irrigation and non-irrigation conditions) were conducted on Wide Hollow Creek to estimate average water velocities in the creek.

Results from the two dye studies are shown in Table 11. Travel time during irrigation season (from 101st Ave down to the mouth of Wide Hollow Creek) was nearly one day. During non-irrigation season, travel time increased to almost five days. The travel time difference between these two seasons is entirely due to the amount of flow in the creek, which increases during irrigation season due to irrigation water sources.

Due to intermittent flow conditions during the non-irrigation season, travel times could not be measured between 101st Ave and 64th Ave during the non-irrigation dye study. This section of the creek was problematic because it had intermittent flow conditions. For the non-irrigation season, travel time between 101st Ave and 64th Ave was estimated using the velocity observed during the non-irrigation season from 64th Ave to 48th Ave (the nearest studied stream segment).

Table 11. Time of travel - dye study results on Wide Hollow Creek.

Wide Hollow Creek reach description	October 1-2, 2013 Irrigation season		October 23-25, 2013 Non-irrigation season	
	Time of Travel (days)	Average Velocity (m/s)	Time of Travel (days)	Average Velocity (m/s)
101st Avenue to 80th Avenue	0.198	0.137	0.9*	0.008*
80th Avenue to 64th Avenue	0.250	0.120	0.9*	0.008*
64th Avenue to 48th Avenue	0.094	0.220	0.760	0.033
48th Avenue to 28th Avenue	0.115	0.258	0.517	0.057
28th Avenue to 16th Avenue	0.115	0.168	0.444	0.043
16th Avenue to 3rd Avenue	0.135	0.190	0.688	0.037
3rd Avenue to Fines Ditch	0.094	0.212	0.167	0.119
Fines Ditch to White St. (Union Gap)	0.063	0.215	0.125	0.107
Total from 101st Ave to Union Gap	1.06	0.19	4.56	0.06
Gage location	**Oct 1-2, 2013 Average Flow (cfs)**		**Oct 23-25, 2013 Average Flow (cfs)**	
101st Ave gage	6.5		0.2	
40th Ave gage	19.8		0.9	
28th Ave gage	20.3		1.8	
White Street gage	29.2		4.9	

* Due to intermittent streamflow, these travel times could not be measured, and were estimated.

Light extinction surveys

Ambient light entering the water column is reduced in the water column due to water coloration and particles in the water. Insufficient light can limit algal productivity, especially for bottom algae (periphyton) attached to the streambed.

Ambient light intensity at successive depths were measured in the water column in Wide Hollow Creek (Figure 27). Ecology measured light profiles at 64th Ave, 24th Ave, 16th Ave and Fines Diversion. The light extinction coefficient is the slope of the natural log of ambient light intensity in the water versus depth. Water samples were collected at the same time for determination of organic and inorganic suspended solids. Figure 28 shows the relationship between measured slopes (light extinction) and suspended solids (inorganic suspended solids – ISS and organic suspended solids – detritus).

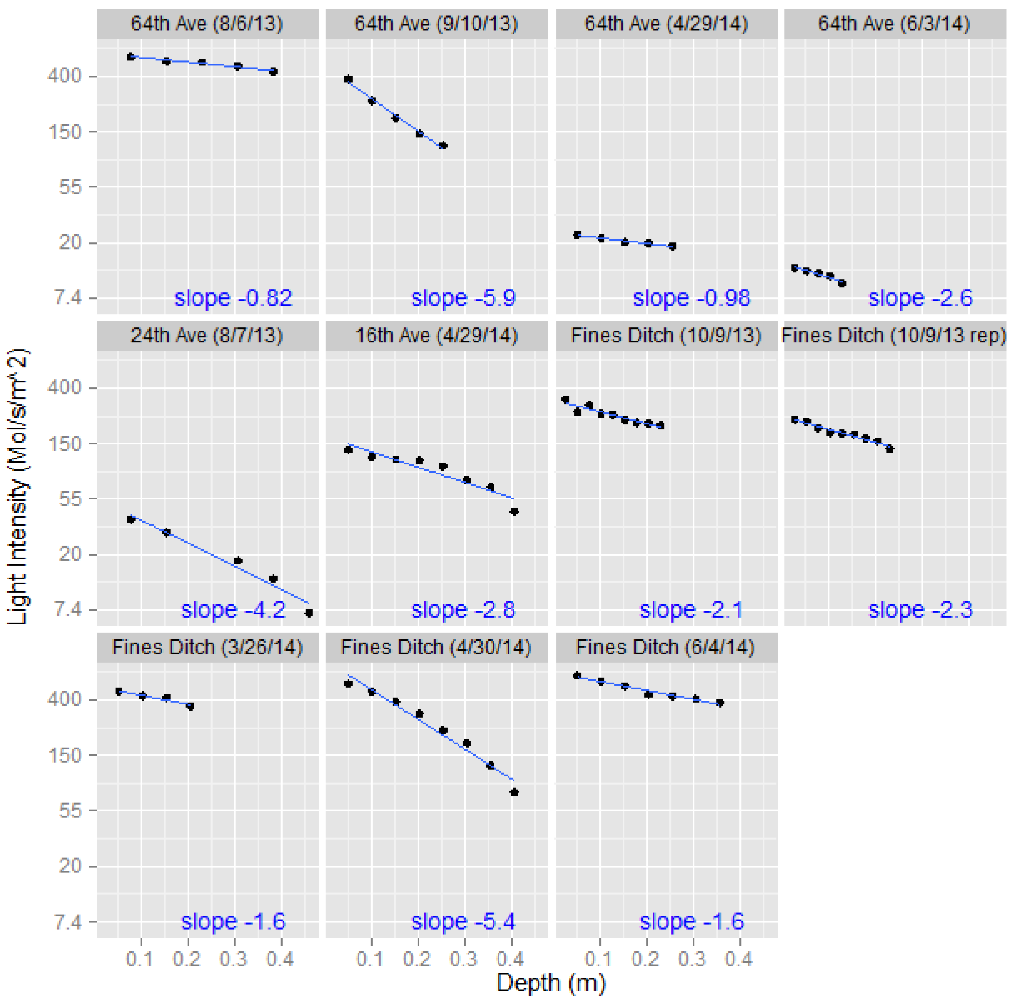


Figure 27. Light extinction survey results on Wide Hollow Creek.

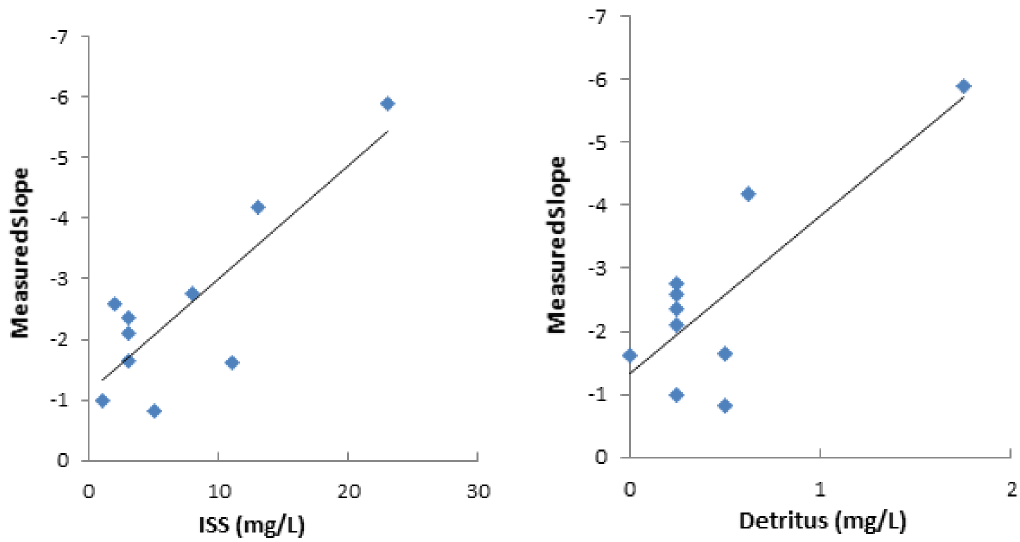


Figure 28. Relationship between measured slopes and detritus and inorganic suspended solids.

Groundwater measurement and water quality results

A groundwater investigation along Wide Hollow Creek was performed using a set of 11 instream piezometers during the period July 2013 to June 2014. Details are provided in Appendix A. The piezometers provided information regarding the location and quantity of groundwater discharged into Wide Hollow Creek. They also provided measurements of water quality of the groundwater prior to discharge into the creek.

The piezometers consisted of one inch galvanized pipes driven to a maximum depth of six feet below the stream bed. The lower end of the piezometers was perforated to allow groundwater to enter the pipe. See Appendix A for details regarding the location, construction, installation, development and sampling of these piezometers.

Ecology measured vertical hydraulic gradients (VHG) at each piezometer to identify locations where groundwater flowed into Wide Hollow Creek. When VHG was positive, groundwater flow into the stream was inferred. When VHG was negative, the loss of water from the stream to groundwater was inferred. Four of the piezometers in Wide Hollow Creek had positive VHG. Measured values of VHG are tabulated in Appendix A.

VHG was calculated as the difference in hydraulic head between groundwater and stream stage, divided by the depth below the stream bed of the piezometer perforation midpoint. To calculate VHG, water levels were measured inside and outside of the piezometer pipe, using the top of the piezometer casing as a common reference point. The measurement inside the pipe represents the hydraulic head of the groundwater and the measurement outside the pipe represents the stream stage.

Hydraulic conductivity of streambed sediment was estimated based on constant head injection tests on the piezometers. This provided one type of evidence to estimate the flux of groundwater recharge. See Appendix A for test results. See the modeling section below for final estimates of groundwater inflow into Wide Hollow Creek.

Quarterly, Ecology collected water quality samples from the four piezometers where groundwater inflow to the creek was inferred based on positive VHG. Water samples were submitted to the laboratory for analysis of alkalinity, chloride, orthophosphate, total phosphorus, nitrate/nitrite, ammonia, total persulfate nitrogen, iron, and dissolved organic carbon analysis. Groundwater temperature, conductivity, pH, and DO were also measured in a continuous flow cell. Result averages for groundwater are summarized Appendix A.

The water quality results from the piezometers are compared to water quality in the creek and various tributary sources in Figure 29. Results are compared for two synoptic samplings: one during irrigation season (Aug 6-7, 2013) and one during non-irrigation season (Mar 4-5, 2014). Average values are indicated on the figure by filled circles and the ranges of values are indicated by vertical bars. Each of the source type categories along the horizontal axes includes multiple sampling locations. Because two of the piezometers were not sampled in August, water quality data from November were used for these piezometers when creating this figure. The November samples seemed representative of the irrigation season based on comparison, even though the irrigation season had ended a few weeks earlier.

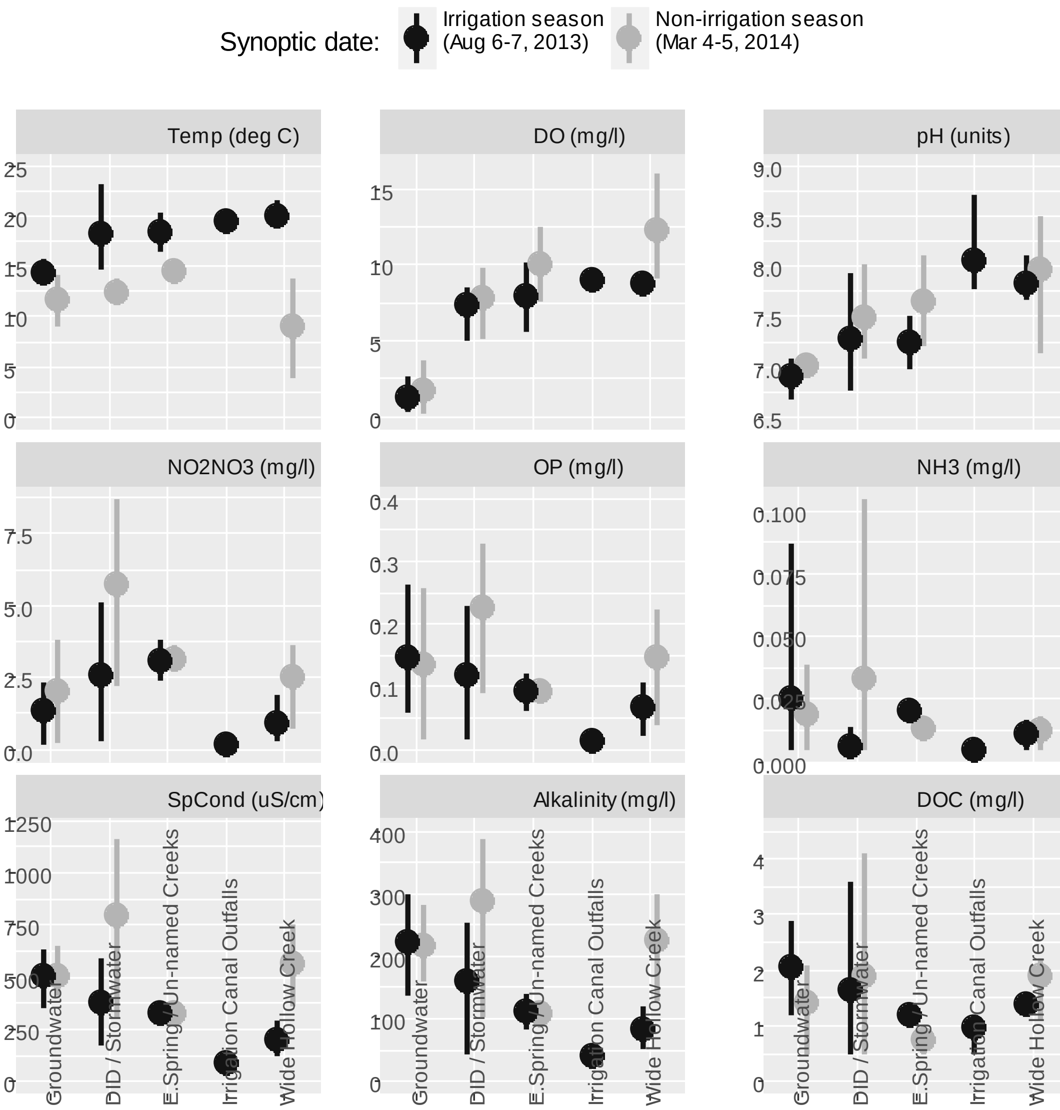


Figure 29. Average and range of nine parameters during two synoptic surveys of Wide Hollow Creek, comparing groundwater, tributary sources to the creek, and water in the creek.

Parameter abbreviations: Temp=temperature, DO=dissolved oxygen, NO2NO3=nitrate/nitrite, OP=orthophosphate, NH3=ammonia, SpCond=specific conductivity, DOC=dissolved organic carbon.

Figure 29 shows that groundwater has distinct differences from each of the other source types during both irrigation and non-irrigation season, discussed below.

Specific conductivity shows a consistent average value of approximately 500 uS/cm in groundwater during both seasons. The closest source type to groundwater is DID/stormwater, which averaged approximately 400 and 800 during irrigation and non-irrigation seasons, respectively. It is possible that groundwater makes up a large fraction of the DID/stormwater, but additional sources of water are required to explain the differences in specific conductivity. East Spring and Un-named Creeks have a groundwater component based on their specific conductivity values.

Based on both specific conductivity and flow measurements, Wide Hollow Creek is primarily composed of groundwater and DID/stormwater during the non-irrigation season. During the irrigation season the creek is primarily composed of irrigation outfall water, which has the lowest specific conductivity of all the source types.

DO and pH of groundwater were lower during both August and March than the other source types. Groundwater had nearly neutral pH (7) and low DO (< 4 mg/L).

Average groundwater temperature was cooler than the creek during August (irrigation season) and warmer than the average creek temperature during March (non-irrigation season). Some, but not all, of the DID/stormwater sources were nearly as cool as groundwater during August, maybe partly as a result of travelling through underground piping. The other source types were all warmer than groundwater during the August synoptic.

The highest average nitrate-nitrite and orthophosphate levels were observed in both groundwater and DID/stormwater. Average values of these nutrients in Wide Hollow Creek are higher during the non-irrigation season due to the absence of irrigation outfall water. Nutrient concentrations are low in irrigation outfall water, which resulted in lower nutrient levels in the creek during the August synoptic.

Biological and habitat assessment

Detailed results of the 2013 assessment of biology and habitat conducted by Ecology's biological monitoring staff are in Appendix B.

During the summer of 2013, five sites on Wide Hollow Creek were sampled according to Ecology standard protocols (Adams, 2010) for habitat, water and sediment chemistry and biological communities (macroinvertebrates, periphyton and fish). Biological communities provide information about environmental conditions based on the range of tolerance to environmental conditions observed by individual taxa. Physical habitat measurements and water and soil chemical samples were taken where biological samples were collected to describe environmental conditions at the time of sampling.

The assessment also compared benthic community metrics and habitat variables to other streams in the Columbia Basin. Other streams in the Columbia Plateau Ecoregion were also assessed in 2013 by Ecology's biological monitoring staff, and were targeted reference sites (Ambient Biological or Sentinel sites). Reference sites are streams with minimal or no impact from human activities. Comparisons were made using various biological community metrics and non-metric multidimensional scaling (NMDS) with Bray-Curtis dissimilarities.

Sediment and water parameters

Twenty four sediment chemistry parameters were measured at the Wide Hollow sites, none of which exceeded the proposed sediment quality values in Washington (Michelsen, 2011).

Water quality parameters taken during the survey provide a "snapshot" of conditions at the time of sampling, but do not incorporate temporal variability in conditions. Water quality of the stream water during the biological monitoring was generally similar to results from the synoptic sampling.

Among the Wide Hollow sites, chlorophyll-a was noted to be highest at the 80th Ave site. The highest chloride and conductivity values were observed at the two most downstream sites (3rd Ave and near the mouth). High turbidity at one of the sites was reported, but this was likely due to the monitoring date for this site, which occurred during high turbidity in the Naches River. The irrigation canals likely brought the turbidity into Wide Hollow Creek from the Naches River.

Macroinvertebrate communities

A total of 98 macroinvertebrate species were observed across the five Wide Hollow sites. No distinct grouping of the sites was identified based on macroinvertebrate communities.

Considerable similarity was indicated in macroinvertebrate communities between Wide Hollow sites versus the other ambient and reference sites within the Columbia Plateau, based on multivariate analysis. However, Wide Hollow sites differed from those other sites in several distinct ways. Wide Hollow sites were associated with:

- lower substrate size
- higher percent sands/fines in the substrate
- more embeddedness of the substrate
- higher concentrations of chloride in the water
- lower Benthic Index of Biotic Integrity (B-IBI) scores
- absence of stoneflies or species classified as pollution sensitive
- lower proportion of mayflies and caddisflies (EPT species)
- higher proportion of non-insect species

Going downstream among the Wide Hollow sites the monitoring found decreasing taxa richness, decreasing mayfly richness, decreasing caddisfly richness and decreasing clinger richness. These observations indicate increasing stress in the downstream direction.

A detailed comparison is not feasible between this bioassessment and the previous one in Wide Hollow Creek (Kendra, 1988), due to considerable differences in sampling techniques and taxonomic resolution. However, one general similarity between the 2013 and the previous bioassessment was the high numbers of non-insect taxa, including amphipods, oligochaetes, and snails.

Periphyton communities

Across the Wide Hollow sites in this bioassessment, a total of 140 species of periphyton were observed. Among the Wide Hollow Creek sites, highest cell density was observed at the furthest downstream and upstream sites (near 80th Ave and the mouth). Diatoms were the most abundant of the observed algal groups at all of the Wide Hollow sites. The highest relative abundance of cyanobacteria was observed at the site near Kissel Park (32nd Ave).

Considerable similarity was indicated in periphyton communities between Wide Hollow sites versus the other ambient and reference sites within the Columbia Plateau, based on multivariate analysis.

No trend from upstream to downstream was observed in ash-free dry biomass. Neither was a general trend observed for taxa richness, although the lowest taxa richness was found near the mouth. A general trend of decreasing evenness was observed from upstream to downstream, indicating that composition was dominated by fewer, yet abundant species. An increasing trend in the percent of taxa associated with rich nutrient supply was noted. The furthest downstream site had the highest percent of taxa classified as tolerant to brackish conditions.

Electrofishing survey

Backpack electro-fishing was used to detect the presence and relative abundance of fish species in Wide Hollow Creek. Across all Wide Hollow Creek sites, 13 species of fish were captured. The most abundant species were speckled dace and redside shiners, which were captured at all sites. Several species of salmonids were observed across the Wide Hollow sites sampled, with the most salmonids found at the farthest downstream site (in the East Spring Creek portion).

However, the reaches near Kissel Park and 3rd Ave were also supporting a few rainbow trout. WDFW stated that the rainbow trout may be remnant populations of the rainbow released into Wide Hollow by the now-closed Yakima Fish Hatchery (Harvester, 2013).

The numbers of 2013 fish were compared to those collected by Kendra (1987). Similar to the 2013 bioassessment, dace and shiners were the most abundant species in the 1987 assessment as well. In contrast to the 2013 bioassessment, only one rainbow trout was found in the 1987 assessment.

In 2013 the site above 80th Ave was sampled twice, one of which occurred after the end of irrigation season. As mentioned earlier, the reach from 80th Ave. to 64th Ave. went dry immediately following the end of the irrigation season, isolating the fish population between 101st Ave and just above 80th Ave, a disconnected reach watered only by a small groundwater seep. A lone Chinook salmon was found during this second sampling, in a pool above 80th, of a size class believed to be released annually by a junior high school salmon-release program.

WDFW should be consulted to see if construction of a fish blockage below 64th Ave is warranted to eliminate salmonid migration into upstream reaches that go dry. Other portions of Wide Hollow Creek that are dominated by anthropogenic channel routing and hydrology should also be considered as candidates for fish screens (e.g. Fines Ditch). Haring (2001) also made this recommendation in the conclusions of his Salmonid Habitat Limiting Factors analysis for Wide Hollow Creek.

Field study summary

Summarized findings of the Ecology field study include:

- FLOW: This study provided a comprehensive view of all sources of flow to Wide Hollow Creek. These include a variety of sources which feed the creek including irrigation canal outfalls, drainage improvement districts, stormwater, groundwater, and East Spring Creek. This study focused on providing a complete water balance so all source constituents could be accounted for in this creek.
    - The 2013-14 study year had a drier winter than usual, but the irrigation season flow was normal.
    - Wide Hollow Creek received excess irrigation water flow during the irrigation season. It also drained excess groundwater from DIDs.
    - During non-irrigation season, Wide Hollow Creek had perennial flow only from 64th Ave downstream. The perennial flow was due to continuous groundwater inflow beginning near 64th Ave and contributions from DIDs downstream.
    - Water travelled fast in Wide Hollow Creek during the irrigation season. Irrigation water spent about a day running down the creek. During non-irrigation, groundwater in the creek spent almost 5 days running down the creek.
- TEMPERATURE: This study provided a comprehensive review of water temperature in Wide Hollow Creek for an entire year.
    - The summer of 2013 was hot and dry, with above average air temperature, and the winter was drier than normal. Water temperatures in Wide Hollow Creek were above water quality criteria in July-Aug 2013 and June 2014.
    - Most of Wide Hollow Creek was well shaded by trees and shrubs during the growing season, preventing the creek from having even higher water temperature.
- NUTRIENTS: Most of the dissolved inorganic nitrogen (DIN) and phosphorus (SRP), forms available to be taken up and used by algae and aquatic plants, originated from within the Wide Hollow watershed via groundwater inflows and DID contributions. Out of basin irrigation water had comparatively lower nutrient levels, despite providing most of the flow during the irrigation season. Regardless of source, the levels of nutrients were too high to be considered limiting for algal growth in most of the creek.
- DO and pH: Continuous DO and pH were measured at three locations in Wide Hollow Creek. Overall, DO and pH levels at these locations were influenced by the source waters to the creek, as well as instream algal productivity.

Wide Hollow Creek had under-saturated low DO and pH levels during the non-irrigation season when groundwater (with low DO and pH levels) dominated as the source water to the creek. During the irrigation season, out-of-basin irrigation water introduced higher DO and pH levels to the creek.

Varying levels of algal productivity caused hourly DO and pH levels to fluctuate each day, with daily maximum DO and pH levels occurring during the afternoon, and daily minimums occurring during the late evening or early morning. The magnitude of this diel swing was the greatest at the White Street gage, indicating a higher level of algal productivity at this location, also the location with the most light due to less riparian vegetation.

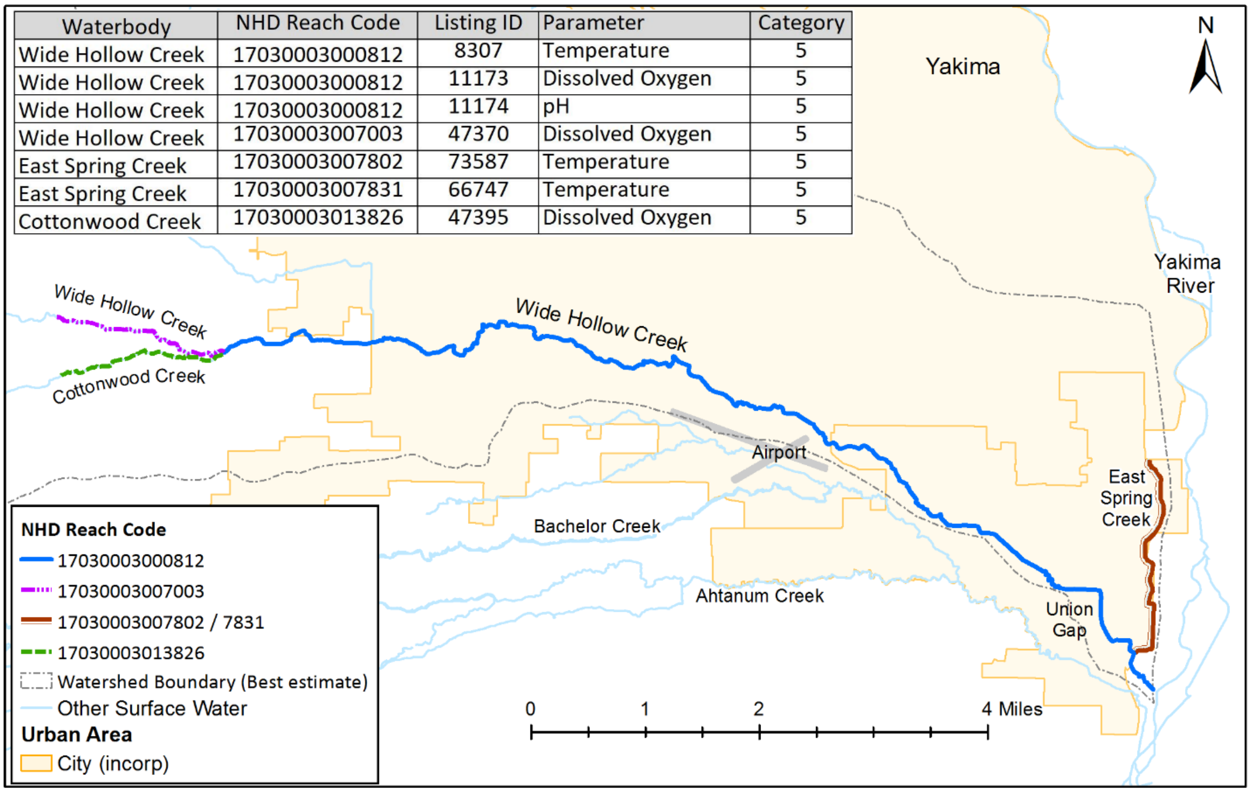
- Potential DO levels (based on reaching DO saturation) would have met the DO water quality criterion, despite seasonally high water temperature. Potential pH levels (based on reaching pH saturation) also would have met pH water quality criteria, except during the non-irrigation season when highly-alkaline groundwater dominated in the creek.
- ALGAL PRODUCTIVITY: Algal productivity can be limited by cold water temperature, low nutrients, or low light. The data collected during this study supports the conclusion that algal productivity in Wide Hollow Creek was most limited by light due to riparian shade. During parts of the year, algal productivity in the creek was additionally light-limited because of inorganic suspended solids in the water, much of which originated in the imported Naches River irrigation water. Nutrient levels and water temperature were not limiting during the study.
- BIOLOGY / HABITAT: Five sites in Wide Hollow Creek sites were compared to other streams in the Columbia Basin plateau, some of which were considered reference sites (with less human impacts). In general, Wide Hollow Creek sites had higher percent sands/fines in the substrate, more embeddedness of the substrate, lower Benthic Index of Biotic Integrity (B-IBI) scores, an absence of stoneflies or species classified as pollution sensitive and a higher proportion of non-insect species.
- FISH SURVEY: The fish caught in the 2013 Ecology fish survey in Wide Hollow Creek were similar to what were caught in the 1987 Ecology fish survey. Primarily, the creek supports warm-water cyprinid fish. A few rainbow trout were also found, apparently indicating satisfactory habitat for their survival. Most of the salmonids caught were in the East Spring Creek part of Wide Hollow Creek, which was a historical spring branch tributary to the Yakima River, through which Wide Hollow Creek is now routed.

Assessment of 303(d) listings based on observed field measurements from study

The locations for the 2012 303(d) listings for water temperature, DO and pH in the Wide Hollow Creek basin (Table 3) have been consolidated into common assessment units for the 2014 303(d) list as shown in Figure 30. Based on the measurements that Ecology made from July 2013 through June 2014, this study recommends the following in regards to each new assessment unit:

- The DO listings in Wide Hollow Creek and Cottonwood Creek above Dazet Road (where Cottonwood Creek and Wide Hollow Creek join): These were dry during the study year; therefore, Ecology was unable to confirm any DO excursions; however, these reaches are intermittent year-to-year, and historically were intermittent as well, as drawn on the 1899 USGS map. These reaches may have had perennial flow before the Yakima-Tieton Irrigation District pressurized their system, but they are again intermittent now, appearing to run only during snowmelt spring freshets in some years, and remaining dry for the rest of the year. These branches do not have the perennial flow to support the beneficial use of salmonid spawning, rearing, and migration, therefore, this study recommends that the DO listing for these reaches be removed from the 303(d) list.

- The water temperature, DO, pH listings in Wide Hollow Creek from 101st Ave to the mouth were confirmed to be valid. Figure 31 shows the time periods during the Ecology study period when daily temperature observations were above temperature criteria, pH observations above criteria and DO observation below the minimum DO criterion.
    - Water temperature exceeded criteria for the last half of June, all of July and August, and the first half of September.
    - DO levels were below the 8.0 mg/L criterion in the morning hours for parts of Wide Hollow from July to September, and all of Wide Hollow in the non-irrigation season (mid-Oct to mid-March) when low DO from groundwater predominated in the creek.
    - pH levels were usually within pH criteria throughout Wide Hollow Creek during the study year, except in the spring of 2014 when levels exceeded the 8.5 maximum criterion during a spring algal bloom. Most of the high pH measurements were from the 101st Ave gage, reflecting the pH of water discharged from the Yakima Valley Canal.
- For East Spring Creek, the temperature listing was confirmed during the Ecology study period. Figure 32 shows the time periods when observed 7-DADMax temperature went above the temperature criterion. The temperature datalogger was lost during the study so continuous data was only collected from July through October 2013. Additionally, Figure 32 shows observed pH and DO measurements meeting the criteria during the study; however, DO measurements were instantaneous measurements made in the afternoon when DO levels were highest from photosynthesis, so the daily minimum DO levels are not known. Based on the known field measurements from the study, East Spring Creek should not be listed for pH and DO.
- There were many sources of flow to Wide Hollow Creek during the study period. Some of them did not meet Wide Hollow Creek's numeric criteria for temperature, DO and pH, and therefore were not supportive in helping Wide Hollow Creek attain the water quality standards for aquatic life. Table 12 lists the sources to the creek and whether their discharge for temperature, DO and pH did or did not meet the numeric criteria for different periods of the study.



Waterbody	NHD Reach Code	Listing ID	Parameter	Category
Wide Hollow Creek	17030003000812	8307	Temperature	5
Wide Hollow Creek	17030003000812	11173	Dissolved Oxygen	5
Wide Hollow Creek	17030003000812	11174	pH	5
Wide Hollow Creek	17030003007003	47370	Dissolved Oxygen	5
East Spring Creek	17030003007802	73587	Temperature	5
East Spring Creek	17030003007831	66747	Temperature	5
Cottonwood Creek	17030003013826	47395	Dissolved Oxygen	5

Figure 30. Current (2019) 303(d) Category 5 listings and associated assessment units.

Four assessment units are shown in Figure 30: Wide Hollow Creek upstream of the Yakima Valley Canal, Wide Hollow Creek, Cottonwood Creek, and East Spring Creek. Assessment units are identified by NHD Reach Codes.

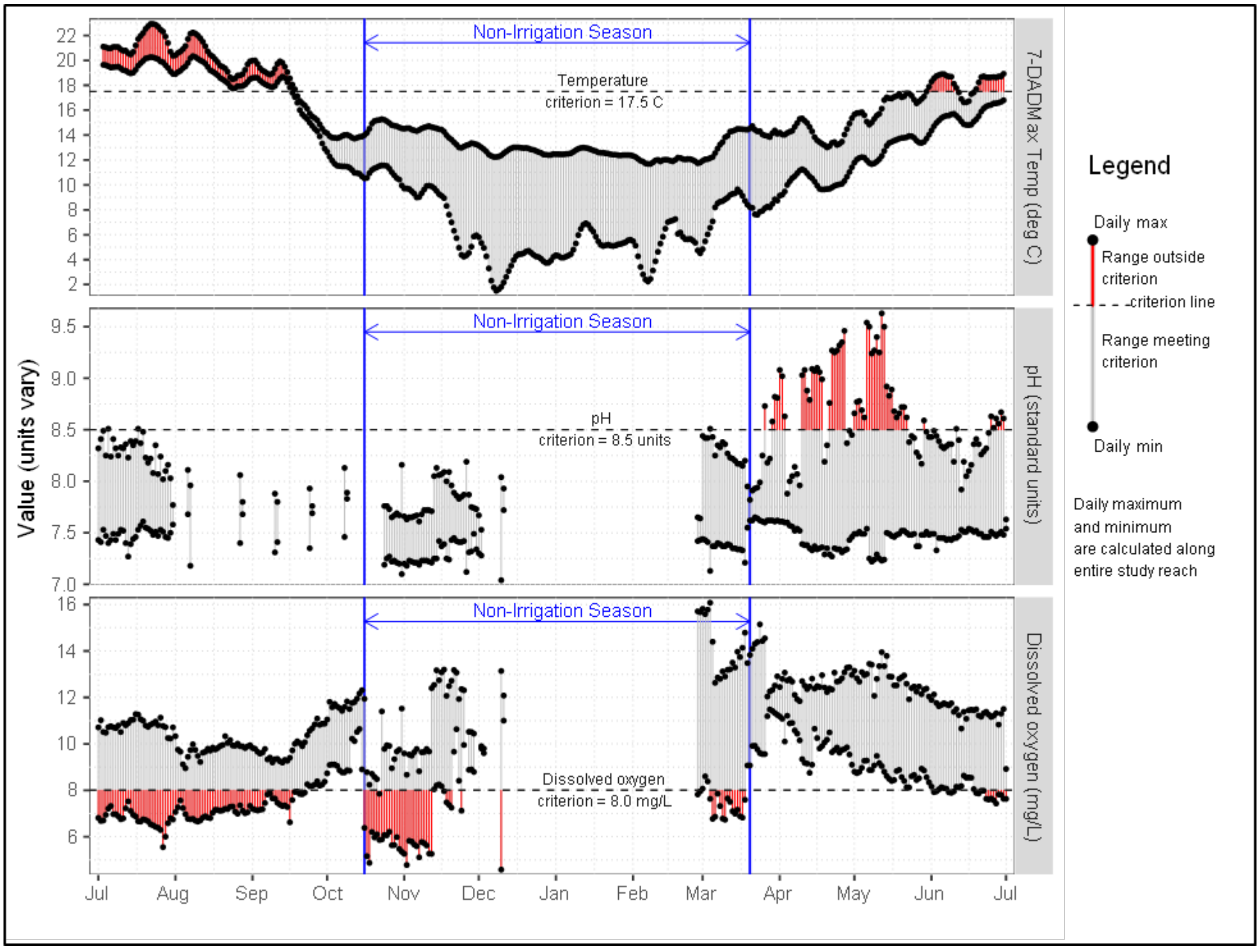


Figure 31. Summary of daily observation of 7-DADMax water temperature, dissolved oxygen, and pH measurements in Wide Hollow Creek during Ecology study year compared to respective water quality criteria.

7-DADMax temperature depicted in this figure represents daily ranges of the 7-DADMax temperatures of all temperature dataloggers in Wide Hollow Creek from 101st Ave. to the mouth. The highest 7-DADMax temperature amongst all dataloggers was recorded during late July, 2013. DO and pH depicted represent combined daily (diel) ranges recorded at the three water quality gage stations (101st Ave, 40th Ave, and White St.). The lowest DO measurements were recorded in Oct-Dec 2013. The highest daily values of pH were recorded during spring 2014.

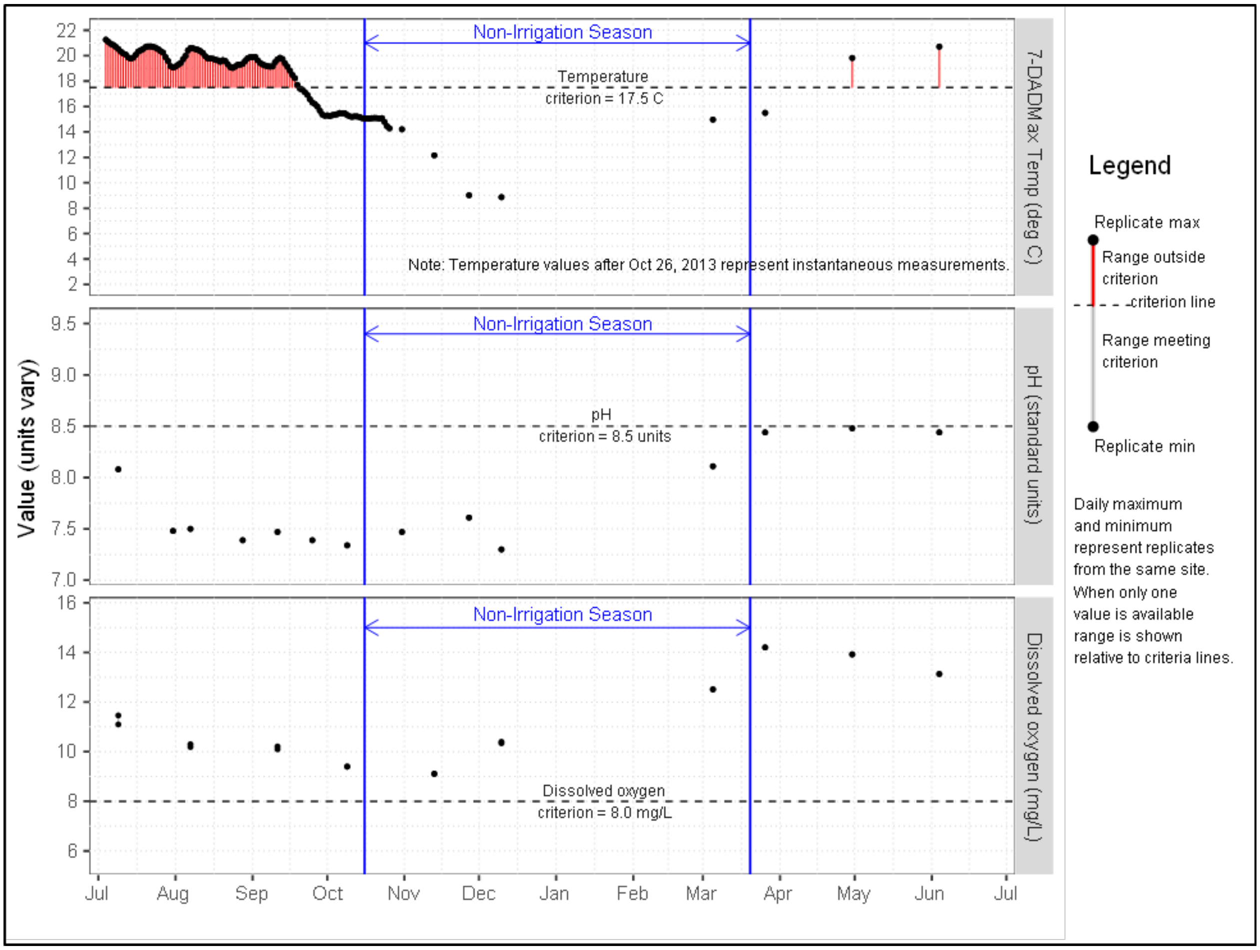


Figure 32. Summary of daily observation of water temperature, dissolved oxygen, and pH measurements in East Spring Creek during Ecology study year compared to respective water quality criteria.

7-DADMax temperature was not calculable after November 2013 because the temperature datalogger was lost in East Spring Creek. Instantaneous measurements are plotted during the lost time period. East Spring Creek was measured by instantaneous readings only once during each 2-day synoptic survey and the readings do not reflect the full diel range of temperature, DO and pH that East Spring Creek may exhibit. In general, measurements were made around mid-afternoon on day 2 of each synoptic, and should have reflected higher temperature, DO, and pH levels expected during the day.

Table 12. Tabulation of minimum dissolved oxygen, minimum and maximum pH, and 7-DADMax or maximum temperature from measurements of Wide Hollow Creek sources during the Ecology study period.

Location ID	Short Name	Site Description	DO (mini-mum)	pH (mini-mum)	pH (maxi-mum)	Temperature(highest 7-DADMax)
37-IS-16	Yak Valley Canal	Yakima Valley Canal discharge to Wide Hollow Creek near 101st Ave	8.77	7.67	8.34	19.6*
37-SS-48	DID #48	DID #48 outfall at 64th Ave	8.67	7.41	8.11	21.4
37-SS-38	DID #38	DID #38 outfall at 64th Ave	7.76	6.87	8.26	20.2
37-IS-33	Congdon	Congdon Orchards discharge to Wide Hollow Creek	8.41	7.1	8.46	20.1*
37-SS-11B	Randall Pipe	Pipe outflow discharge to Wide Hollow Creek 300 ft. downstream of 48th Ave	5.13	6.8	7.09	11.7*
37-IS-17.5	Randall Pond	Randall Park Pond outlet on 44th Ave	4.56	7.2	8.49	31.2
37-IS-17	DID #40	DID #40 outfall at 38th Ave and Logan Ave	7.87	7.59	8.1	20.2
37-IS-20B	NC Canal at 32nd	Naches and Cowiche Canal discharge near 32nd Ave	8.7	7.51	8.72	22.2
37-IS-20A	NC Canal at 12th	Naches and Cowiche Canal discharge near 12th Ave	9.17	7.52	8.33	22.2
37-IS-26	SW Yakima 12th	City of Yakima stormwater outfall at 12th Ave bridge (NE corner)	8.51	7.77	8.29	20.7*
37-IS-15	DID #4	DID #4 outfall at Colonial Nursery	7.66	7.62	8.07	17.6*
37-IS-23	Spring Ck Irrig	Spring Creek Irrigation District inflow	7.55	7.49	8.92	20.2
37-IS-13	DID #24 L2	DID #24 outfall L2 near Pioneer Ln and Cornell Ave	6.33	6.89	7.35	15.5
37-SS-6	SW Yakima 3rd	City of Yakima stormwater outfall at 3rd Ave	7.84	8.03	8.14	22.3*
37-IS-12C	DID #24 at 3rd	DID #24 outfall L1 at 3rd Ave	3.84	6.98	7.25	15.5*
37-IS-22	SW Union Gap	Union Gap stormwater outfall (E5-41) under Ahtanum bridge	7.76	6.91	8.88	24.4*
37-IS-21	SW Yakima RR	City of Yakima stormwater outfall at RR tracks	4.59	6.77	7.23	18.2*
37-FW-2B	Un-named Creek	Un-named creek behind Union Gap Mill	4.27	6.95	7.45	17.4
37-FW-2	East Spring Creek	East Spring (Chambers) Creek behind Union Gap Public Works	9.1	7.3	8.48	21.3

*Highest instantaneous grab sample from synoptic survey; *not* 7-DADMax temperature

Shaded values do not meet water quality criteria. 7-DADMax temperature was not calculable at some sites because they did not have temperature dataloggers, in which case the highest instantaneous measurement is tabulated. Sources without continuous data were measured by instantaneous readings only once during the 2-day synoptic survey and do not reflect the full diel range of temperature, DO and pH that the source water may exhibit. In general, measurements were made between 8:00am to 3:00pm in a downstream manner starting with 101st Ave in the morning of day 1 and the Naches-Cowiche irrigation discharge at 32nd on day 2.

Streamflow and Water Quality Simulation

Overview

Ecology's field monitoring and sampling were designed to collect an environmental dataset of sufficient resolution and quality to develop and calibrate a water quality model for Wide Hollow Creek. As discussed above, field data collection occurred from July 2013 through June 2014 and included a variety of continuous time series measurements and synoptic sampling events. Data collection was suspended during winter (mid Dec 2013 - Feb 2014) when freezing weather prohibited electronic gaging and water quality measurements.

The water quality model discussed below was used to continuously simulate streamflow, temperature, DO, pH and other water quality parameters in the creek under dynamic flow conditions over the course of one year (July 2013 through June 2014). The model was calibrated to improve the match between simulated and observed values.

After the model was calibrated to observed field data, the model's mass balance was used to:

- Calculate the relative contribution of different sources of constituents for the current water quality conditions.
- Evaluate water quality responses to scenarios that may represent potential watershed management decisions for Wide Hollow Creek.

Modeling framework

Four specialized software tools (listed below) were used to create a streamflow and water quality model for Wide Hollow Creek.

Ttools

Ecology used the Oregon Department of Environmental Quality (ODEQ) and Ecology's TTools extension for ArcMap (Ecology, 2015) to sample and process GIS data for input into the QUAL2Kw model. Ttools was used to segment the creek into 500 meter reach intervals, to calculate slope for these reaches, and to sample vegetation types adjacent to the creek.

Reach segments were based on the creek position in 2013 NAIP aerial photography. Slopes for these reaches were calculated using a 10 meter digital elevation model (DEM).

Vegetation types were sampled from an Ecology GIS analysis which assigned vegetation codes to polygons within a 150 meter wide buffer across the creek (75 m on either side).

Shade.xls

Ecology used the Shade.xls model (Pelletier, 2015) to calculate effective shade along the creek. Effective shade is defined as the fraction of incoming solar shortwave radiation above the vegetation and topography that is blocked from reaching the surface of the stream.

Shade values were calculated every hour at 100-meter intervals along the streams and then averaged to 500-meter intervals for input to the QUAL2Kw model. The Shade model was adapted from a program originally developed by the ODEQ as part of the HeatSource model. The Shade model uses mathematical simulations to quantify potential daily solar load and generate percent effective shade values.

Vegetation shade was calculated based on assigning vegetation codes to polygons in GIS, which were sampled using Ttools. Topographic shade was calculated by sampling a 10 meter digital elevation model (DEM) using Ttools software.

QUAL2Kw

Ecology used a numerical model, QUAL2Kw version 6.0 (Pelletier and Chapra, 2008; Chapra et al., 2008) to simulate streamflow and water quality. This is a finite difference model which uses a kinematic wave method for dynamic flow routing. The kinematic wave equation is used to drive advective transport through free-flowing segments and to calculate flow, volumes, depths, and velocities resulting from variable upstream inflow. In addition, the QUAL2Kw framework allows input of continuous changes in boundary loads and meteorology. Among other inputs, this model uses the effective shade calculated by Shade.xls.

The QUAL2Kw 6.0 modeling framework was used to simulate temperature, algal productivity and to make predictions about water quality under various scenarios. The QUAL2Kw model framework and complete documentation are available at http://www.ecy.wa.gov/programs/eap/models.html.

The QUAL2Kw 6.0 modeling framework has the following characteristics:

- One dimensional. The channel is well-mixed vertically and laterally.
- Non-steady, non-uniform flow using kinematic wave flow routing. Continuous simulation with time-varying boundary conditions for periods of up to one year.
- Dynamic heat budget. The heat budget and temperature are simulated as a function of meteorology on a continuously varying or repeating diel time scale.
- Dynamic water-quality kinetics. All water quality state variables are simulated on a continuously varying or repeating diel time scale for biogeochemical processes.
- Heat and mass inputs. Point and nonpoint loads and abstractions are simulated.
- Bottom algae in the stream bottom, as well as sediment diagenesis are simulated.
- Variable stoichiometry. Luxury uptake of nutrients by the bottom algae (periphyton) is simulated with variable stoichiometry of N and P.

The updated (kinematic wave) version of QUAL2Kw was selected for Wide Hollow Creek because it was considered necessary to simulate continuous changes in flow, temperature, nutrients, biomass, and pH over an entire growing season, including representation of diel variations.

QUAL2Kw model setup

Spatial layout

Figure 33 (top portion) is a schematic showing the model setup, including the segmentation scheme used in the model. The first step in building the model was to digitize the centerline of the creek in GIS (ArcMap version 10.2.2) using 2013 aerial photography from the U.S. Dept. of Agriculture's National Agriculture Imagery Program (NAIP). The centerline was then segmented into 500 meter reaches using Ttools software extension for ArcMap. Total model length was 11.4 miles (18.4 km), composed of 36 reaches. The model simulates values for each reach.

Except during storm and snow-melting events, little flow is expected to enter the creek from the upper watershed. This affected the choice of where to place the first node of the model, which is referred to as the *model headwater* in this report.

Figure 33 (bottom portion) shows a detail of the model headwater location. The model headwater was placed downstream of Dazet Road because Wide Hollow Creek and Cottonwood Creek were always observed to be dry at Dazet Road during field work throughout the entire study period. QUAL2Kw does not allow inclusion of dry creek beds in the model. Ecology notes that no flow observations were made above Dazet Road during the sampling hiatus (mid-December until early March). It is unknown if any flow occurred above Dazet Road during this hiatus.

The model headwater lies approximately 100 meters upstream of the Yakima Valley Canal discharge into Wide Hollow Creek near 101st Ave. It lies just downstream of the confluence of Cottonwood and Wide Hollow Creeks. A marshy area exists between Dazet Road and the Yakima Valley Canal. Groundwater seeped out of this marshy area as a small perennial flow, which represents the headwater flow for the model. This flow represents background conditions in Wide Hollow Creek prior to the first major irrigation discharge into the creek from the Yakima Valley Canal.

During the non-irrigation season (mid-October to mid-March), the uppermost section of the model (between the model headwater and 64th Ave) was not interpreted as meaningful. This section is approximately 4 km long and represents a seasonally intermittent section of the creek. This is because intermittent flow conditions (disconnected pools of water) were observed here several times during the non-irrigation season. Because QUAL2Kw does not allow zero flow conditions, a minimal amount (0.07 cfs) of non-irrigation season flow was assigned in the model to this portion of the creek. This allowed Ecology to use a single model year-round, instead of creating separate models for irrigation and non-irrigation seasons.

Model schematic

All sources and diversions which were included in the model are shown as a schematic diagram in Figure 34, along with monitoring locations for both surface water and groundwater. Point sources are shown along the left side of the figure. Surface water monitoring and piezometer locations are shown in the central portion of the figure. Withdrawal diversions are shown along the right side. Point sources which operated only during irrigation season are distinguished in this figure by placing the source name in parentheses.

The location of nonpoint sources (groundwater) are shown by blue shading in the central portion of the schematic. Spatial areas of groundwater gain from Figure 34 could only be estimated using available data, as discussed in the section below on groundwater gains/Losses.

Anthropogenic point sources and diversions have a strong influence on streamflow in Wide Hollow Creek. During irrigation season, point sources to the creek provide the bulk of flow in the creek. During non-irrigation season, flow in the creek is impacted by flow from DID and stormwater drains.

Because of this difference between irrigation and non-irrigation season, the following sub-sections detail the sources and diversions used in the model according to the following categories:

- Year-round point sources and diversions
- Irrigation season only point sources and diversions
- Point sources which were dry during the study year
- Groundwater gains and losses (nonpoint sources and diversions)

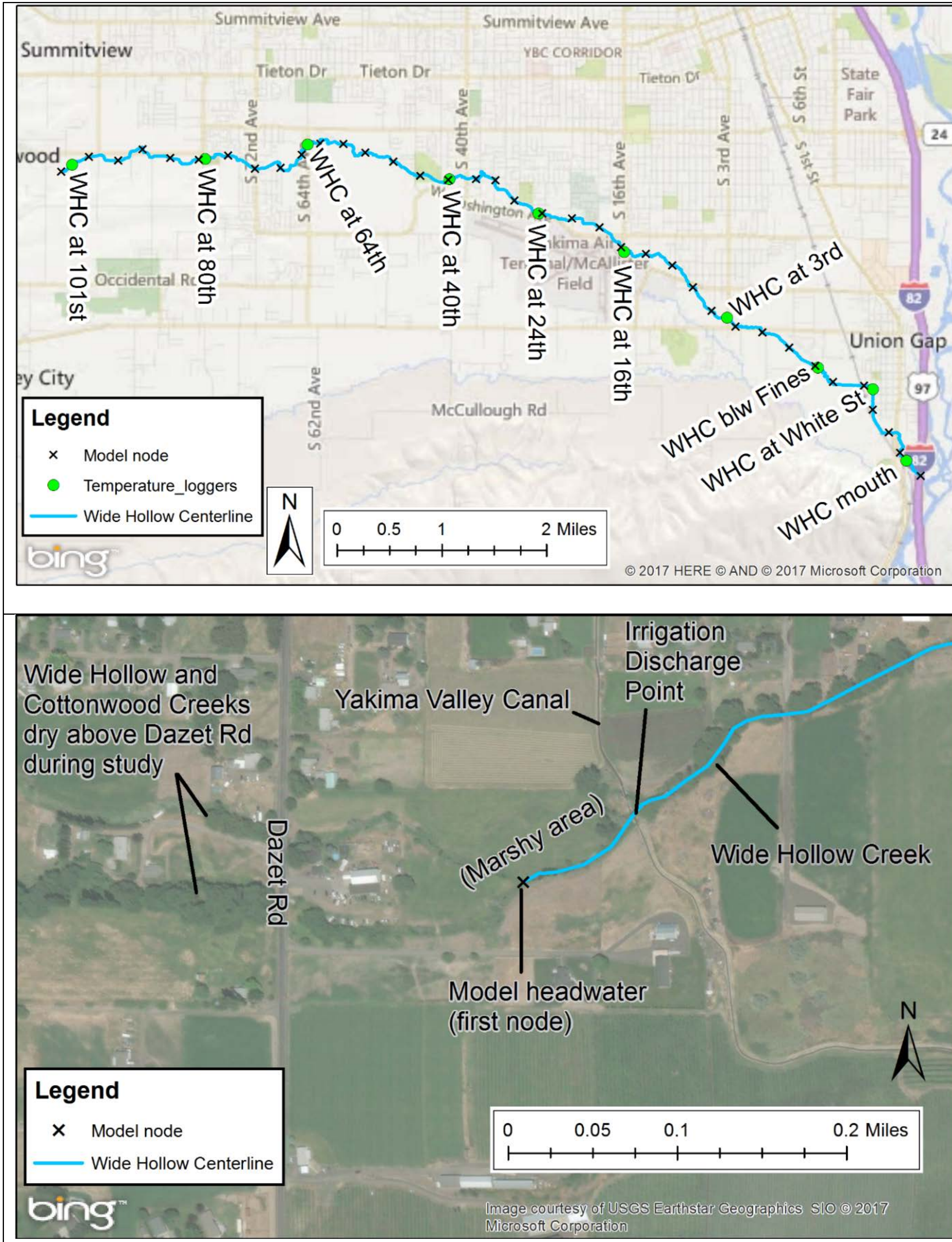


Figure 33. Model segmentation and temperature logger locations (top). Model headwater detail (bottom).

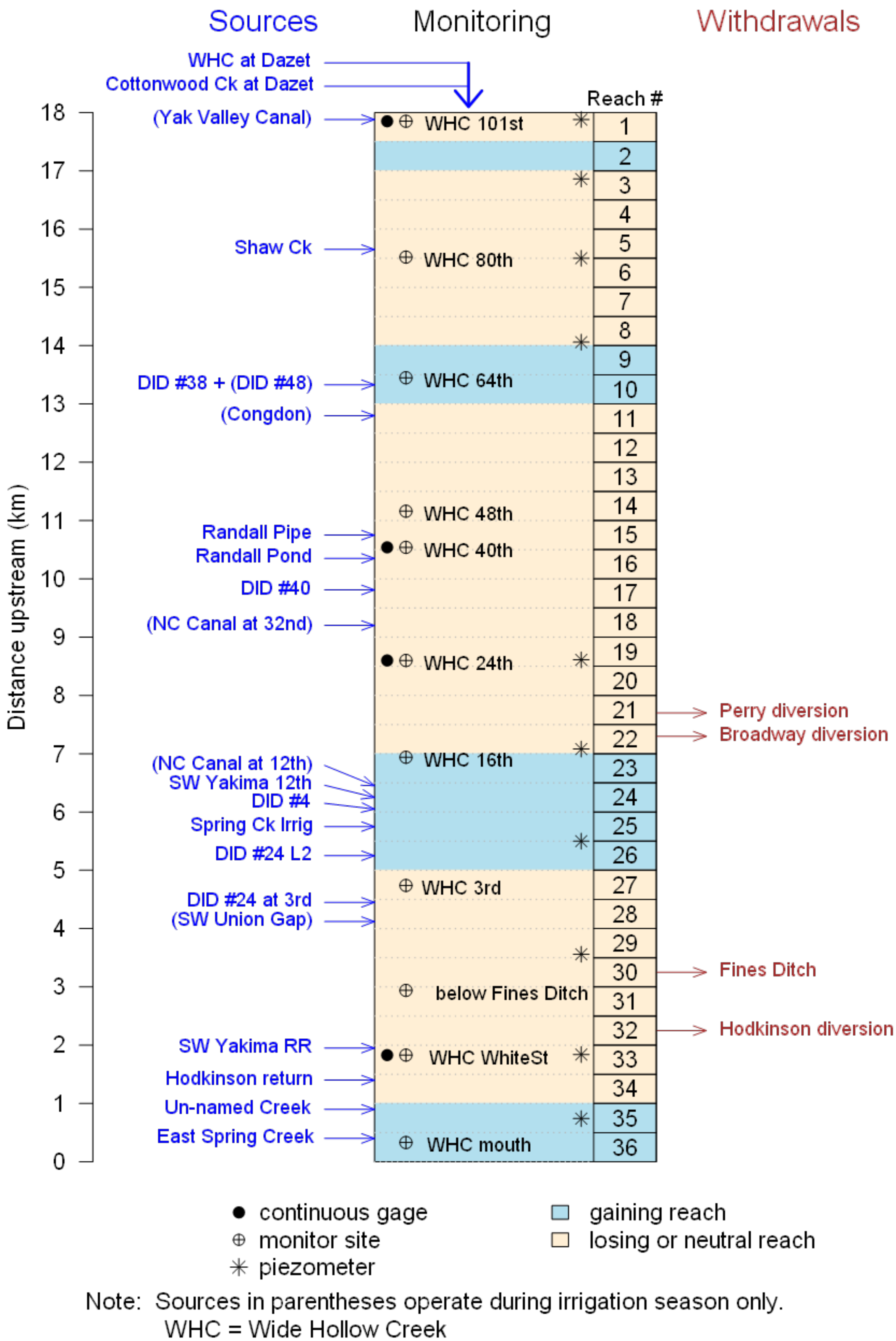


Figure 34. Schematic of QUAL2KW model set up of Wide Hollow Creek.

Year-round point sources and diversions

Table 13 lists all known point sources which contributed flow year-round to Wide Hollow Creek.

These sources are especially important during the non-irrigation portion of the study period (late-October through mid-March). The non-irrigation portion of the study was used for identifying ground-water gains and losses to the creek for the following reasons:

- Low flow in the system during baseflow
- No rapidly fluctuating irrigation inputs to the creek
- During cold periods, warming from groundwater entering the creek was identifiable

Flow from these point sources during the non-irrigation season was therefore important to this study. Measured flow during the non-irrigation season (late Oct to early Mar) is graphed in Figure 35. With the exception of East Spring Creek, most flows are less than 1-2 cfs. For modeling input, linear interpolation between measurements was used to generate hourly time series. Most of these sources were relatively constant during the non-irrigation season. Monitoring of these sources occurred at least monthly, except during the winter (mid-Dec through Feb).

The largest point source during the non-irrigation season was East Spring Creek. This was a natural spring creek that shows up on the 1860s GLO maps as a historical tributary to the Yakima River.

A large diversion withdrawal from Wide Hollow Creek occurred year-round at Fines Ditch, including during non-irrigation season. A flow gage was installed in Fines Ditch to monitor this withdrawal. Unfortunately, the location was ineffective due to the irrigation controls in the ditch which changed water stage in the ditch in an unpredictable manner, which resulted in stage (water depth) not correlating to field measured flow.

Because of issues with this flow gage location, withdrawals at Fines Ditch were instead based on residual model flow at the White Street flow gage. In other words, excess flow in the preliminary model (when compared to observed flow in Wide Hollow Creek at the White St gage) was interpreted to be due to withdrawals at Fines Ditch, and included as such in the final model.

Table 13. Year-round point sources and diversions to Wide Hollow Creek.

Source / diversion	Variability	Note
DID #38	consistent	See note below on DIDs.
Pipe at Randall Park	consistent	Source of water unknown.
Randall Park Pond outlet	consistent	Pond is fed by trunk of DID #48.
DID #40	consistent	See note below on DIDs.
DID #4	consistent	End of the pipe was completely submerged during irrigation season due to water level in creek. See note below on DIDs.
DID #24 L2	consistent	End of the pipe was completely submerged during irrigation season due to water level in creek. Sampled during irrigation season from manhole access on South Cornell Ave, sampled at end of pipe during non-irrigation season. See note below on DIDs.
SW Yakima 12th	consistent	Southwest corner of bridge
Spring Creek Irrigation District	variable	The ad hoc irrigation district diverts water from Spring Creek near the south end of the airport and conveys water along a ditch to Pioneer Rd. At Pioneer Rd. the water enters an underground pipe with laterals running south. Left-over flow in the pipe discharges into Wide Hollow Creek at multiple locations. Flow was measured at the pipe orifice. Sometimes the diversion ditch was dry and sometimes it was full. This source represents one of the more uncertain components of the water budget, although the highest flow measured during non-irrigation season never represented more than 7% of the total flow in the creek.
DID #24 at 3rd Ave	consistent	See note below on DIDs. This pipe was not submerged in creek.
Fines Ditch diversion	variable	A debris dam across Wide Hollow just downstream of the diversion raises the water head in order to divert water from the creek into the Fines Ditch. An attempt was made to gage the streamflow in Fines Ditch but continual changes in control points (i.e., flash board changes and debris dam modifications) made the rating impossible. The diversion flow was therefore calculated to match measured flow at White Street.
Stormwater outfall - Railroad tracks (City of Yakima)	consistent	End of pipe submerged in creek during irrigation season, sampled from a manhole access approximately 1500 ft upstream along railroad tracks. Sampled at end of pipe during non-irrigation season.
Hodkinson diversion + return	consistent	Water from the creek diverted to a pasture or to a barn to service animals and then returned to the creek several hundred feet downstream.
Un-named creek - Union Gap below fish ladder	consistent	The flow is composed of groundwater upwelling in the lower flood terrace of the Yakima River, but primarily is a terminus for a groundwater drain that runs under Washington St and Main St in Union Gap. This seepage ditch would run whether or not Wide Hollow Creek was diverted through Union Gap.
East Spring Creek (Chambers Creek)	consistent	The spring creek lies in a lower flood terrace of the Yakima River and is fed from naturally upwelling groundwater. The spring creek is also the terminus of a groundwater drain that runs under Ahtanum Rd. During the irrigation season, irrigation water also appears to enter the creek, maybe from the end of the Old Union Canal. East Spring (Chambers) Creek was located and mapped during the 1860s public land survey and is the true historical tributary to the Yakima River in this lower terrace location. East Spring Creek is now considered a tributary of Wide Hollow Creek after Wide Hollow was re-routed to Union Gap to supply water for the historical millworks.

Note: Drainage improvement districts (DIDs) are a network of curtain drains designed to intercept high groundwater in the soil.

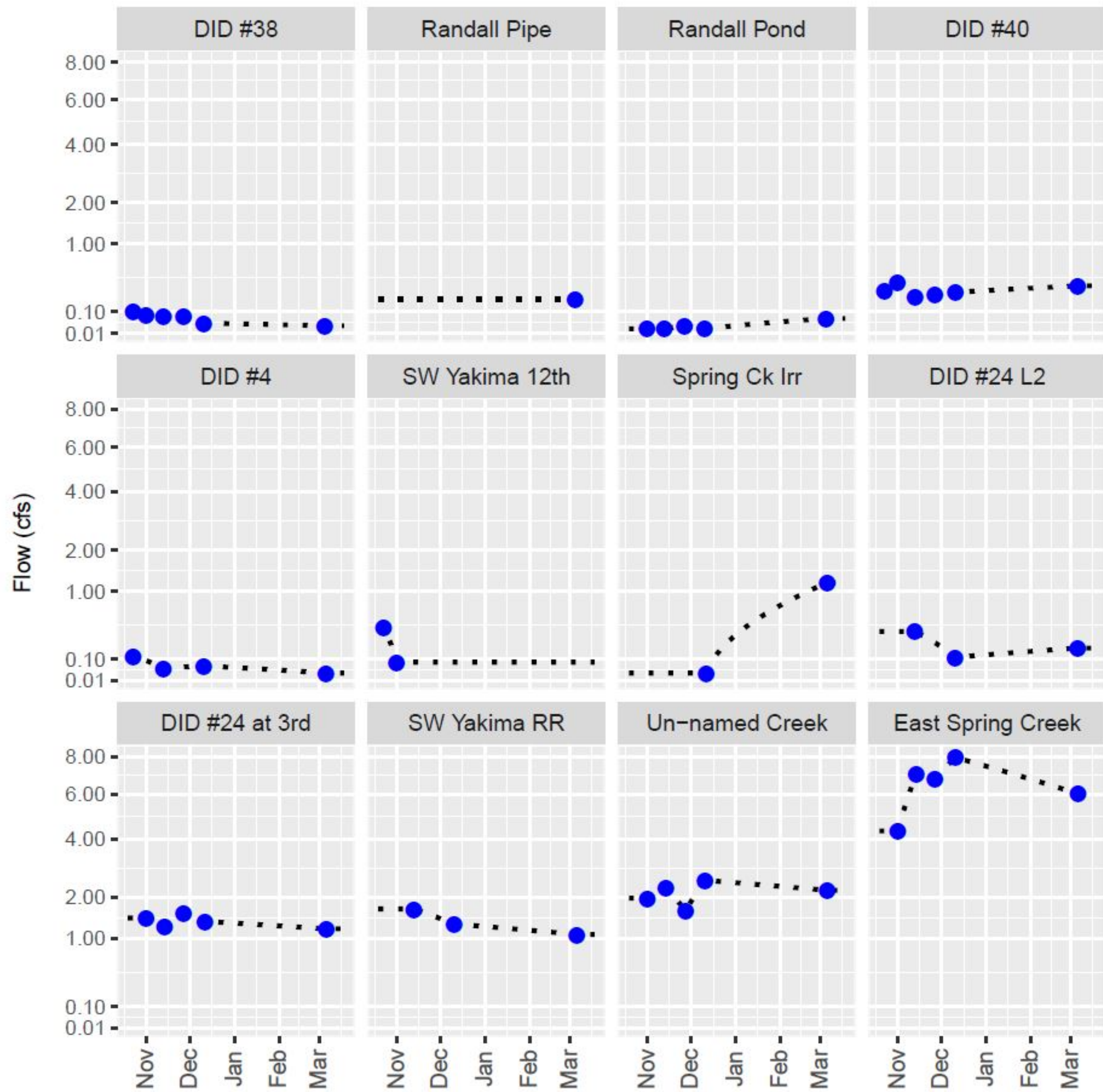


Figure 35. Year-round point sources and diversions.

The y-axis on the above figure uses a square-root scale to allow both higher flow and lower flow to be plotted together. This scale causes linear interpolation between values to appear as a curved line.

Irrigation season only point sources and diversions

Table 14 lists all known point sources which contributed to Wide Hollow Creek only during irrigation season. Monitoring of these sources occurred at least monthly.

Figure 36 shows the time series for all point sources (both year-round and irrigation season). Flow measurements are shown as blue dots, linear interpolations as black lines. Both the irrigation and non-irrigation season point sources are shown to allow comparison of levels.

No flow measurements were possible for the three largest point sources during irrigation season:

- Yakima Valley Canal (near 101st Ave)
- Congdon Orchards (near 62nd Ave)
- Naches-Cowiche Canal (near 32nd Ave)

These flows could not be measured due to accessibility and rapidly changing flow, as can be seen in Figure 36. In particular, flow from Congdon Orchards changed on a daily or hourly basis.

The flows for these sources shown in the figure below were calculated by entering all other known flows into the model and then determining the residual flow at the following gaging stations:

- WHC at 101st
- WHC at 40th
- WHC at 24th

Flow for the above three sources was then set based on residual flow at these gages, adjusted for travel time between the source and the gage.

Table 14. Irrigation season only point sources and diversions to Wide Hollow Creek.

Source / diversion	Variability	Note
Yakima Valley Canal discharge	variable	Variable discharge rate from canal overflow
DID #48	consistent	This DID appears associated with Congdon Orchards irrigation water, rather than as a curtain drain for groundwater.
Congdon Orchards discharge	variable	Highly variable discharge rate (daily/hourly)
Naches-Cowiche Canal discharge (near 32nd Ave)	variable	Variable discharge rate (daily/hourly)
City of Yakima Stormwater outfall - (12th Ave NE)	consistent	12" pipe on NE side of bridge. Ran during 2013 irrigation season, but not much flow during 2014 irrigation season. This pipe may have connection to an irrigation canal such as Broadway Irrigation.
Naches-Cowiche Canal discharge (near 12th Ave)	variable	Variable discharge rate (daily/hourly)
City of Union Gap Stormwater pipe E5-41	consistent	
Perry Technical School diversion	consistent	
Broadway Irrigation diversion	consistent	

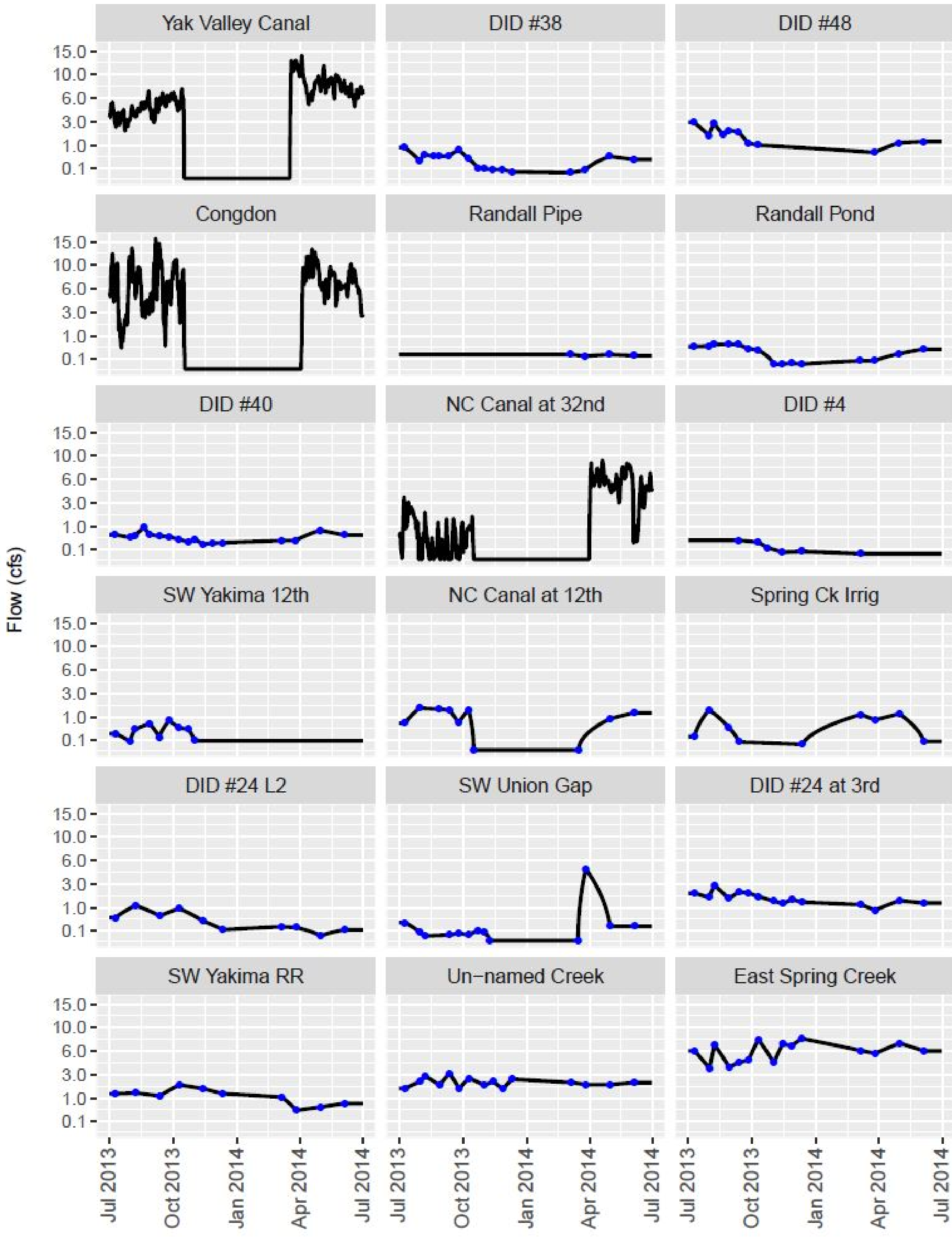


Figure 36. Full study year flow rates (cfs) for all point sources to Wide Hollow Creek.

Measurements shown as blue points.

The y-axis uses a square-root scale. This scale causes linear interpolation between values to appear as a curved line.

Point sources that were dry during the study year

As listed earlier in Table 8, there were potential point sources to the creek which were observed to be dry during every sampling event of the 2013-14 study period. These sources could be potentially large sources of upper watershed winter run-off and stormwater to the creek, but were not simulated in the model because they were dry during the study.

Groundwater gains and losses (nonpoint sources and diversions)

Surface water in the area of Ahtanum Creek (including Wide Hollow Creek) is exchanged into and out of a thin, shallow aquifer composed of semi-consolidated alluvial sediments overlying the Thorp gravel (Foxworthy, 1962). Many reaches of the creek lose water into this shallow aquifer, while several reaches gain groundwater out of this aquifer. This section describes how groundwater gains and losses were estimated and included in the QUAL2Kw model.

Ecology used four different lines of evidence when assigning groundwater to the model:

Seepage from banks and thawed reaches during winter (field observations)
Groundwater was observed seeping out from the ground and the channelized banks of the creek along three portions of the creek: 101st Ave., around 64th Ave., and near the mouth. Additionally, reaches that did not freeze in the winter included 101st Ave, 64th Ave., and most of the creek below 16th Ave. The headwater flow for the model does not represent streamflow from the upper watershed (which was dry during the study period), but is instead groundwater seepage entering the creek between Dazet Rd and the Yakima Valley Canal discharge location. Field observations were made of an isolated area of thawing in the creek near 64th Ave. during a cold period when upstream and downstream areas were solidly frozen.

Differential flow measurements
Groundwater inflow was estimated based on differential flow measurements during the non-irrigation season (baseflow); estimates could not be made during the irrigation season due to the volatility in flow. The baseflow measurements provide estimates of net gain or loss from the creek which may include a combination of both gaining and losing reaches. No estimate of groundwater flow could be made using this method from 101st Ave. to 64th Ave. during baseflow, due to intermittent (disconnected) flow in the creek. The amount of groundwater entering the creek at 64th Ave could only be roughly estimated using this method.

Vertical hydraulic gradient (piezometer measurements)
Groundwater gains and losses were also calculated based on the measured vertical hydraulic gradients from piezometer. One source of uncertainty in these calculations is vertical anisotropy in hydraulic conductivity. The range of VHG measurements is shown in Figure 37 below. Hydraulic gradients near 64th Ave were not measured because piezometers could not be driven into the ground due to cemented gravel here (likely Thorp Gravel). A positive gradient at 64th Ave. was included in the interpolation when using VHG to estimate groundwater flow, but this is only an estimate, which was used as to check consistency with the other methods.

Winter water temperature (model calibration)
Winter water temperatures measured in the creek were also used to refine the estimates of groundwater flow and temperature, as part of model calibration. Because the creek was cold and there was little energy from sunlight, groundwater impacts on temperature were evident. Sunlight

energy (shortwave solar radiation) is decreased during wintertime, and the impact of known sources on creek temperature could be accounted for since temperature was monitored for these sources. Known source flows appeared relatively consistent and stable during the winter. Due to relatively slow travel time in the creek, the impact of groundwater was localized near the source.

With the exception of near 101st Ave, areas of groundwater inflows were the only reaches that Ecology observed beaver activity. This could be due to beavers prefer groundwater gaining reaches, since these areas are less likely to freeze or dewater during the winter.

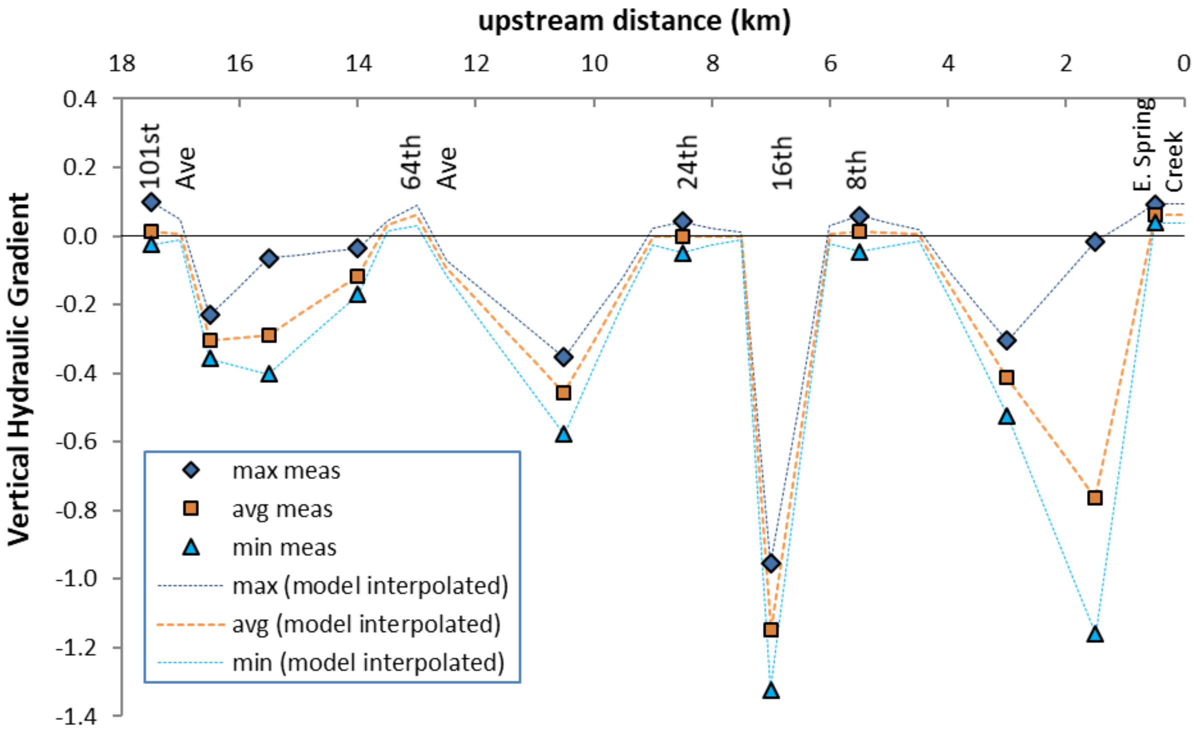


Figure 37. Measured range (max/avg/min) of vertical hydraulic gradient, interpolated for model. *Interpolated values near 64th Ave were estimated based on other lines of evidence.*

Estimates of water losses to the shallow aquifer used in the model were based exclusively on piezometer measurements of vertical hydraulic gradient (VHG). Stream losses were not readily apparent in residual flow differences measured during field surveys. Piezometer measurements of negative VHG were generally larger than positive VHG (Figure 37 above).

Initial estimates of groundwater losses based on VHG were unreasonably large, given the small amount of water available in the creek. To keep water losses in the model consistent with observed field measurements, vertical anisotropy of 0.01 (the ratio of vertical to horizontal hydraulic conductivity) was assumed when calculating water losses. For calculating gains, a vertical anisotropy of 0.1 was used. This difference in anisotropy was chosen such that stream losses could fit the measured flow balances.

Net gains/losses of groundwater calculated from the above methods and used in the QUAL2Kw model for Wide Hollow Creek are shown in Table 15. No groundwater gains were assigned to 24th Ave in the model because stream losses and gains likely balanced each other to provide little or no net gain to the stream. There was also an issue at this location in distinguishing between groundwater and water flowing from point source DID #40. It was difficult to measure flow within this DID pipe which was partially submerged. The DID is primarily draining groundwater, so the two sources cannot easily be sorted.

Table 15. Net gains/losses of groundwater used in the QUAL2Kw model.

Type	Description	*Approximate* Distance Upstream (km)	Inflow/ Outflow (cfs)
Gain	101st Ave	17	+0.35
Loss	101st-64th Ave	14-16	(-0.34)
Gain	64th Ave	13	+1.06
Combined loss/gain	64th Ave to 12th Ave	8-12	(-0.25)
Gain	10-12th Ave	6-7	+1.06
Loss	10th Ave to Union Gap	2-4	(-0.80)
Gain	E. Spring Creek (Union Gap)	0-1	+1.41
			Net Total +2.50 cfs

Groundwater inflow and losses in the QUAL2KW model were small and tended to balance each other, so that the net inflow throughout the whole model is less than 3 cfs. Much of this water enters near the mouth of the creek (near East Spring Creek) in Union Gap.

The approximate distances and extent of individual groundwater gains shown in Table 15 and the model source schematic (Figure 34) above should be interpreted with caution. Within the model, gains were typically limited to one or two reaches for simplicity's sake. However, the observed isolated thawing at 64th Ave and immediate cooling downstream did suggest that the groundwater was indeed only entering the creek in that single reach. For much of the rest of the creek, it's unknown whether groundwater tends to enter the creek within a single model reach (500 m) or distributed along several model reaches. This could not be determined using the available methods because differential flow, piezometers and model calibration points are spaced widely enough that little information can be inferred between these points. Observations of seepage from the banks was the only type of flow directly observable, but these observations were not sufficient to determine the spatial extent of gains or losses.

As discussed above, the influence of groundwater on the creek could not be determined during the irrigation season (due to the highly variable irrigation inflows). Therefore, the groundwater inflow calculated from the non-irrigation season was applied year-round. Essentially, the irrigation season was over-laid in the model on top of the baseflow (non-irrigation) season, with new inputs from the irrigation sources.

QUAL2Kw model calibration

Model calibration means adjusting parameters so that model simulated data fit the observed data in an optimal fashion. Model calibration included the following areas:

- Hydro-geometry and water velocity calibration: Matching simulated water width and depth, and simulated travel times against observed width, depth and water velocity.
- Streamflow mass balance calibration: Matching simulated flow to continuous and synoptic measurements made in the creek (by adjusting groundwater and assigning flow to those irrigation sources which could not be measured). Checking flow balance by matching simulated specific conductance and chloride concentrations (conservative parameters) against observations made in the creek to ensure that flow sources in the model are reasonable.
- Solute and suspended solid calibration: Matching simulated solute and suspended solid levels (suspended solids, dissolved nutrients and carbon, alkalinity, etc.) against observed levels (by adjusting sinks and sources of solutes and suspended solids to account for the mass balance in the water).
- Water temperature calibration: Matching simulated water temperature against observed data logger temperatures (by adjusting water depth, shade and back scattered long wave radiation).
- DO and pH calibration: Matching simulated pH and simulated DO levels against continuous pH and DO synoptic measurements taken in the creek (by additional adjustment of parameters that control algal productivity in the creek).

Model performance evaluation

Model performance was evaluated by comparing simulated data against in-stream observed measurements.

There are two general approaches for assessing the quality of a calibration: subjective and objective. Subjective assessment is based on a visual comparison (plots) between the simulated and observed data. In contrast, objective approaches hinge on developing some quantitative measures of the quality of the fit (Chapra, 1997).

Both subjective and objective approaches were used for this study. Subjective assessment relied on time series and longitudinal plots. Objective assessment relied on two measures of fit: root mean squared error (RMSE) and bias. These two measures complement each other as follows:

- RMSE provides a measurement of total error that will be zero only when the simulated and observed data match exactly. RMSE is always a positive number.
- Bias is the average difference between the simulated and observed data. It indicates whether the model tends to over- or under- predict. If bias is positive, then the model is over-predicting observed data; if bias is negative then the model is under-predicting observed data. Bias is zero when all differences average out (highs and lows cancel each other). At zero bias there may still be non-zero total error (RMSE > 0).

The equations for RMSE and bias are shown below, for comparing n model simulated data values (D_{mod}) against an equal number of observed data values (D_{obs}), summed over the number of data values. Data values could represent temperature, concentration, pH, etc.

$$RMSE = \sqrt{\frac{\Sigma(D_{\mathrm{mod}} - D_{obs})^2}{n}}$$

$$Bias = \frac{\sum(D_{\mathrm{mod}} - D_{obs})}{n}$$

QUAL2Kw hydro-geometry and water velocity calibration

Under given flow conditions, travel time of water through the model is determined based on water velocity. Both water velocity and depth were defined as a function of flow in QUAL2Kw using rating curves, briefly described below.

Rating curves

Water velocity, depth and width in the creek have an important influence on water movement and water quality such as the sensitivity of water temperature to meteorological conditions. These parameters were simulated in QUAL2Kw using rating curves. These three rating curves are inter-related; for a rectangular channel, the velocity, depth and width exponents sum to one.

Depth and velocity rating curves were specified using empirical coefficients in QUAL2Kw, and width was then calculated by the model assuming a rectangular channel. The rating curves used for velocity and depth both have the same form:

$$X = aQ^b$$

Where X represents either velocity or depth, Q = flow, and a, b represent empirical coefficients determined from velocity-discharge and depth-discharge rating curves. These empirical coefficients are set for each reach of the model and determine the simulated velocity and depth of water in that reach under all flow conditions.

Velocity and depth rating curves were initially calculated based on field observations of depth and point velocities at monitoring sites, then adjusted based on time-of-travel dye studies (see below) and observed temperature data. Time-of-travel studies provide better averages of velocity for a reach than do field measurements of velocity at a single monitoring site.

Time-of-travel dye studies

Two time-of-travel dye studies (representing irrigation and non-irrigation conditions) were conducted on Wide Hollow Creek to estimate average water velocities in the creek.

Due to intermittent flow conditions during the non-irrigation season, travel times could not be measured between YV Canal and 64th Ave. during the non-irrigation dye study. This section of the creek was problematic for creating the model since QUAL2KW cannot handle intermittent flow conditions. Ecology chose to simulate a minimum flow condition in this section of the creek throughout the non-irrigation season.

Travel times simulated in the model using rating curves match observed travel times from the dye studies (Figure 38). Travel time during irrigation season (from the model headwater down to the mouth of Wide Hollow Creek) is a little longer than one day. During non-irrigation season, travel time increases to nearly five days. The travel time difference between these two seasons is entirely due to the amount of flow in the creek, which increases during irrigation season due to canal overflow sources.

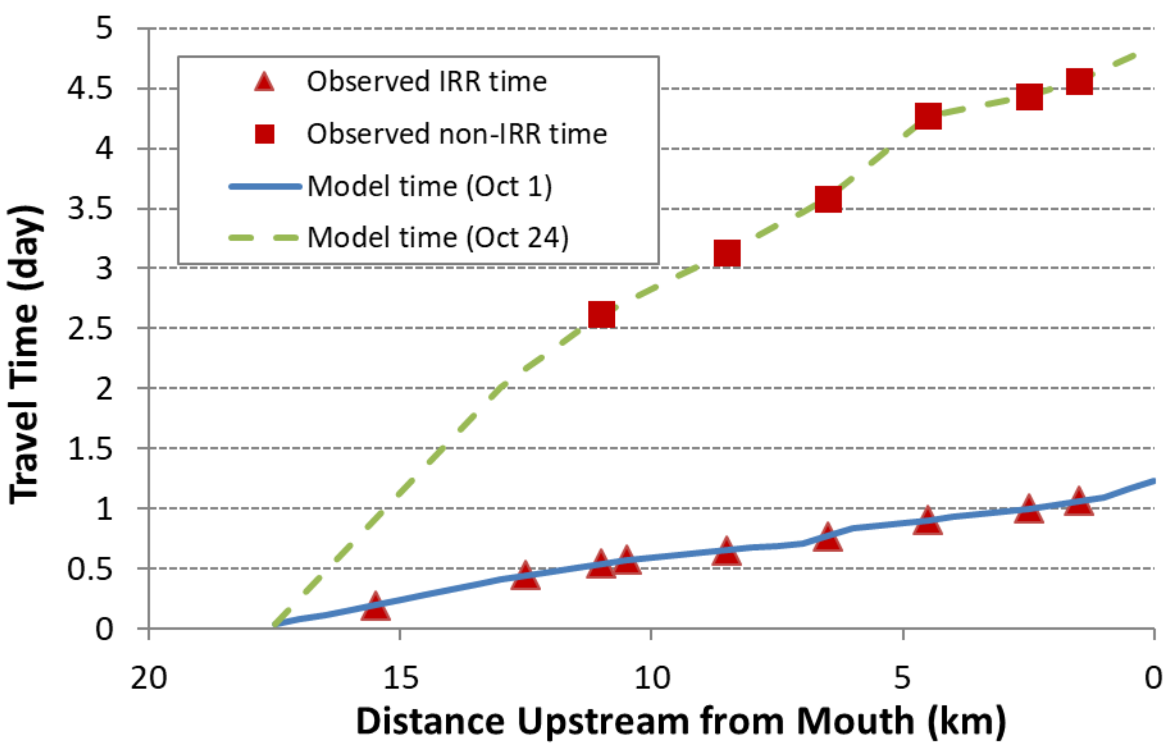


Figure 38. Comparison of model simulated vs. observed travel times from two dye studies.

QUAL2Kw streamflow simulation

After developing and testing the model geometry, a dynamic flow balance was simulated for Wide Hollow Creek. First, all measured sources and losses of water flow were entered into the model as time series.

As described above, to the extent possible, all point source inputs were measured during each synoptic survey for flow contribution to the creek. Flow was interpolated between measurements for some sources, others were developed from continuous streamflow gaging (see Figure 36).

Streamflow calibration

After assigning all the sources and diversions within QUAL2Kw, the mass balance of streamflow in the model was checked against observed measurements made in the creek during the study (Figure 39). This step ensured that the sources of water used in the simulation provided a reasonable representation of water in the creek throughout the study season.

Model flow inputs were adjusted during calibration by identifying groundwater inflows and losses, and determining flow for large irrigation season sources which could not be measured directly. Measured point sources were not adjusted during calibration.

Streamflow measurements in the creek relied on synoptic measurements at individual sites as well as 4 continuous gaging stations. Issues were encountered during non-irrigation season with the stream gage at 28th Ave, which was biased high when compared to nearly all other flow in the model. Data from this gage during non-irrigation season were therefore qualified as inconsistent with other observations, and not used for calculating goodness-of-fit statistics. Only synoptic flow measurements at this site were relied on for flow calibration during non-irrigation season.

Table 16 shows the goodness-of-fit statistics for modeled versus observed streamflow in Wide Hollow Creek. Overall, the model simulated the dynamic flow in Wide Hollow Creek very well for the whole study year. A correct flow balance is the basis for creating all of the other mass balances in the model and provides a primary step in developing a fate and transport model for water temperature, DO, and pH.

Summary of flow input and loss (withdrawals)

Figure 40 presents the water inputs and losses by category and season from the QUAL2Kw model with the calibrated flow balance. This summary is calculated for sources and losses from 101st Ave. down to the White Street gage. From there, Wide Hollow Creek is diverted through Union Gap where it enters the former East Spring (Chambers) Creek drainage. East Spring Creek, groundwater and other flow sources below White St. are not included in this summary.

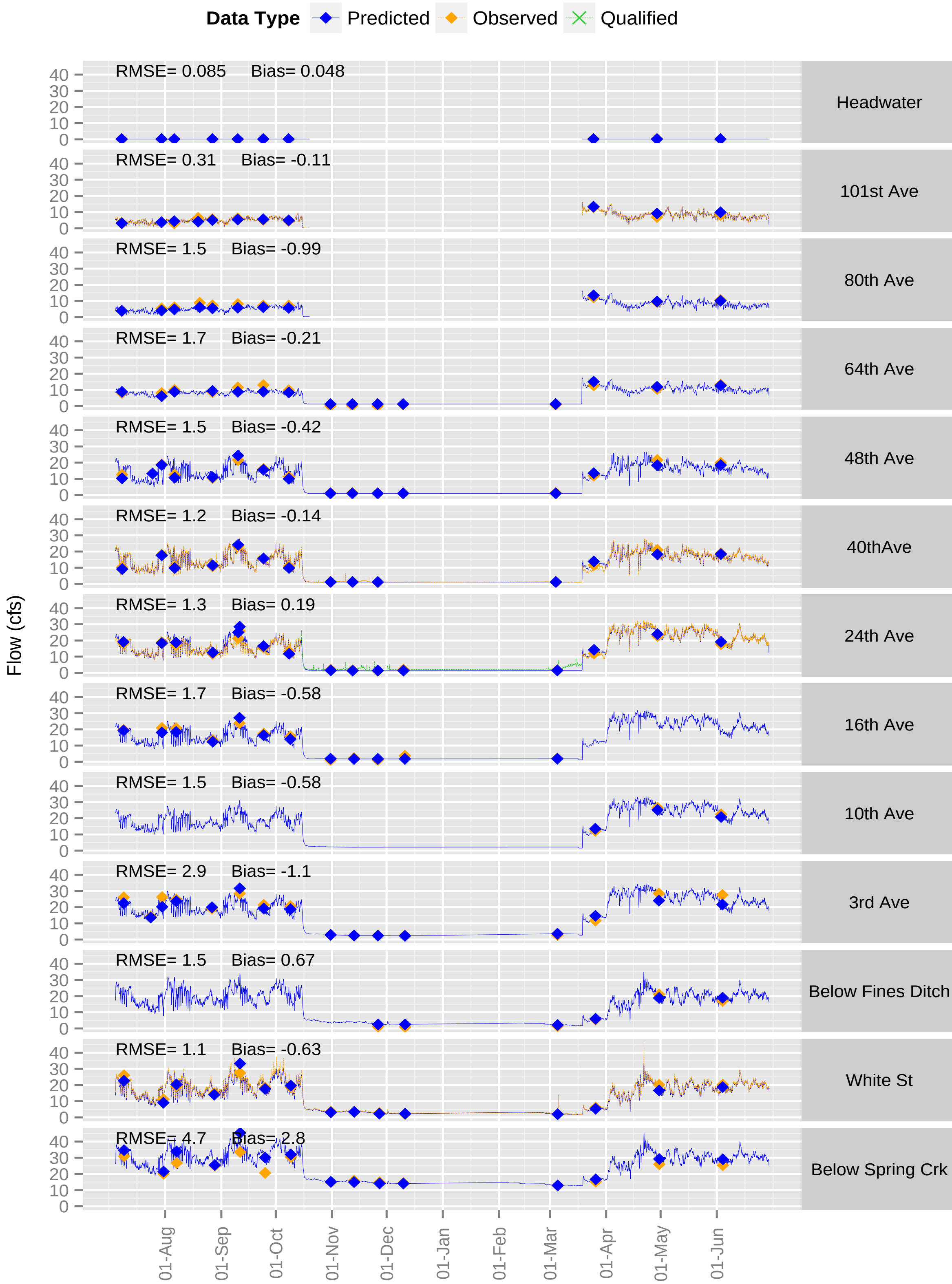


Figure 39. Model simulated flow (blue) vs measurements (orange), showing statistics of fit for the full year.

Table 16. Goodness-of-fit statistics between simulated and measured flow.

Site	Average Flow (cfs)		RMSE (cfs)		Bias (cfs)	
	IRR	Non-IRR	IRR	Non-IRR	IRR	Non-IRR
Headwater	0.1	---	0.1	---	0.0	---
101st Ave	6.6	---	0.3	---	-0.1	---
80th Ave	7.8	---	1.5	---	-1.0	---
64th Ave	10.6	0.5	2.0	0.8	-0.7	0.7
48th Ave	15.5	1.1	1.8	0.2	-0.5	-0.2
40th Ave	15.4	1.2	1.3	0.4	-0.2	-0.1
28th Ave	18.6	2.5	1.3	0.3	0.2	-0.3
16th Ave	18.8	2.0	2.1	1.0	-0.8	-0.2
10th Ave	20.4	---	1.5	---	-0.6	---
3rd Ave	22.6	2.6	3.5	0.4	-1.7	0.1
Below Fines Ditch	14.5	1.2	1.7	1.3	0.1	1.2
White St	18.0	3.3	1.3	0.5	-0.7	-0.4
Below Spring Creek	25.4	14.5	5.7	0.5	4.4	-0.3

Non-irrigation season (Oct 15, 2013 to Mar 19, 2014) streamflow was composed of nonpoint sources (groundwater seepage) and point sources (DIDs, stormwater pipes, and tributaries). Fines Ditch was the only large diversion for this period. Due to intermittent flow in the creek, flow during the non-irrigation season was not considered meaningful above 64th Ave.

Irrigation season was represented in this study by combining two time periods: Jul 1-Oct 15, 2013 and Mar 19-Jun 30, 2014. During the irrigation season, flow was dominated by the large irrigation providers. In order of volume: Congdon Orchards, Yakima Valley Canal, and Naches-Cowiche Canal. During the winter non-irrigation season, these did not discharge to the creek.

As describes above, these large sources could not be measured directly, and were inferred based on streamflow gages.

Most of the other inputs were consistent in both seasons. Spring Creek irrigation district and Randall pond flowed perennially, as did most DIDs inputs, the city of Yakima stormwater outfall near Union Gap and the Randall Park lake outlet.

No stormwater precipitation events were measured during the study; some stormwater sources were perennial due to groundwater drainage, as opposed to precipitation events; however, the Union Gap stormwater outfall near Goodman Road only ran during irrigation season, draining irrigation runoff near Ahtanum Road.

Groundwater inputs could only be measured during the non-irrigation season; they could not be measured during the irrigation season. For this reason, the non-irrigation season groundwater inputs were held constant through the irrigation season with the same flow.

The headwater flow (any flow from above 101st Ave.) consisted of groundwater seepage during the study period, July 2013 through June 2014.

Flow from the DIDs increased slightly during irrigation season, possibly because some of the irrigation water was apparently getting into the DID system, as did flow from the pond at Randall Park which was also supplemented by a DID system.

Stream losses are termed abstractions in QUAL2Kw, and these include groundwater losses and the diversion at Fines Ditch. Abstractions from the creek at Fines Ditch were greater during the irrigation season because of increased flow in the creek, which flowed into the ditch.

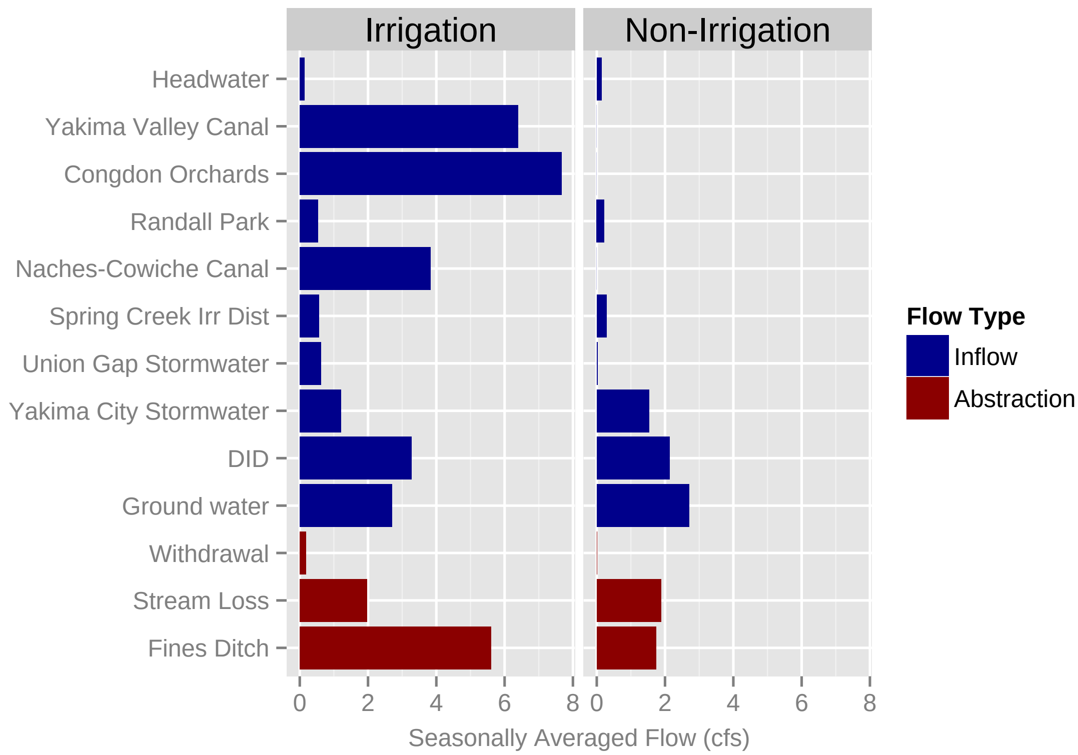


Figure 40. Summary of the sources and losses of water to Wide Hollow Creek during irrigation and non-irrigation seasons.

Specific conductivity and chloride calibration

Mass balances of conductivity and chloride concentrations were used as a secondary confirmation of the correct flows of point and nonpoint source contributions to Wide Hollow Creek. The combined inputs of these conservative solutes should add up to the observed patterns in the creek.

Conductivity and chloride were measured from all sources in the field during synoptic surveys and groundwater surveys.

Conductivity was continuously monitored at the gage stations at 101st Ave., 40th Ave and White Street. Both conservative tracers were also measured in the creek during each synoptic survey.

Figures 41 and 42 compare simulated versus observed conductivity levels during non-irrigation and irrigation seasons, respectively. Figure 43 compares the simulated versus observed chloride levels for the whole study period. Both comparative mass balances confirmed that the flow sources and losses used in the model adequately represent the composition of water in the creek.

Figures 44 and 45 present the conductivity and chloride loads entered into the model by category and season. DID and groundwater inputs dominated the conservative tracer loads. East Spring Creek, groundwater and other flow sources below White St. are not included in this summary.

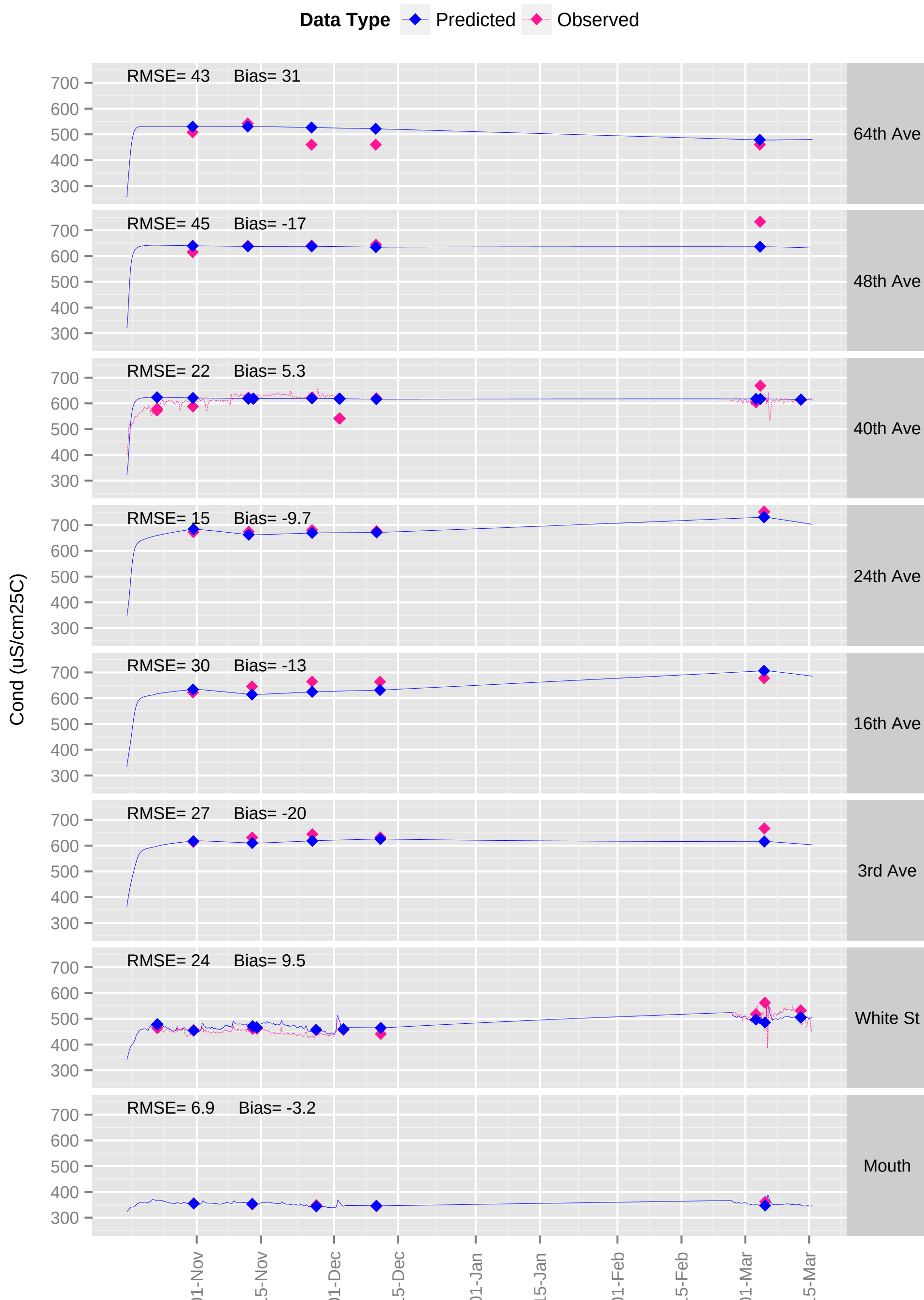


Figure 41. Comparison between simulated and observed specific conductance during the non-irrigation season.
Observed data from continuous gages are shown as lines and synoptic measurements are shown as points.

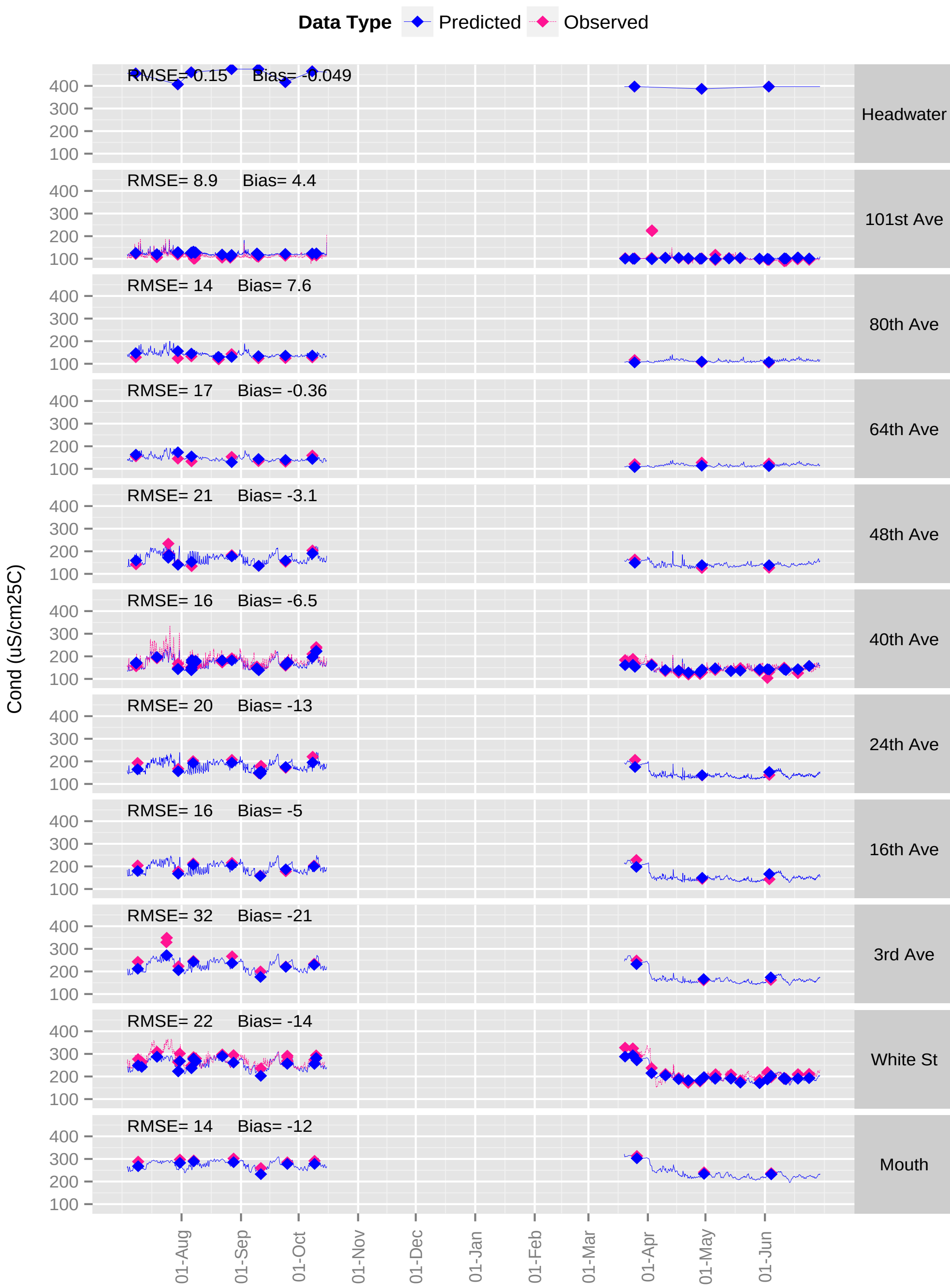


Figure 42. Comparison between simulated and observed specific conductance during the irrigation season.

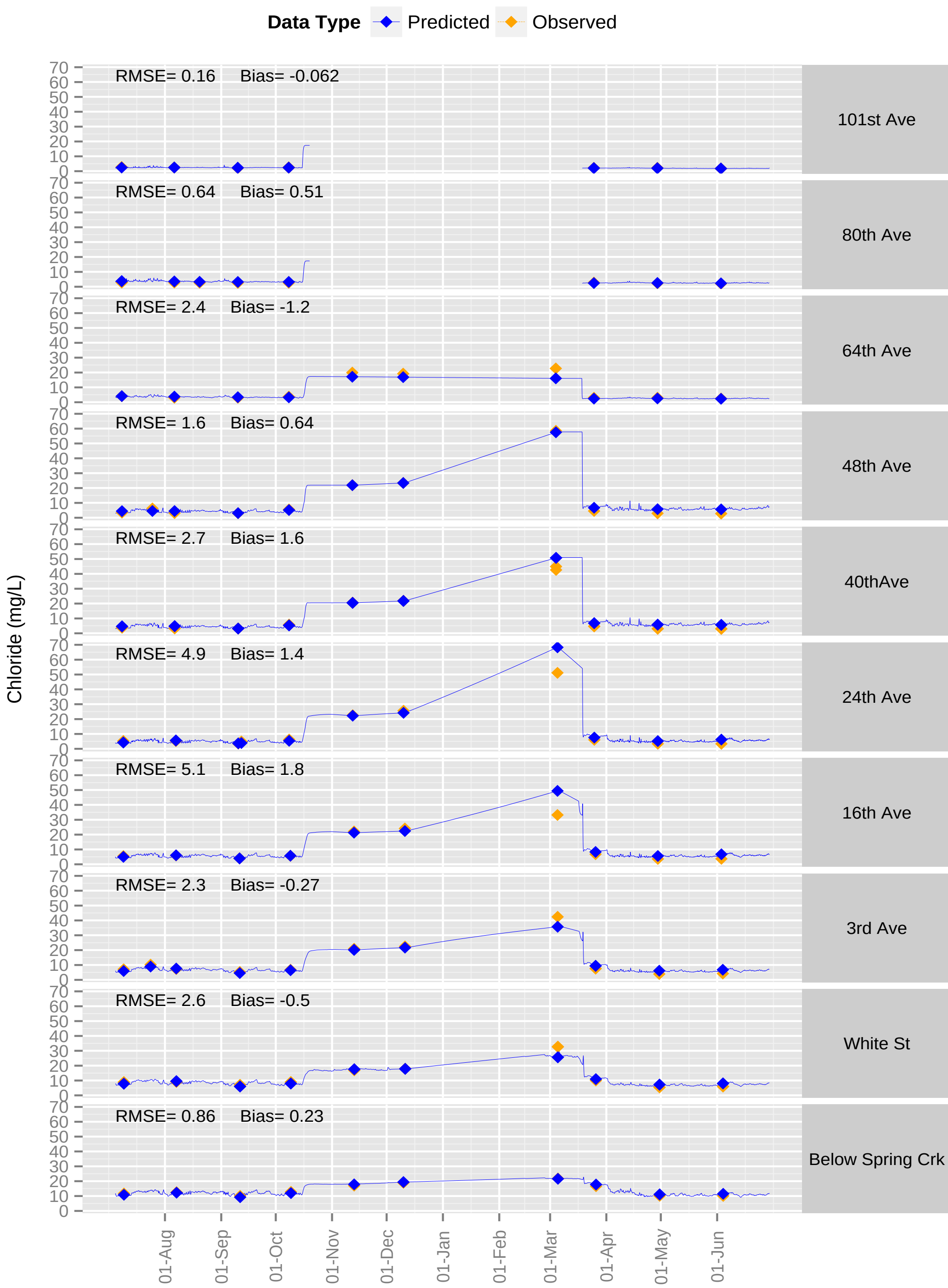


Figure 43. Comparison of simulated and observed chloride concentrations.

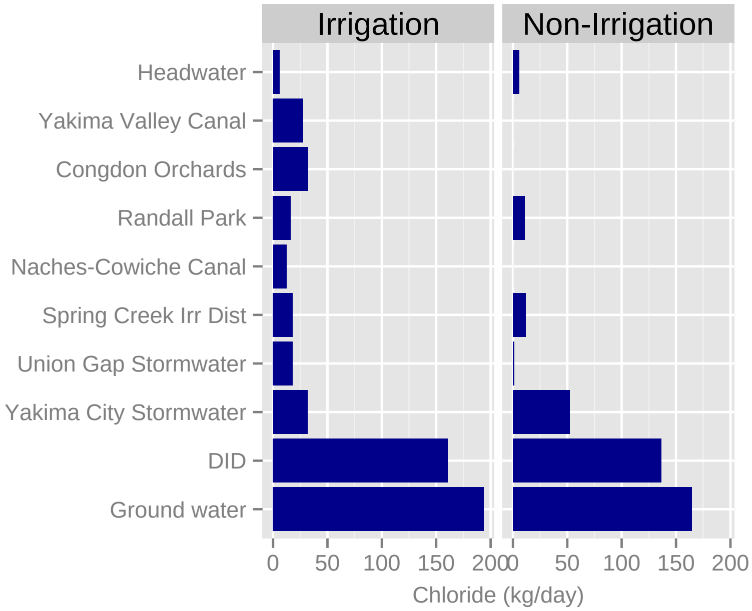


Figure 44. Summary of the seasonal loads of chloride to Wide Hollow Creek by category.

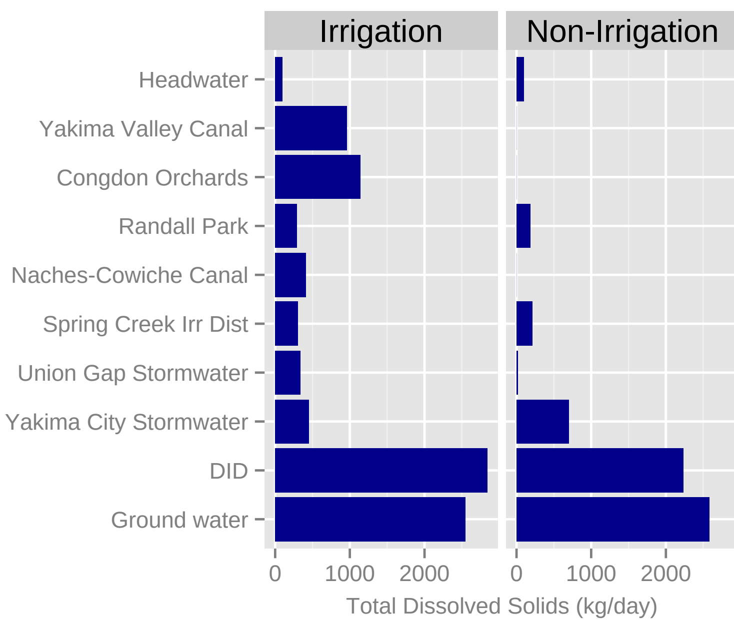


Figure 45. Summary of the seasonal loads of conductivity to Wide Hollow Creek by category.

QUAL2Kw water temperature simulation

The QUAL2Kw model was next used to simulate water temperature in Wide Hollow Creek. The temperature simulation relied on the following data sources for model inputs:

- Flow balance from the calibrated QUAL2Kw model (described above).
- Time series of hourly temperature for all source inputs to the creek. Some sources were measured monthly from which an hourly time series of temperature was developed (Appendix F). Some sources had a temperature datalogger (Dugger, 2013) that was used to create a time series of hourly temperature. Temperature dataloggers were also placed in Wide Hollow Creek to serve as observations for comparison to the calibrated model (Dugger, 2013).
- Meteorology for the study year was also put into the QUAL2Kw model (described below).
- Calculated effective shade (described below). Effective shade had to be calculated using the Shade model and input into the QUAL2Kw model.
- Measured temperatures of nonpoint sources (groundwater). Groundwater temperatures were based on monthly temperature measurements inside of gaining instream piezometers. These temperatures varied somewhat over the course of the study year. Temperatures in the range of 9-15°C were used for groundwater entering Wide Hollow Creek.

Meteorology

- Short wave solar radiation which was downloaded for the Ahtanum weather station monitoring location from Washington State University's AgWeatherNet site.
- Long wave solar radiation was calculated using QUAL2Kw's internal Satterlund model, which was chosen as providing the best match between simulated and observed data during calibration.
- Air temperature, relative humidity, wind speed, and cloud cover. These parameters were downloaded for the Yakima Regional Airport monitoring location operated by the National Weather Service. Data were downloaded from the MesoWest online site.
- Some observed air temperatures and relative humidity data were collected by Ecology data loggers during the study year (Dugger 2013). These measurements were used to check downloaded weather conditions.

Vegetation and effective shade calculations

Near-stream vegetation cover, along with channel morphology and stream hydrology, are important factors that influence stream temperature. To obtain a detailed description of existing riparian conditions in Wide Hollow Creek, a combination of GIS analysis, interpretation of aerial photography, and hemispherical photography was used.

Vegetation cover is represented in the model as effective shade. Effective shade is defined as the fraction of incoming solar shortwave radiation that is blocked from reaching the surface of the stream. Ecology's Shade model (Pelletier, 2015) was used to calculate effective shade along Wide Hollow Creek. Several sources of shade to Wide Hollow Creek were combined when calculating effective shade: near stream vegetation, regional topography, and stream incision.

Riparian vegetation in the study area (Figure 46) was mapped and classified in GIS using color digital aerial photos flown during July and August 2010. Vegetation types were mapped as polygons within a 250-foot buffer on either side of the creek. For calculating effective shade, each vegetation type was assigned three characteristic attributes: maximum height, average canopy density, and streambank overhang. Vegetation types were classified into *current vegetation* categories (Table 17).

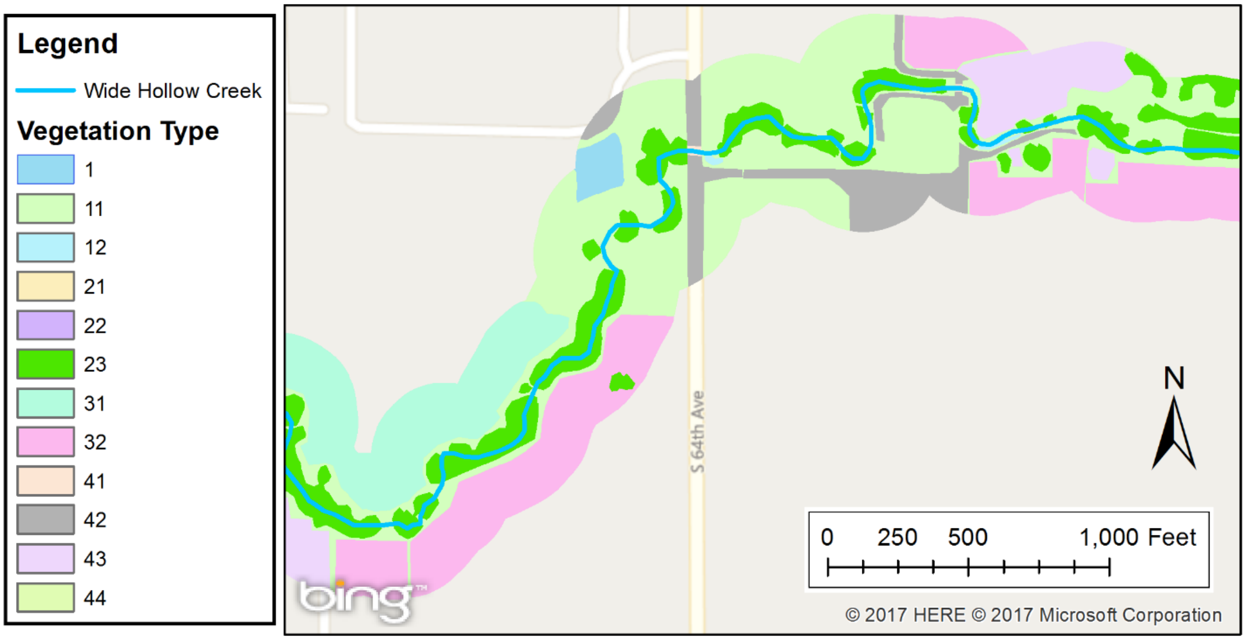


Figure 46. Example of digitized vegetation polygons which were used for calculating effective shade.

Table 17. Vegetation classification used in the Shade.xls model.

Code	Description	Height (m)	Density (%)	Overhang (m)
1	Water	0	1	0
11	Short Grass (pasture/resid)	1	0.8	0.05
12	Shrub	2	0.7	0.2
21	Trees, short	5	0.7	0.5
22	Trees, medium	10	0.7	1
23	Trees, tall	20	0.65	6
31	Agricultural crops/hay	1	0.7	0.1
32	Agricultural orchard	4	0.7	0
41	Creek under bridge/culvert	1	1	1
42	Paved	0	1	0
43	Developed, residential	4	0.3	0
44	Developed, commercial	7	0.3	0

To increase the accuracy of the vegetation interpretation and to ground-truth the Shade model outputs, hemispherical vegetation photographs (Figure 47) were taken during October 1, 2013. At each temperature monitoring location, photographs were taken from the center of the channel. Effective shade estimates were calculated from the hemispherical photographs (Stohr, 2008).

Figure 47. Example of a hemispherical vegetation photograph taken at the center of Wide Hollow Creek.

After mapping the vegetation type polygons, a longitudinal profile of Wide Hollow Creek was created by sampling the vegetation polygons at 100 meter intervals along the creek. Sampling was performed on both the right and left banks of the stream, using TTools extension for ArcView (Ecology, 2015). Sampling was performed at right angles to the stream, using a 4 meter spacing out to 32 meters from the stream bank.

Stream aspect, elevation, and topographic shade angles to the west, south, and east were also sampled at each 100-meter interval. Topographic shade angles were obtained using a 10 meter digital elevation model (DEM). Channel morphology was included in the shade model based on elevation data obtained from cross-sections of Wide Hollow Creek in Yakima County's HEC-RAS model. In some locations the creek is channelized within narrow, steep banks, which provide additional shade to the creek. The average depth of the creek below nearby channel banks in the Shade model was 2.9 meters.

The output from TTools was then used as an input into Ecology's Shade model (Pelletier, 2015) to estimate effective shade along Wide Hollow Creek. Effective shade calculated by the Shade Model was then compared to estimates calculated from hemispherical photos to confirm model accuracy (Figure 48).

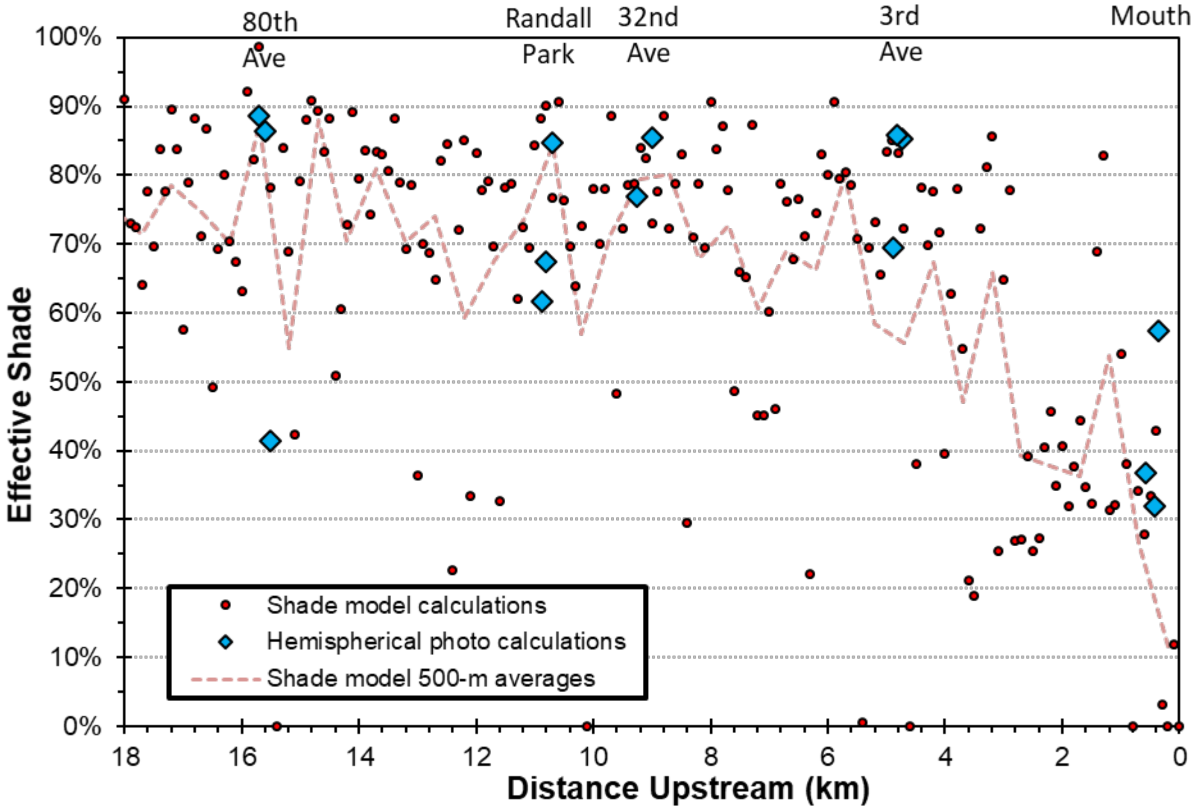


Figure 48. Effective shade calculated by the shade model compared to hemispherical photograph calculations.

Finally, the shade model was used to calculate hourly values of effective shade for each reach of the QUAL2Kw model. These values were then copied from the shade model into the QUAL2Kw model.

Temperature calibration

The primary model parameters adjusted during temperature calibration were stream depth and effective shade. Adjustments during temperature calibration included:

- Original shade model values were reduced using a multiplier of 0.95 for the entire creek during all seasons.
- Winter time shade model values (Dec-Mar) were reduced using an additional multiplier of 0.6 to simulate the loss of leaves from deciduous trees along the stream banks. Spring and fall shade model values (Oct-Nov and Apr-May) were proportionally reduced using linear interpolation between the summer and winter time multiplier.
- Depth rating curves were adjusted as needed to better match observed daily maximum and minimum temperatures in the creek.
- To keep the creek warmer during nighttime, long wave radiation back-scatter from vegetation overhanging the creek was added to the model as a special feature.

Depth adjustments during calibration tended to better represent average stream depths than the depth measurements made at monitoring sites. This is because monitoring sites are chosen for accessibility rather than depth representation. In particular, pools are undesirable locations for measuring flow.

One problem encountered during calibration was that some portions of the creek became too cool during nighttime. After making the shade reductions above, simulated daytime creek temperatures matched observations reasonably well, but nighttime temperatures were too low. Because the reaches of the creek which were too cool at night tended to occur in areas with heavy vegetation, the nighttime problem was solved by adding long wave radiation back scatter from vegetation to these portions of the creek. This radiation represents higher emissivity of the vegetation surrounding the creek, which releases heat during the night and acts as an insulating factor to keep the creek warm during nighttime.

As discussed above, the temperature calibration during the non-irrigation season was used to refine locations and estimates of groundwater flows into the creek during winter. This was effective because groundwater warmed the creek in localized areas during cold periods. The model was not sensitive to groundwater temperature during the warm summer period when irrigation flow was high (see Appendix H – Model sensitivity analysis).

For quantitatively assessing model performance, simulated temperatures during the hottest months of the study year were compared against observed values (Table 18). This table uses statistical goodness-of-fit statistics described above: the root mean squared error (RMSE) and bias. Statistics in this table are shown for hourly and daily maximum temperatures.

The tabulated values above show a good fit overall based on RMSE for both hourly and daily maximum temperatures, which is typically less than 1°C. The best fits occur during the hottest months of July and August, while the cooler month of October shows higher average RMSE. Water at two locations (64th Ave and 16th Ave) were especially impacted by water which backed up due to beaver activity. Deeper water at both of these locations affected water temperature at data logger locations.

For qualitatively assessing model performance, simulated temperatures were plotted against observed values (Figures 49 through 52). Plots were made of hourly and the running 7-DADMax temperatures in 2013 and 2014. Due to intermittent flow conditions, simulated temperatures are not shown during the non-irrigation season from 101st Ave. to 64th Ave. Goodness-of-fit statistics are shown for each reach on these plots.

Based on both quantitative and qualitative measures, the calibrated temperature simulation adequately matches observed measurements made in the creek. RMSE generally remains less than 1°C overall and bias is reasonable during the hottest months of July and August. Bias is larger than desired at sites with beaver activity which caused water to back up, especially during the cooler months of September and October.

Table 18. Root mean squared error (RMSE) and overall bias of differences between QUAL2Kw predicted and observed daily maximum and average temperatures (°C) in Wide Hollow Creek.

Site	Statistic	July 2013		August 2013		September 2013		October 2013	
	Type	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias
101st Ave.	Hourly	0.44	-0.27	0.31	-0.19	0.29	-0.19	0.18	-0.09
	daily Max	0.19	0.07	0.12	0.02	0.23	-0.09	0.14	0.09
80th Ave.	Hourly	0.68	-0.24	0.54	-0.19	0.70	-0.47	0.68	-0.59
	daily Max	0.46	0.24	0.43	0.32	0.54	-0.08	0.33	-0.23
64th Ave.	Hourly	0.65	-0.38	0.67	-0.42	1.02	-0.74	2.31	-1.62
	daily Max	0.51	-0.15	0.42	0.11	0.82	-0.20	1.19	-0.53
40th Ave.	Hourly	0.68	-0.38	0.55	-0.38	0.73	-0.59	0.89	-0.76
	daily Max	0.32	0.06	0.27	-0.07	0.53	-0.36	0.84	-0.64
24th Ave.	Hourly	0.40	-0.03	0.32	-0.03	0.43	-0.19	0.47	-0.18
	daily Max	0.48	0.00	0.40	0.21	0.44	0.05	0.58	-0.04
16th Ave.	Hourly	0.77	-0.41	0.84	-0.53	1.13	-0.91	1.49	-1.31
	daily Max	0.39	0.11	0.42	0.03	0.84	-0.48	1.22	-0.95
3rd Ave.	Hourly	0.48	-0.19	0.53	-0.35	0.77	-0.63	1.10	-0.96
	daily Max	0.40	0.28	0.28	0.00	0.65	-0.43	1.10	-0.92
Fines Ditch	Hourly	0.42	-0.21	0.52	-0.37	0.69	-0.56	0.77	-0.70
	daily Max	0.29	-0.05	0.28	-0.07	0.53	-0.32	0.66	-0.59
White St.	Hourly	0.53	0.13	0.50	-0.17	0.71	-0.50	0.80	-0.71
	daily Max	0.58	0.53	0.36	0.27	0.48	-0.15	0.49	-0.26
Near Mouth	Hourly	0.49	0.38	0.32	0.09	0.38	-0.19	0.41	-0.21
	daily Max	0.79	0.77	0.51	0.47	0.34	0.12	0.36	0.06

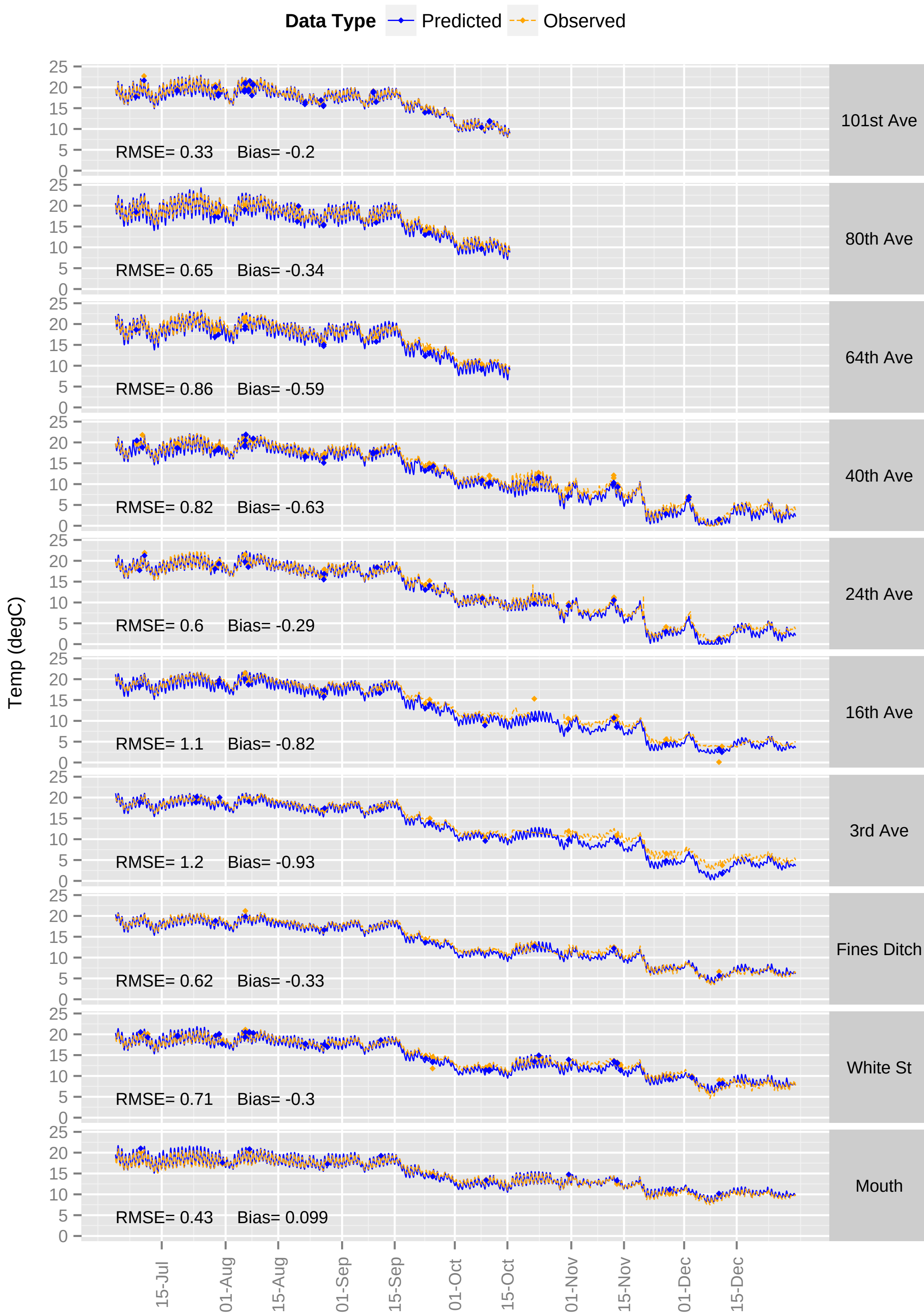


Figure 49. Hourly simulated (predicted) versus observed temperatures in Wide Hollow Creek during the 2013 portion of the study year.

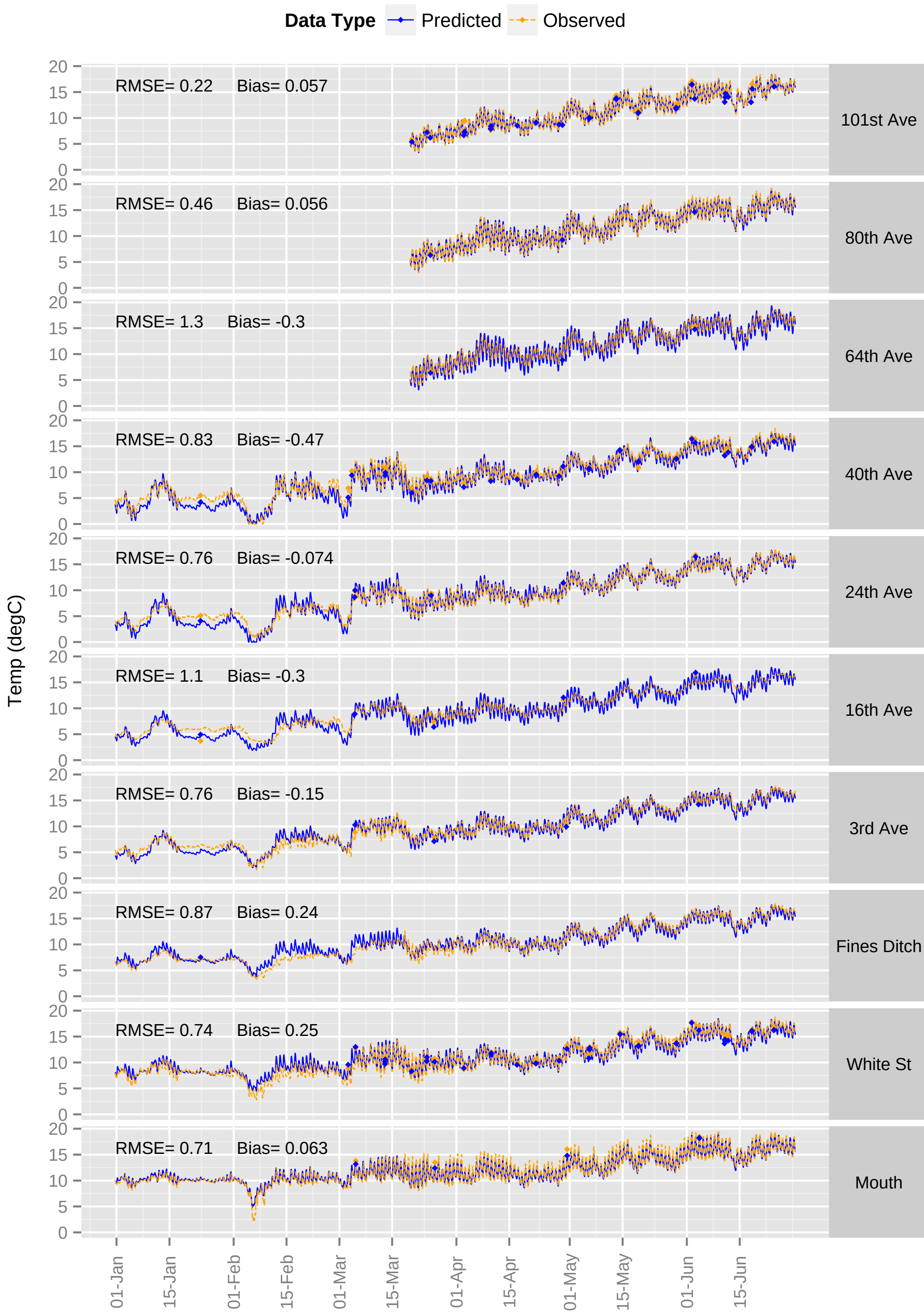


Figure 50. Hourly simulated (predicted) versus observed temperatures in Wide Hollow Creek during the 2014 portion of the study year.

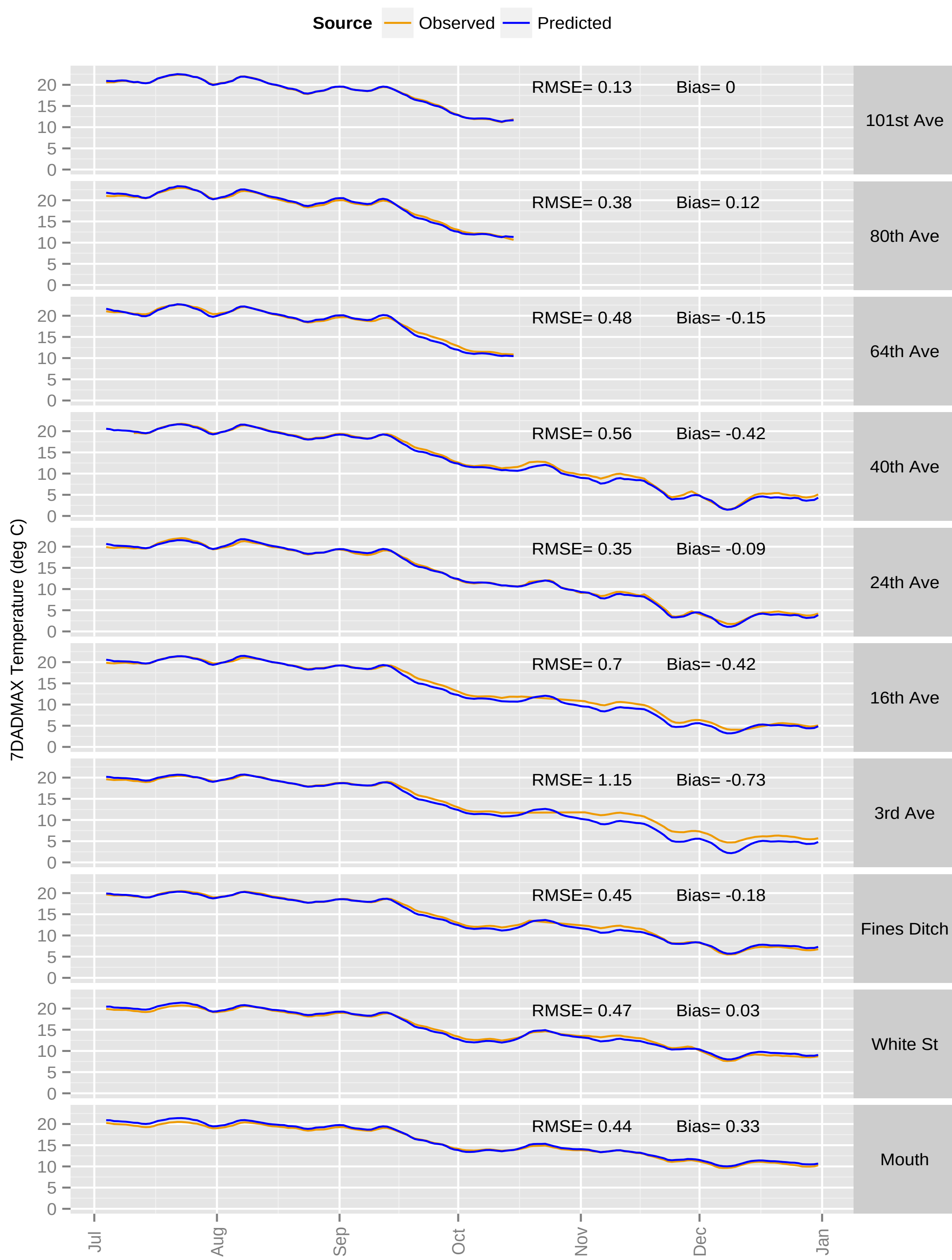


Figure 51. Daily 7-DADMax simulated (predicted) versus observed daily 7-DADMax temperatures in Wide Hollow Creek during the 2013 portion of the study year.

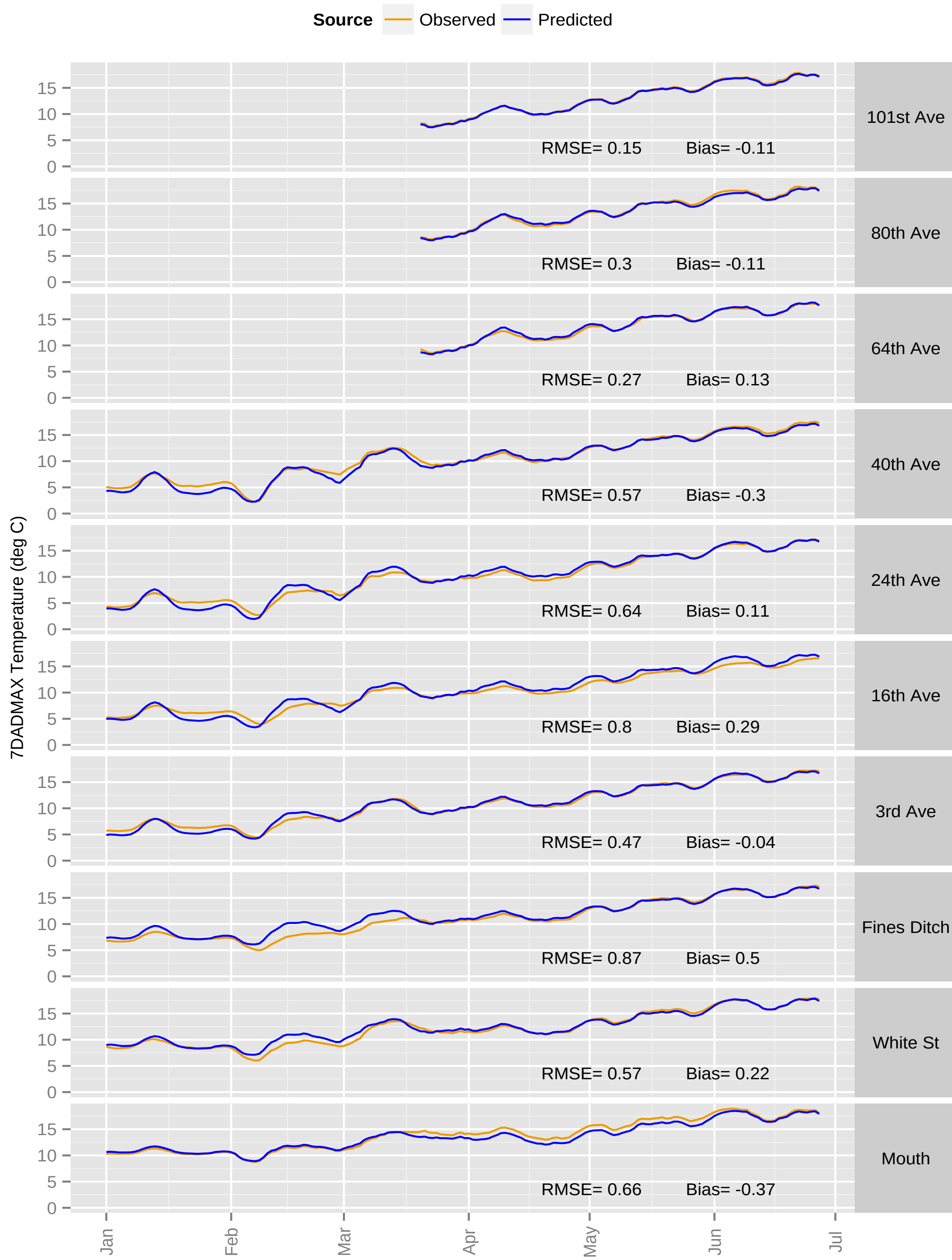


Figure 52. Daily 7-DADMax simulated (predicted) versus observed daily 7-DADMax temperatures in Wide Hollow Creek during the 2014 portion of the study year.

Several sensitivity analyses were used to test various assumptions made during model calibration, and to determine the relative importance of various factors that affect stream temperatures. The results of the sensitivity analyses are presented in Appendix H.

Model calibration and sensitivity analysis indicated the following difference in stream temperature regulation between irrigation versus non-irrigation seasons:

- Irrigation season: Temperature in the creek was strongly influenced by large point source discharges of irrigation water.
- Non-irrigation season: Temperature in the creek was more weakly and locally influenced by smaller point and nonpoint source discharges.

Stream temperature during irrigation season (the hottest part of the year or summer critical period) was strongly influenced by the temperature and flow conditions from several large point sources of irrigation water overflow entering the creek. These sources included the Yakima Valley Canal, Congdon Orchards, and Naches-Cowiche Canal. High flow during irrigation season meant brief travel-times. The larger volume of water in the creek and shorter residence times meant that the creek was less sensitive to weather conditions.

Stream temperature during non-irrigation season was more weakly influenced by temperature and flow conditions from the smaller sources of water entering the creek (DIDs and groundwater). Low flow during non-irrigation season meant longer travel-times. Impacts from these smaller sources of water were more localized. The smaller volume of water in the creek and longer residence times meant that the creek was more sensitive to climate conditions.

QUAL2Kw suspended solids and solutes simulation

The QUAL2Kw model was next used to simulate the inorganic suspended solids (ISS) and detritus (organic suspended solids), nutrients, and dissolved organic carbon (DOC) mass balances in Wide Hollow Creek. Nutrient forms included inorganic and organic phosphorus, ammonia, nitrate, and organic nitrogen.

This simulation relied on the following data sources for model inputs:

- Flow balance from the calibrated QUAL2Kw model (described above).
- Time series of hourly suspended solids and solutes for all source inputs to the creek.
    - Most sources were measured monthly from which a time series of suspended solids and solutes was developed (Appendix F).
    - For the irrigation canal discharges of suspended solids to Wide Hollow Creek, a relationship was developed from a daily time series of turbidity monitored at the City of Yakima Water Treatment Plant on the Naches River.
    - Groundwater nutrient and DOC levels were based on monthly nutrient measurements inside of gaining instream piezometers. There was no assignment of suspended solids from groundwater sources.
- A number of rate parameters were used to calibrate nutrient transformations, settling losses, and algal nutrient uptake; as well as DOC hydrolysis and oxidation rates; and settling rates to

account for downstream longitudinal loss of suspended solids (Appendix G – QUAL2Kw Model Calibration).

- The calibration plots for the suspended solids and solutes, as well as an evaluation of model performance (comparing the simulated and observed values) are located in Appendix G.

Summary of suspended solids and solutes mass balances

East Spring Creek, groundwater and other flow sources below White St. are not included in the mass balance summaries.

Figure 53 and Figure 54 present the ISS and detritus loads in the Wide Hollow Creek model by category and season. The largest suspended solid load to Wide Hollow Creek was during the irrigation season and mostly from the irrigation canals, which also dominated the input of flow. As discussed earlier, most of the suspended solid load in the irrigation canal is from the Naches River, the source of the irrigation water (see Figure 19).

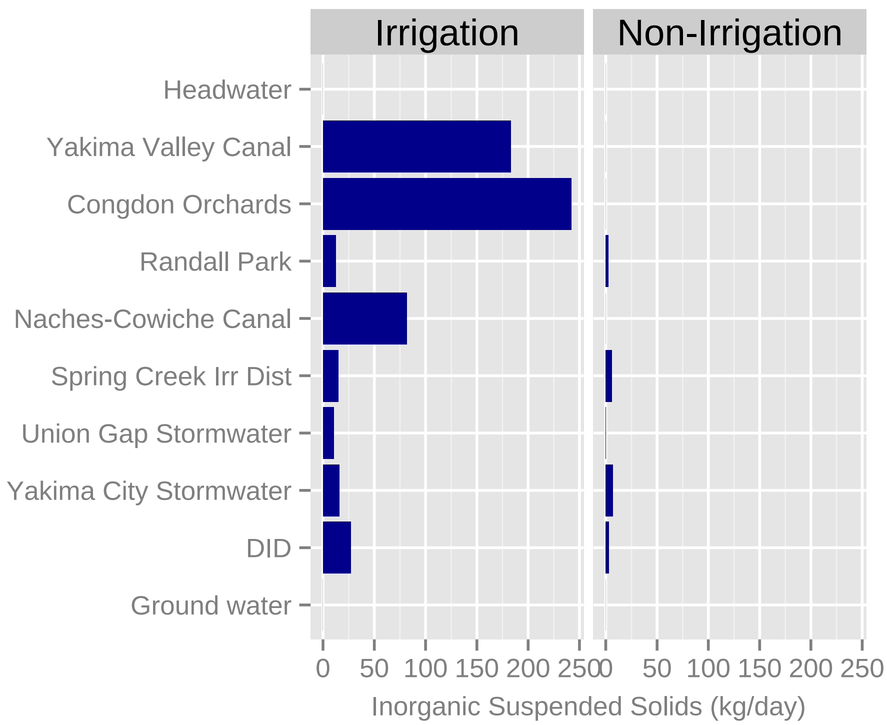


Figure 53. Summary of the seasonal loads of inorganic suspended solids to Wide Hollow Creek.

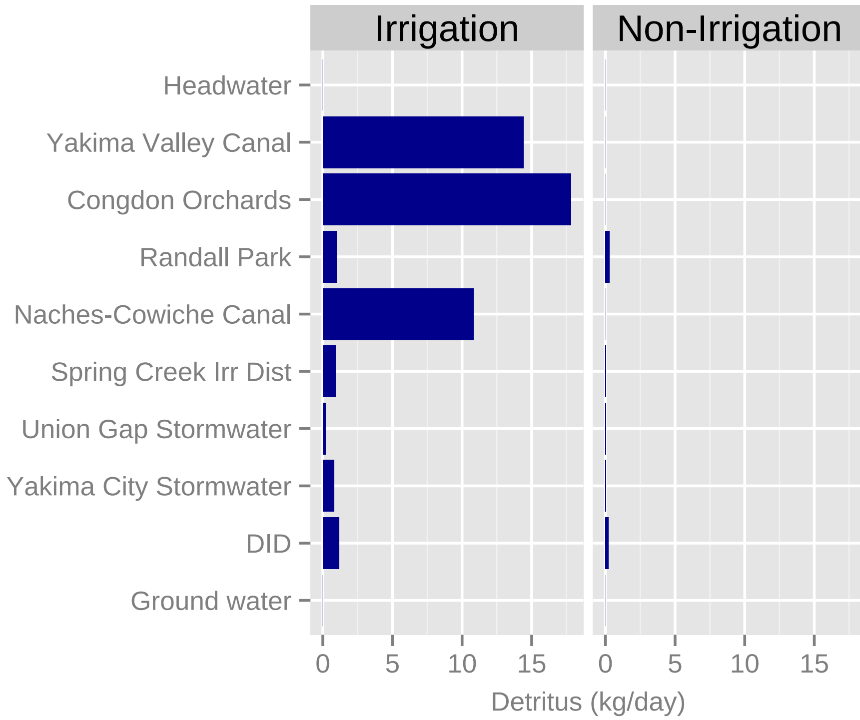


Figure 54. Summary of the seasonal loads of detritus to Wide Hollow Creek.

Figure 55 presents the seasonal nitrate loads entered into the model by category. The largest load of nitrate to Wide Hollow Creek over the study period was from DID sources. Contributions of nitrate loads from groundwater and the City of Yakima stormwater drain were also large year-round.

Figures 56 and 57 present the seasonal organic nitrogen and ammonia loads entered into the model by category. Note that these loads are 3 to 10 times less than the nitrate load. In general, the largest seasonal loads of organic N and ammonia to Wide Hollow Creek were from groundwater sources (including DID, Randall Park, and stormwater drainage of groundwater). During the irrigation season, the irrigation canals also contribute.

By contrast, even though most of the water in the creek during the irrigation season was from the irrigation canals, they contributed relatively smaller nitrate loads. This is because the source of the irrigation water (the Naches River) had relatively low concentrations of nitrate (see Figure 19).

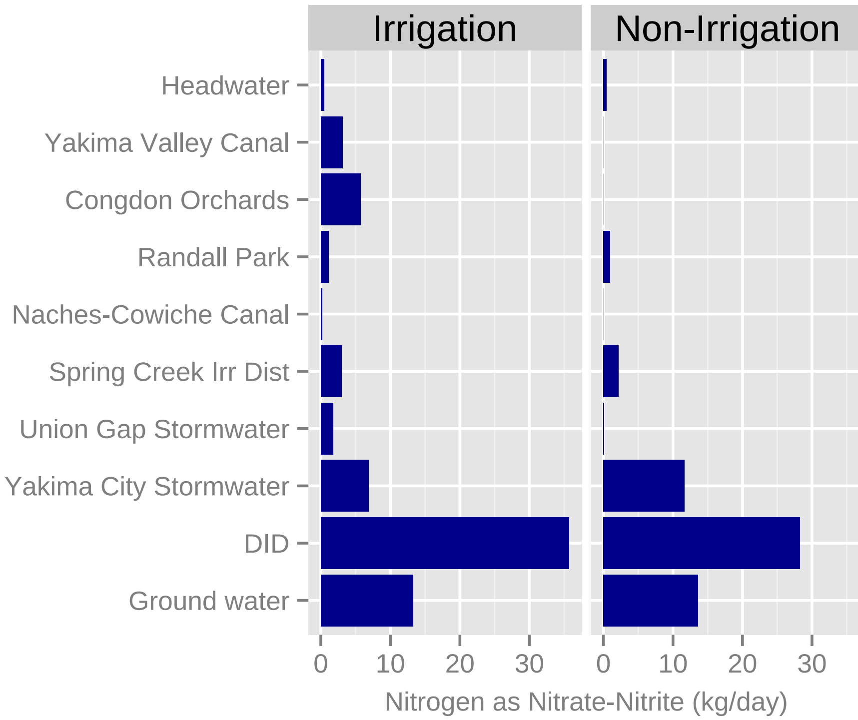


Figure 55. Summary of the seasonal loads of nitrate to Wide Hollow Creek by category.

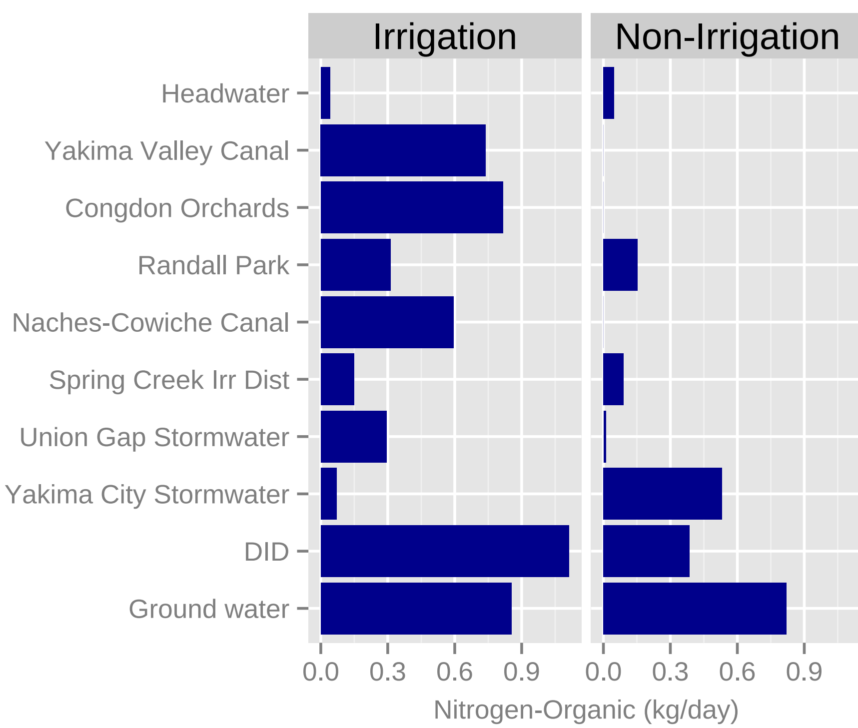


Figure 56. Summary of the seasonal loads of organic nitrogen to Wide Hollow Creek.

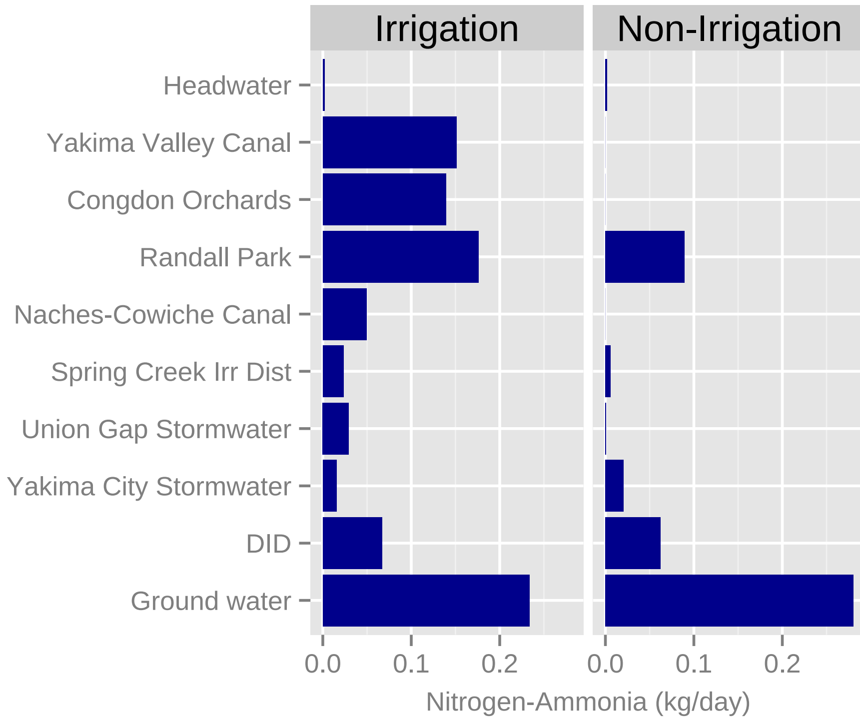


Figure 57. Summary of the seasonal loads of ammonia to Wide Hollow Creek.

Figures 58 and 59 present the seasonal organic and inorganic P loads entered into the model by category. Note the difference in scales where the inorganic x-axis is about 4 times greater. Groundwater dominated the organic P load to the creek year-round, as did the irrigation canals during irrigation. The organic P in the irrigation canals was probably particulate from sloughed algae in the irrigation water. The groundwater organic P was a dissolved fraction.

The largest inorganic P load was from DID sources. Note that this load is about 5 times greater than the highest organic P load. Groundwater inputs of inorganic P and Randall Park were also large contributors year-round. The Randall Park inorganic P load was surprising given the relatively small flow, but there is a large waterfowl population in Randall Park pond, which is the source of the water. By contrast, the loads from the irrigation canals were relatively much smaller, given their large flow contribution. Again, the source water for the irrigation (Naches River) had comparatively lower concentrations of inorganic P.

Figure 60 presents the carbonaceous biochemical oxygen demand (CBOD) loads to Wide Hollow Creek. CBOD was measured as dissolved organic carbon in the field study. Groundwater sources added year-round loads to the creek, while the irrigation water was the dominant source during the irrigation season. Most of the CBOD was considered to be a refractory fraction, meaning it did not break down easily, based on relatively constant concentrations upstream to downstream in the creek.

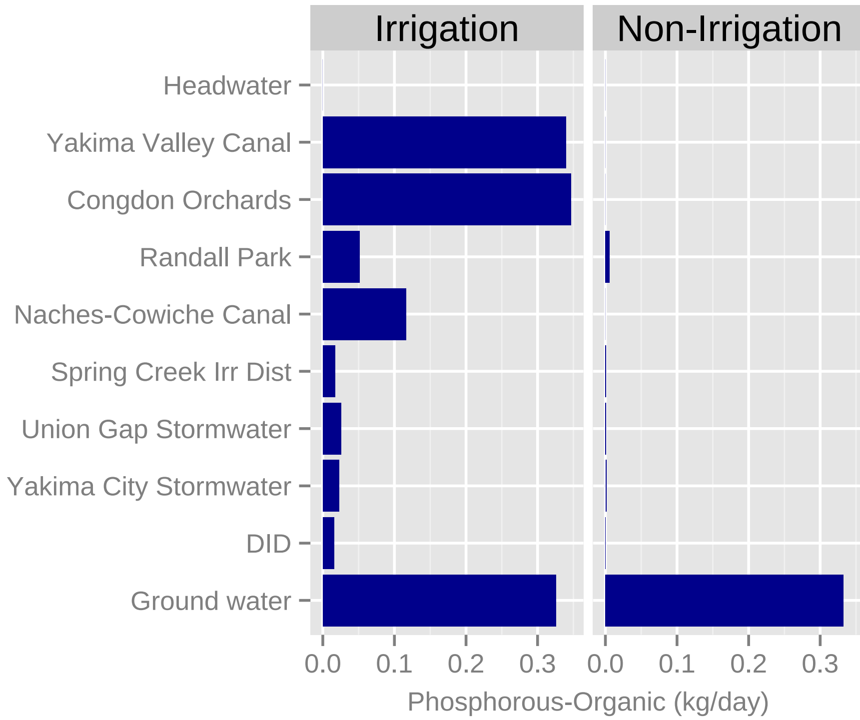


Figure 58. Summary of the seasonal loads of organic phosphorus to Wide Hollow Creek.

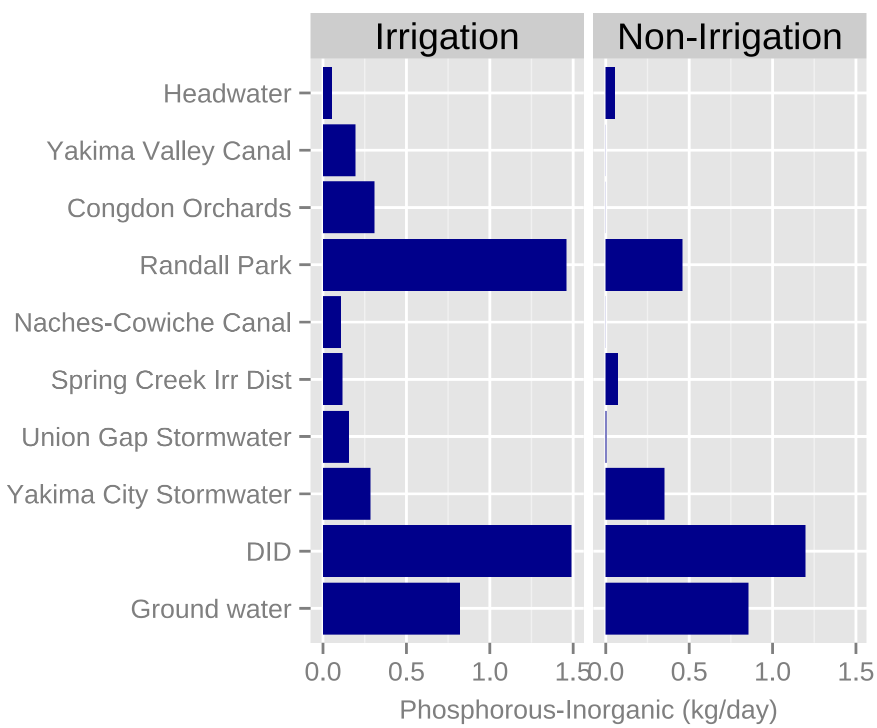


Figure 59. Summary of the seasonal loads of inorganic phosphorus to Wide Hollow Creek.

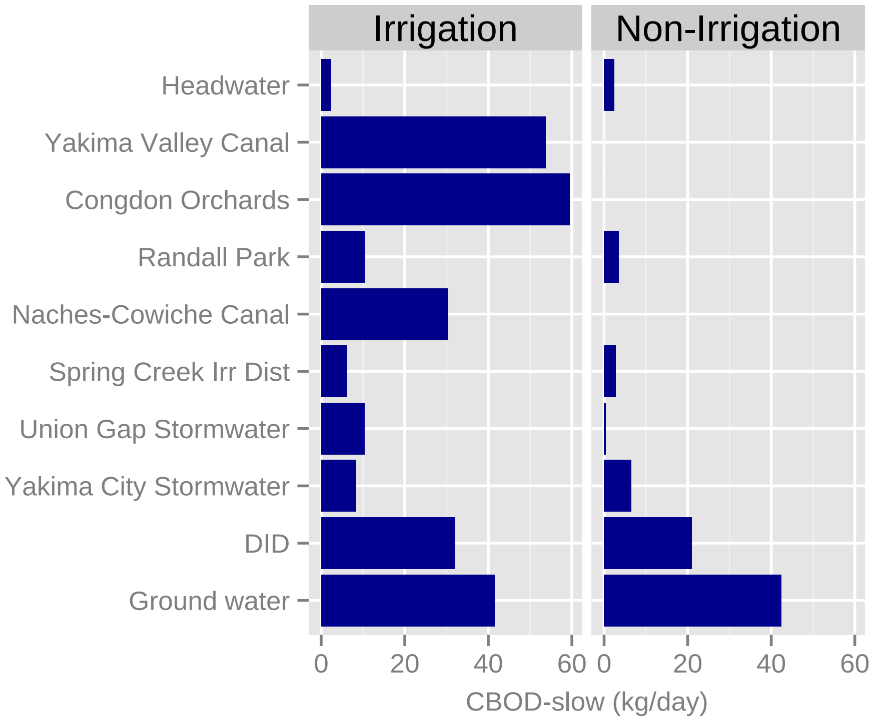


Figure 60. Summary of the seasonal loads of carbonaceous biochemical oxygen demand to Wide Hollow Creek.

QUAL2Kw dissolved oxygen and pH simulation

The QUAL2Kw model was next used to simulate algal productivity, which contributes to the levels of dissolved oxygen (DO) and pH in Wide Hollow Creek. Algal productivity is controlled by temperature, light, and nutrient levels in the water, as well as suitable substrate and space requirements on the creek bottom. The model simulates the effects of light, nutrients and temperature on algal productivity, and in turn, algal productivity's effect on DO and pH levels. The model also simulates sediment oxygen demand and biochemical oxygen demand processes that deplete DO in the water column.

The QUAL2Kw algal productivity simulations were ran for the entire study period from July 2013 to July 2014, to evaluate DO and pH levels during both irrigation and non-irrigation periods.

This simulation relied on the following data sources for model inputs:

- Calibrated flow balances (described above).
- Calibrated effective shade and water temperature (described above) which affect the amount of light and temperature for algae growth.
- Calibrated suspended solids (described above) which also affect the amount of light for algae growth.

- Calibrated nutrient balances (described above) which affect the food supply for algae growth. The first pass of the nutrient balances were fine-tuned during the algal productivity calibration for uptake of nutrients.

Appendix F contains details about model inputs. The primary model parameters adjusted during algal productivity calibration were:

- Original shade model values were changed slightly to match the diel profile of incoming solar radiation. Overall daily shade did not change but the timing of when the solar radiation was strongest over the course of the day was adjusted, usually only within the reach with the continuous water quality gage stations.
- Stream reaeration was adjusted to fit the phase of the DO diel profile.
- Bottom algae (periphyton) growth parameters were adjusted to fit the amount of stream metabolism indicated by the diel DO and pH changes over the course of a day. Some of the bottom algae parameters used in the calibration included:
  - maximum growth rate
  - basal respiration rate
  - photo-respiration rate
  - death rate
  - nutrient kinetic rates for uptake and use requirements

For quantitatively assessing model performance, observed DO and pH levels measured continuously during the study year (at 101st Ave, 40th Ave, and White St.) were compared against simulated values (Table 19). Table 19 uses statistical goodness-of-fit statistics described above (the root mean squared error (RMSE) and bias) to compare daily average, daily maximum, and daily minimum.

Table 19. Root mean squared error (RMSE) and overall bias of differences between QUAL2Kw simulated and observed daily average, minimum, and maximum dissolved oxygen (mg/L) and pH (standard units) in Wide Hollow Creek.

		Daily average		Daily minimum		Daily maximum	
Parameter	**Site**	**Bias**	**RMSE**	**Bias**	**RMSE**	**Bias**	**RMSE**
Dissolved Oxygen	WHC at 101st	-0.5	1.0	-0.2	0.7	-1.1	1.6
	WHC at 40th	0.1	0.5	0.3	0.7	-0.3	0.8
	WHC at White St	0.2	0.8	0.3	0.6	0.2	1.3
pH	WHC at 101st	-0.2	0.3	0.0	0.1	-0.3	0.4
	WHC at 40th	0.1	0.1	0.1	0.2	0.0	0.1
	WHC at White St	0.0	0.2	0.1	0.2	0.0	0.4

The tabulated values above show a good fit overall based on the RMSE for DO daily minimum, which is typically less than 0.6 mg/L, and the pH daily maximum, which was less than 0.4 pH.

For qualitatively assessing model performance, simulated DO levels were plotted against observed values (Figures 61 and 62). Plots were made comparing hourly observed and simulated DO and pH levels for the study year. Overall goodness-of-fit statistics based on hourly comparison of the values are also shown for each reach on these plots.

In general, the algal productivity calibration was difficult for Wide Hollow Creek because the creek is made up of a series of small heterogeneous reaches, each having unique channel geometry, vegetation influence, and water balances (alkaline groundwater versus low-conductivity irrigation water). This heterogeneity led to a patchy distribution of algal productivity throughout the creek length. Even though the model captured much of the heterogeneous dynamics suitably, some events, like the algal productivity spike in the spring of 2014 at the White Street location were not captured in the model simulation.

The pH simulations often had limited pH observations to compare to because of poor observed pH probe performance at the continuous monitoring gages. Therefore the confidence of pH predictions, particularly outside of the reaches other than where the continuous gage locations were located in the creek, was considered to be low overall. However, pH also turned out to be of least concern during the study year compared to water temperature and DO as a potential water quality limitation for aquatic life in Wide Hollow Creek.

The model simulated daily minimum DO with good precision at the three continuous monitoring sites, although there was some bias (over-prediction of DO) during the non-irrigation season. The highest pH levels captured by the continuous pH gages were from high pH irrigation water delivered to the creek at 101st Ave. during the spring of 2014.

Several sensitivity analyses were ran to determine the relative importance of various factors that affect DO. The results of the sensitivity analyses are presented in Appendix H.

DO levels were sensitive to perturbation of water depth and shade (both factors affect the amount of light available for algal productivity). Comparatively, the DO levels were insensitive to moderate perturbation of water velocity, air temperature, water temperature, and nutrient levels. The model sensitivity to increased and decreased light reinforce the premise that light is the most limiting factor affecting the algal productivity in Wide Hollow Creek.

Model calibration indicated that source water to the creek can be important to the seasonal levels of DO and pH in parts of the creek, for instance, low DO and low pH groundwater dominated the signals at 101st Ave during the non-irrigation season.

Predicted DO levels during the hottest part of the irrigation seasons (summer critical temperature months of June, July and August) correctly simulated the influence of warmer water temperature on DO levels. The model correctly predicted that combining low DO saturation levels (highest water temperature) in July and August of 2013 with high algal productivity would produce daily minimum DO levels below the minimum DO criterion of 8 mg/L.

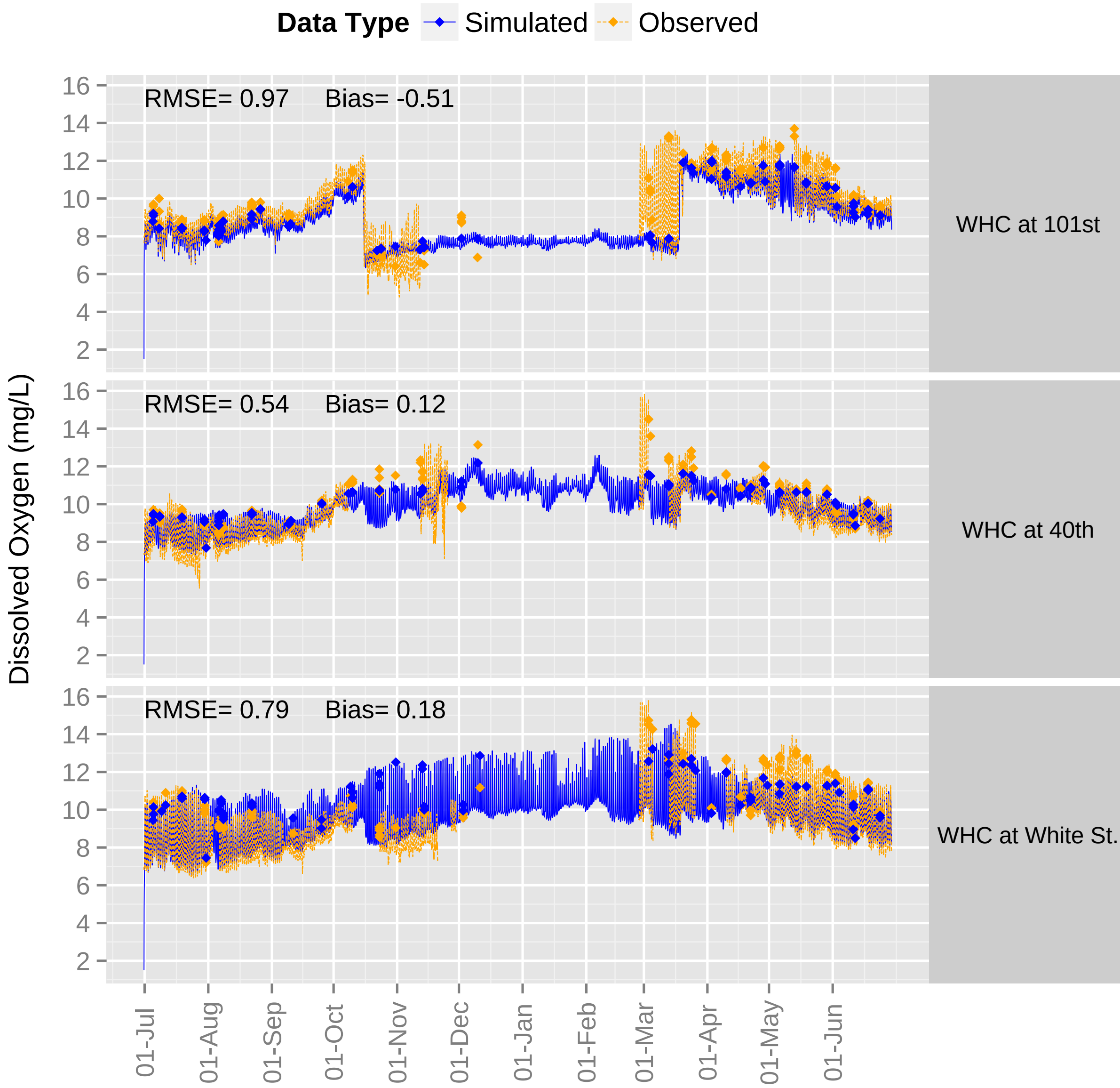


Figure 61. Hourly simulated (predicted) versus observed dissolved oxygen in Wide Hollow Creek during the study year.

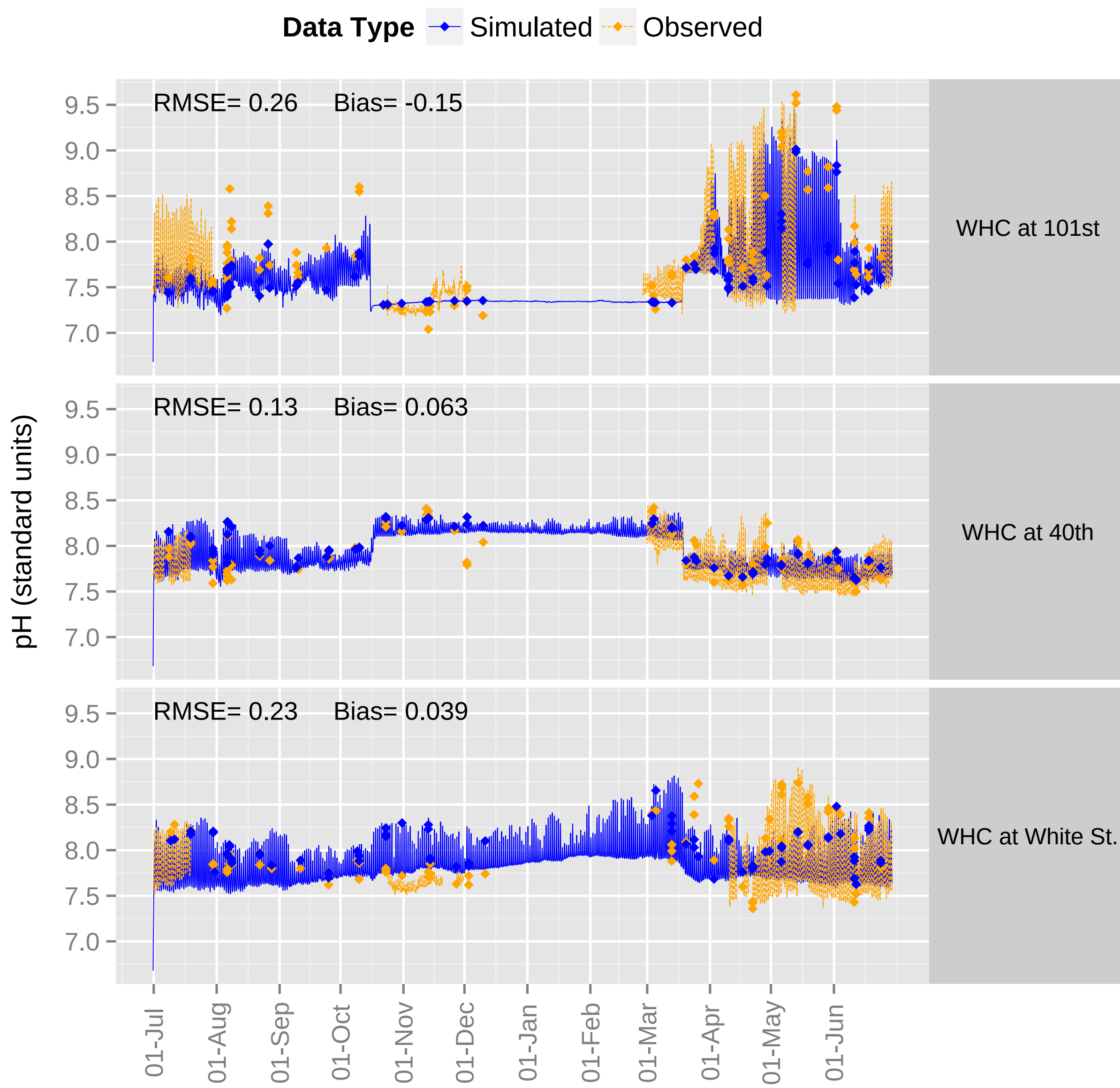


Figure 62. Hourly simulated (predicted) versus observed pH in Wide Hollow Creek during the study year.

QUAL2Kw calibrated model summary

The calibrated QUAL2Kw model adequately simulated water temperature, DO, and pH in Wide Hollow Creek.

Model flow and suspended solids impact both water temperature, DO, and pH. The model calibration for flow indicated that flow in the creek varies from hour to hour during irrigation season, due to the variability of various irrigation sources. The suspended solids calibration indicated that irrigation water imports large amounts of detritus to the creek, especially during the “flip-flop” operation on the Naches River. Suspended solids can affect the availability of light for photosynthesis.

The calibration for water temperature indicated that much of the creek was well shaded during the study year. The warmest temperatures in the creek were found to occur in upstream reaches (near irrigation inputs). Travel time is shorter during the irrigation season due to increased water discharge rate and velocity, which reduces the exposure of creek water to environmental heating.

The model calibration and sensitivity tests for DO and pH indicate that algal productivity in Wide Hollow Creek is mostly controlled by light availability, rather than water temperature or nutrients. Water temperature exceeds temperature criteria, and does not limit algal productivity in Wide Hollow. Nitrogen and phosphorus also do not limit algal productivity because there is an excess of the nutrients in Wide Hollow Creek. Where sufficient light is available to aquatic plants, the model predicts that increased algal productivity will lead to DO and pH diel swings that cause excursions to the DO and pH water quality criteria.

QUAL2Kw model scenarios

Ecology next used the calibrated QUAL2Kw model for Wide Hollow Creek to simulate water quality changes in the creek due to changing boundary conditions; for instance, turning on or off certain water sources to the creek. This was done by running several model simulations (referred to as “scenarios”) in which selected input sources to the creek were set to zero. Scenario simulation results were then compared against the calibrated 2013-14 model (hereafter referred to as the “baseline model”) to evaluate how water quality changed in the scenario simulation.

The model scenarios described below are hypothetical and are not intended to represent planned or anticipated changes to the creek. The scenarios evaluate the sensitivity of the creek’s water quality to various point source inputs (such as irrigation inputs) and shade. Ecology is not aware of any current plans or proposals to reduce or eliminate either inputs to the creek or diversions from the creek.

QUAL2Kw model scenarios set up

The following model setup conditions were used to define the scenarios:

A. Current channel geometry and routing (in other words, present day stream channel conditions were used for the scenario simulations, although historical evidence indicates that channel geometry in Wide Hollow Creek has changed over time).

B. No irrigation flow from Yakima Valley Canal, Congdon Orchards and DID #48. Simulation results for temperature and DO include only the present day perennial portion of the creek from 64th Ave downstream, since the creek becomes intermittent upstream of this location without Yakima Valley Canal irrigation inputs. For pH, results include only 40th Ave and White Street locations (where continuous gaging occurred).

C. No water withdrawals from the following diversions: Perry, Broadway, Fines Ditch, and Hodkinson. Diversions were turned off because without Yakima Valley Canal irrigation inputs, portions of the creek "dry up" due to the simulated diversions. However, water losses from the creek due to infiltration from the creek streambed to groundwater were not changed from the baseline model.

D. No irrigation flow from Naches-Cowiche Canal (both 12th and 32nd Avenues) or Spring Creek Irrigation.

E. No flow from any DID or baseflow stormwater inputs:
   - DIDs #4, #24-L1, #24-L2, #38, and #40
   - Randall pipe and pond
   - Stormwater: Yakima 12th Ave, UG (E5-41), and Yakima RR

F. Reduced shade (50% of present day) due to lack of irrigation water to support riparian vegetation.

G. Decrease groundwater recharge to the creek to 23% of current recharge. Vaccaro and Olsen (2007) estimate the amount of recharge in the Ahtanum basin (which includes the Wide Hollow Creek watershed) would have been 23% of current recharge, because present day recharge is increased due to irrigation application of out-of-basin waters.

There are an unlimited number of scenarios that could be tested but Ecology limited the number to 5 different scenarios in this publication. Ecology can run additional model scenario simulations in the future if requested. Ecology selected the following scenarios, using the designated conditions listed above, as variations:

- Conditions A, B, and C above apply to all scenarios.
- **Scenario #1:** conditions A through C.
- **Scenario #2:** conditions A through D.
- **Scenario #3:** conditions A through E
- **Scenario #4**: conditions A through F.
- **Scenario #5**: conditions A through G (model would not run due to parts of the creek drying up)

Scenarios 1 through 3 simulate the water quality changes in Wide Hollow Creek when progressively reducing the amount of water getting into the creek from the managed additions of irrigation water and groundwater drainage collection systems (DIDs).

Scenario 4 simulates water quality changes in Wide Hollow Creek with the reduced flow and also decreased riparian shade.

Scenario 5, in addition to all the above, attempted to simulate water quality changes in Wide Hollow Creek with reduced groundwater recharge to the creek. No simulated results exist for this scenario because the creek went dry in some places and the scenario simulation could not be completed.

QUAL2Kw model scenarios results

The scenario simulations were run for the full study year (July 2013 through the end of June 2014), which represents a complete cycle of irrigation and non-irrigation periods.

The effective area of Wide Hollow Creek that is watered without irrigation sources is only from 64th Ave downstream. Without irrigation water discharging into the creek at 101st Ave, the creek dries up above 64th Ave. Therefore, the scenario and baseline results shown below represent the creek from 64th Ave. to the mouth. The intermittent portion of the creek (model reaches #1-9) were excluded from both the baseline and scenario results prior to preparing the figures below.

For pH simulations, results are limited to the continuously gaged reaches at 40th Ave. and White Street (model reaches 15 and 33), because there was less confidence in the model predictions outside the reaches which were not gaged.

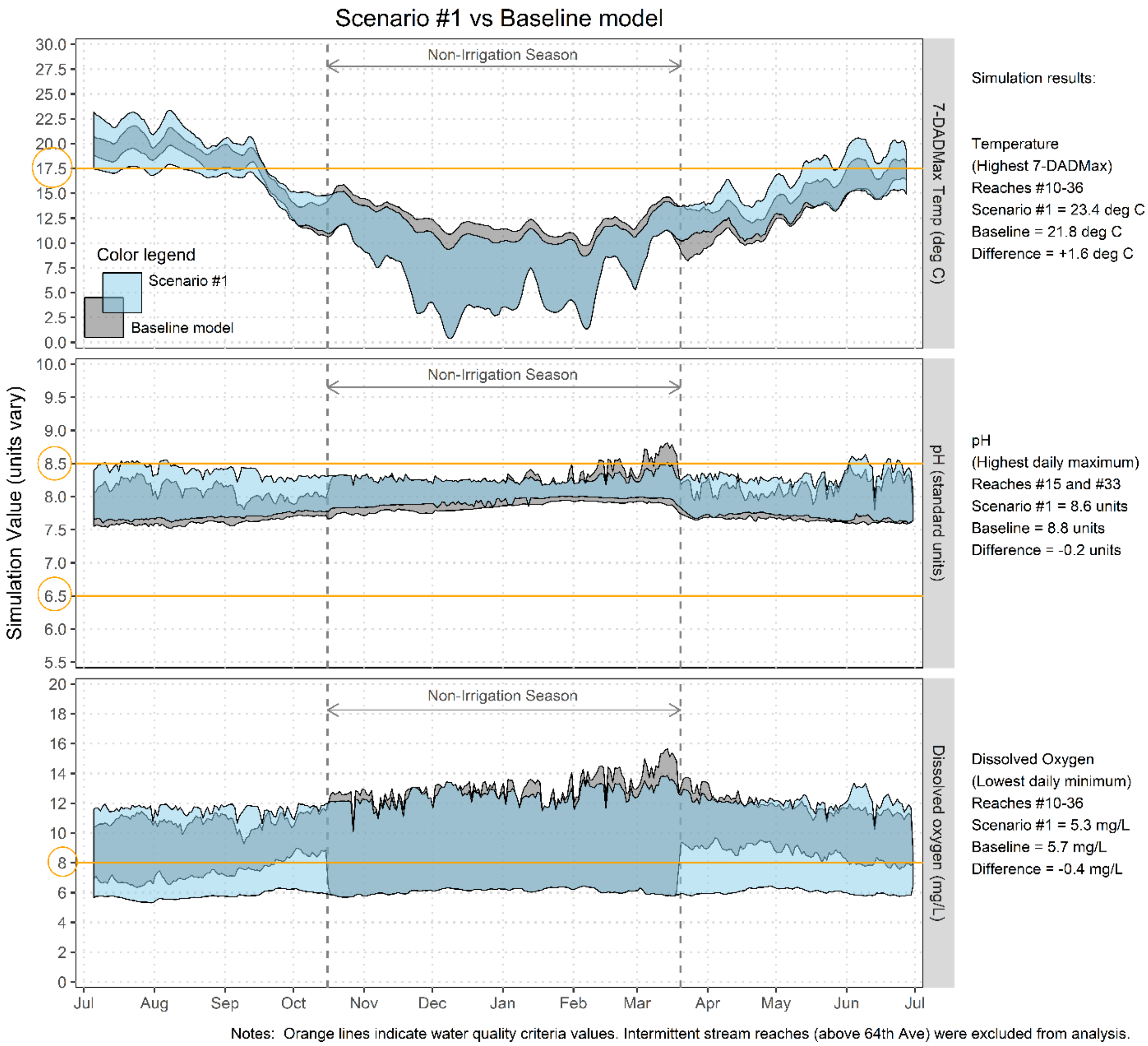


Figure 63. Scenario #1 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen.

Figures 63 to 66 present comparisons between scenarios versus baseline simulation results. These figures show the daily ranges of water temperature (7-DADMax), dissolved oxygen (DO), and pH for the creek from 64th Ave. downstream simulated over the course of the study year. The daily ranges for these parameters are shown as shaded regions on these figures. The baseline model is shown using a gray shaded region and the simulation is shown using a light blue shaded region. When the two regions overlap, the shading color changes to blue-gray. For reference purposes, these figures show water quality criteria as horizontal orange lines with the numeric value circled on the vertical axis. Simulation results are shown beginning on July 5th to allow the model time to adjust from initial starting values on July 1st.

Scenario #1 (conditions A through C above) is compared against the baseline simulation in Figure 63. This scenario simulates the effect of turning off Yakima Valley Canal irrigation water sources to Wide Hollow Creek (but not the Naches-Cowiche irrigation sources). This scenario predicts increased water temperature and decreased DO due to a reduction of water from the Yakima Valley Canal.

Simulation statistics comparing scenario #1 versus baseline simulation (also shown on figure):

- Temperature (highest 7-DADMax): scenario=23.4° C, baseline=21.8° C, change = **+1.6° C**.
- pH (highest daily maximum): scenario=8.6 units, baseline=8.8 units, change = **-0.2 units**.
- DO (lowest daily minimum): scenario=5 mg/L, baseline=5.7 mg/L, change= **-0.4 mg/L**.

Flow is reduced in scenario #1 because sources of water are turned off from the Yakima Valley Canal. Flow impacts are smaller below Fines Ditch (in Union Gap) due to turning off water diversions in the scenario. Average flow for the baseline model was ~20 cfs during irrigation season and ~3 cfs during non-irrigation season. Scenario #1 flow averaged ~7 cfs during the irrigation season.

Reduced flow may enhance the impacts of some other input sources to the creek, especially near 64th Avenue where groundwater inputs enter the creek with little or no flow coming from upstream. This results in cooling and year-round reduction of DO at this location.

Reduced flow also means that water moves more slowly through the system (see Figure 67 and discussion below). Slower moving water has longer exposure times to sources of heating such as solar radiation and ambient air temperature. This results in temperature increases, especially in areas of the creek with few sources of water.

Scenario impacts during the non-irrigation season are due to turning off the Fines Ditch diversion. Without this diversion during non-irrigation season there is increased flow in the White Street and Union Gap portions of the model.

Scenario #2 (conditions A through D above) is compared against the baseline simulation in Figure 64. This scenario simulates the effect of turning off irrigation water sources to Wide Hollow Creek from the Naches-Cowiche Canal (with Yakima Valley Canal input sources also turned off). Similar to scenario #1, this scenario predicts increased water temperature and decreased DO due to a reduction of irrigation water sources.

Simulation statistics comparing scenario #2 versus baseline simulation (also shown on figure):

- Temperature (highest 7-DADMax): scenario=23.6° C, baseline=21.8° C, change = **+1.8° C**.
- pH (highest daily maximum): scenario=8.7 units, baseline=8.8 units, change = **-0.1 units**.
- DO (lowest daily minimum): scenario=4.9 mg/L, baseline=5.7 mg/L, change= **-0.4 mg/L**.

Flow is further reduced in this scenario beginning at 32nd Avenue. The impact to water quality is similar to scenario #1 overall. Average irrigation season flow for scenario #2 was reduced to ~5 cfs, compared to ~7 cfs for scenario #1.

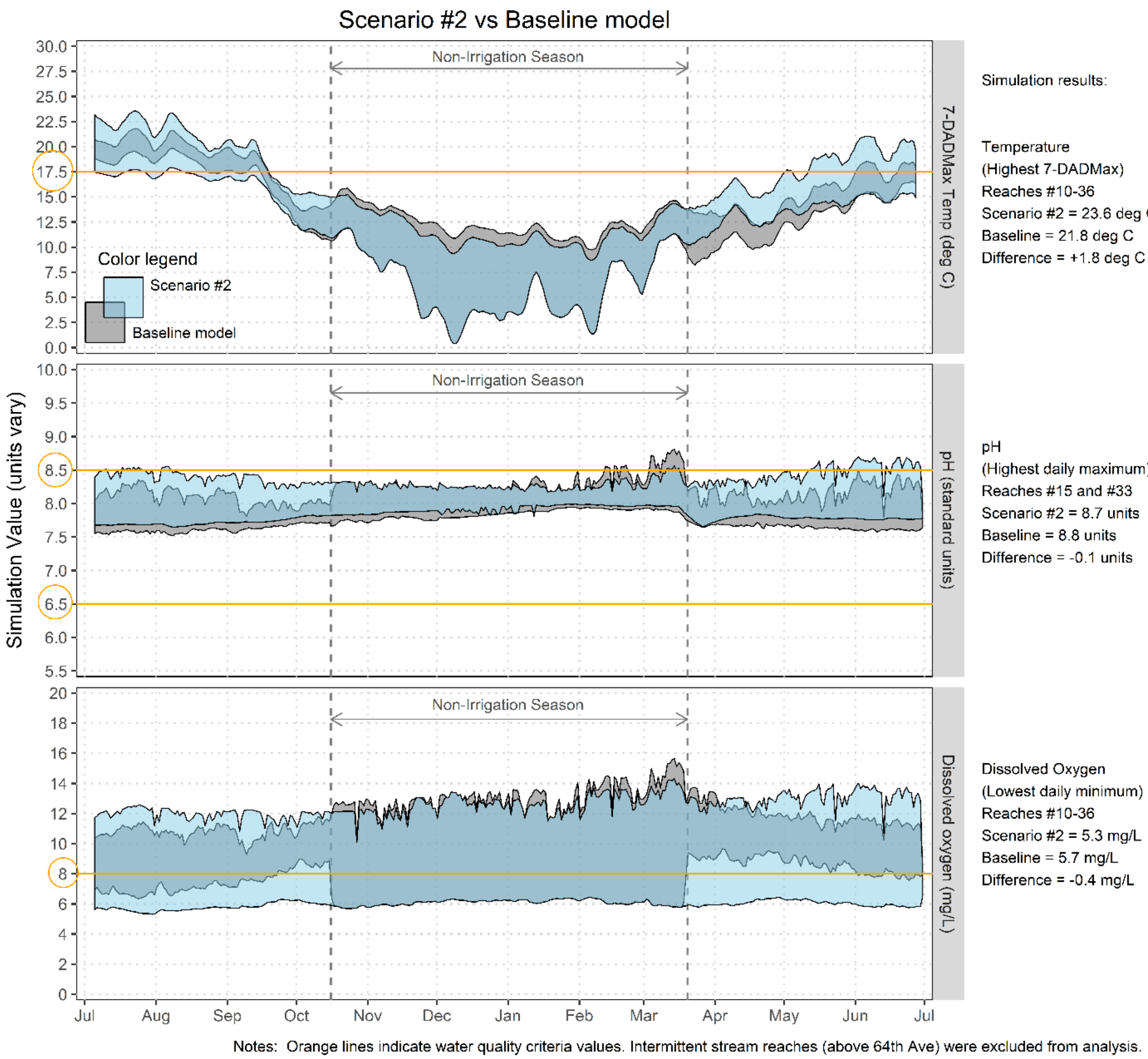


Figure 64. Scenario #2 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen.

Scenario #3 (conditions A through E above) is compared against the baseline simulation in Figure 65. This scenario simulates the effect of turning off groundwater drain sources to Wide Hollow Creek from DID and stormwater outfalls (with Yakima Valley Canal and Naches-Cowiche Canal input sources are also turned off). This scenario predicts an even larger increase in water temperature and larger decrease in DO from irrigation reduction scenarios, as well as an increase in pH.

Simulation statistics comparing scenario #3 versus baseline simulation (also shown on figure):

- Temperature (highest 7-DADMax): scenario=27.8° C, baseline=21.8° C, change = **+6.0° C**.
- pH (highest daily maximum): scenario=9.3 units, baseline=8.8 units, change = **+0.5 units**.
- DO (lowest daily minimum): scenario=2.3 mg/L, baseline=5.7 mg/L, change= **-3.0 mg/L**.

Flow during irrigation season in scenario #3 is only ~2 cfs. This is less than the baseline simulation flow during non-irrigation season which was ~3 cfs.

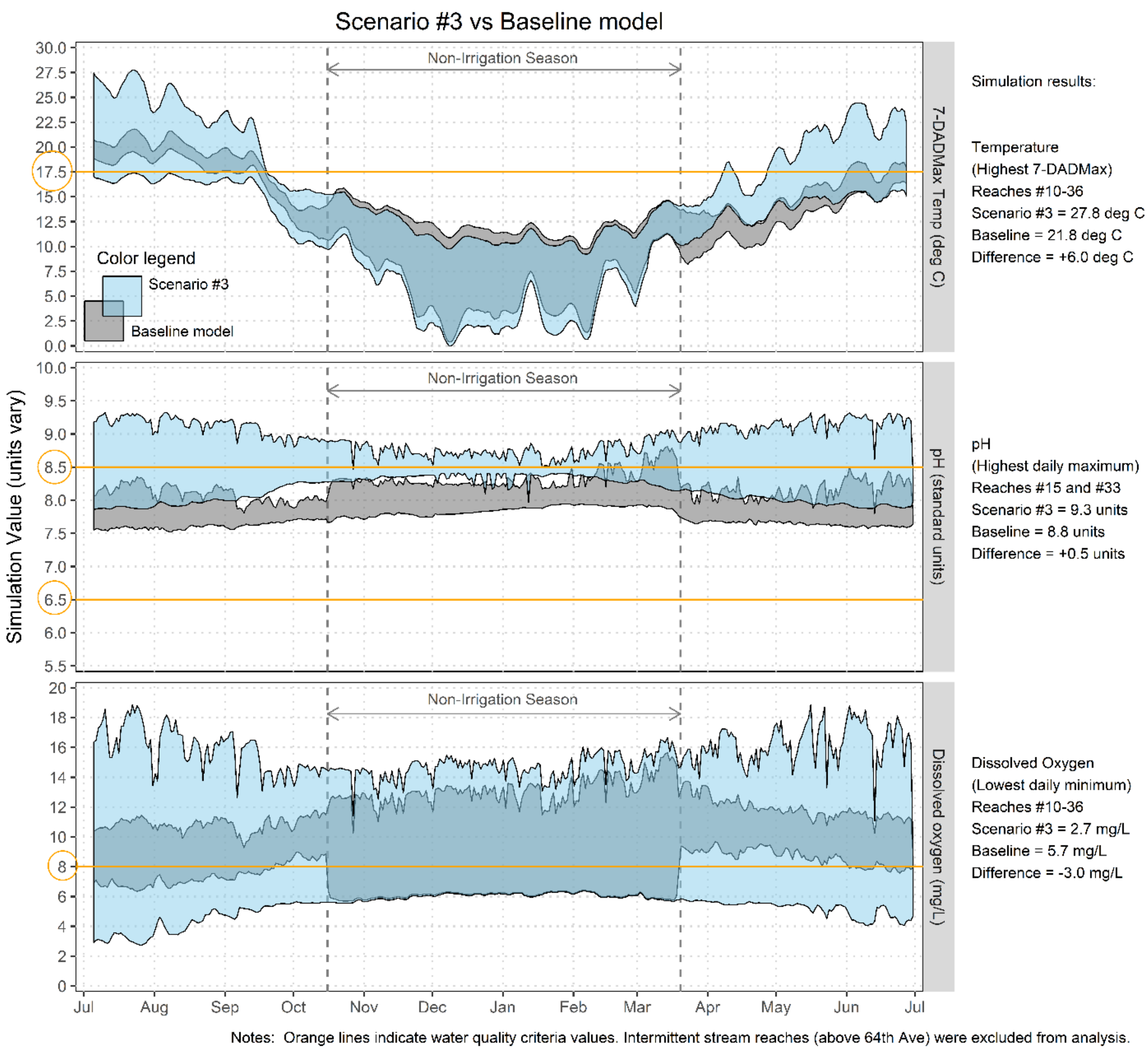


Figure 65. Scenario #3 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen.

Scenario #4 (conditions A through F above) is compared against the baseline simulation in Figure 66. This scenario simulates the effect of reduced shade (50% of present day) due to the lack of irrigation water to support riparian vegetation. Almost all point source inputs to the creek are turned off (similar to scenario #3). This scenario predicts an even larger increase in water temperature and decrease in DO due to the reduction in shade.

Simulation statistics comparing scenario #3 versus baseline simulation (also shown on figure):

- Temperature (highest 7-DADMax): scenario=27.8° C, baseline=21.8° C, change = **+9.1° C**.
- pH (highest daily maximum): scenario=9.3 units, baseline=8.8 units, change = **+0.7 units**.
- DO (lowest daily minimum): scenario=2.3 mg/L, baseline=5.7 mg/L, change= **-3.9 mg/L**.

Scenario #4 used the same amount of flow as scenario #3, only with reduced shade.

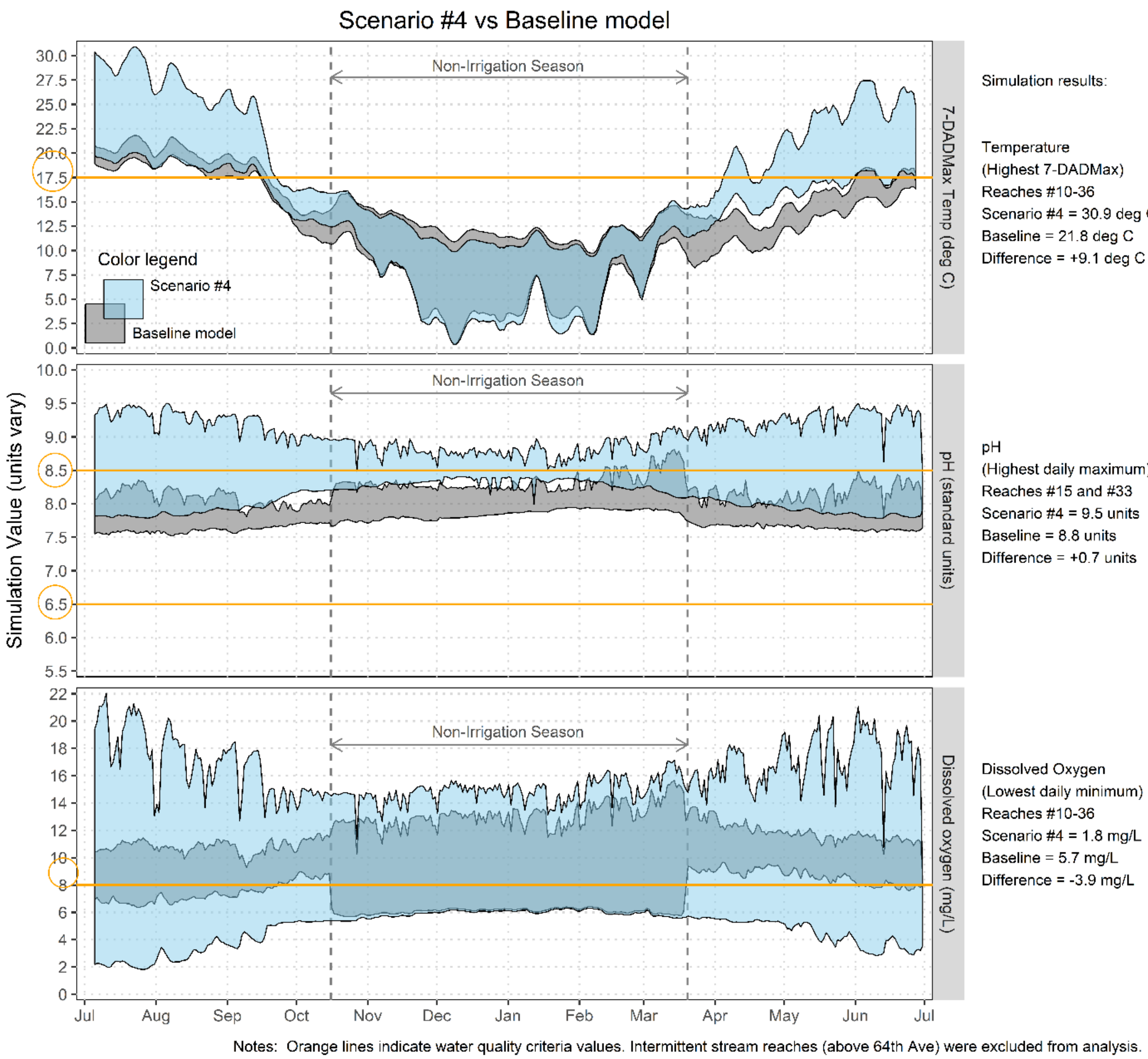


Figure 66. Scenario #4 versus baseline simulation results for temperature (daily 7-DADMax), pH, and dissolved oxygen.

Scenario #5 (conditions A through G above) could not be compared against the baseline simulation because the creek went dry in some places and the simulation could not be completed. This scenario simulates the effect of reduced groundwater recharge to Wide Hollow Creek (23% of present day recharge), mimicking pre-development times when irrigation water was not applied in the basin. Small seeps near 101^{st} Ave., 64^{th} Ave., and 16^{th} Ave. are predicted to infiltrate back underground within a short distance of their appearance. The creek would go dry below these areas. It should be noted that Wide Hollow Creek would remain perennial below Union Gap in scenario 5. This part of the creek includes East Spring Creek, which was a noted perennial spring tributary of the Yakima River in pre-development times.

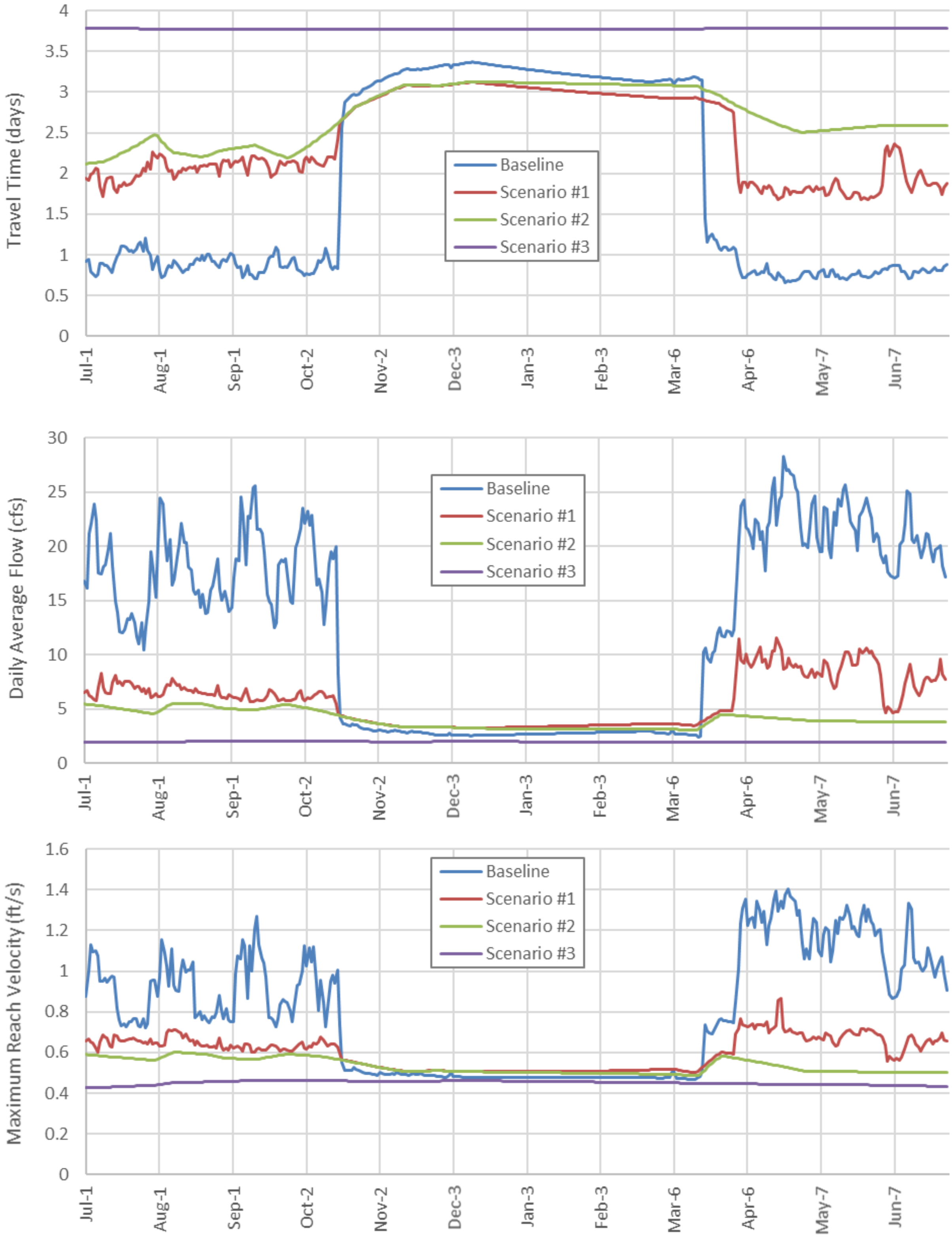


Figure 67. Travel time, daily average flow, and maximum reach velocity comparison between the baseline and scenario simulations (from 64th Ave to the mouth).

Model scenario results summary

The model scenario figures show the predicted daily range of water temperature, DO, and pH in Wide Hollow Creek from 64th Ave. to the mouth. The scenarios only present results from 64th Ave downstream because the creek dries up above 64th Ave. without irrigation water discharging into the creek.

Under study year conditions, the baseline calibrated model predicts (in agreement with the observed measurements) that the creek would not meet the aquatic life criteria for daily maximum water temperature and daily minimum DO from June through September. In addition, daily minimum DO would be below the criterion for all of the non-irrigation season. The criteria for pH would be met most of the time, except for daily maximum pH which briefly exceeds the maximum criterion at the end of the non-irrigation season.

The water quality model predicts that eliminating irrigation water additions to the creek would exacerbate both the magnitude and frequency of the water temperature, DO and pH exceedances. Scenario #2 (no irrigation water) predicts that the irrigation season would have even higher daily maximum water temperature exceedances starting in May, year-round DO daily minimums below the criterion, and slightly higher daily pH maximums (exceeding the 8.5 criterion) June through September.

As source waters to the creek are further reduced to only groundwater seeps (scenario #3) and the riparian canopy is reduced 50% (increasing algal productivity in scenario #4), the model predicts even more drastic excursions from criteria for water temperature, DO and pH levels. In July, daily maximum water temperatures could exceed 30°C and the daily minimum DO could drop to 2 mg/L. Additionally, the entire range of daily pH levels would be expected to sharply shift upwards (year-round) because the high-alkaline groundwater has a higher pH potential.

Even though the model scenarios predict that water temperature in the creek increases when irrigation inputs are reduced, it is unlikely that discharging additional irrigation water would cool the creek. This is because the irrigation water temperature (from the Naches River) sometimes exceeds water quality temperature criterion (17.5 degrees C) before it is discharged to Wide Hollow Creek. Currently, the fully shaded portions of Wide Hollow Creek slightly cool down the irrigation water as it moves downstream in the creek.

Meanwhile, although reducing irrigation water inputs increases the proportion of cooler groundwater in Wide Hollow Creek, it also increases the residence time of water in the creek which allows more time for the groundwater to heat up after it enters the creek. As shown in the scenarios above, reducing irrigation water is not predicted to improve water temperature and actually exacerbates the problem.

The model also indicates that the DO levels in Wide Hollow are improved with irrigation water addition by diluting the low-DO groundwater with high-DO irrigation water, and reducing residence time of the water which keeps the water temperature cooler (increasing the DO saturation of the water). By similar mechanisms, irrigation water additions improve pH levels in Wide Hollow Creek, particularly by diluting the highly alkaline groundwater.

Simulating pre-development flow conditions (23% of current groundwater flow) in Wide Hollow Creek (below 101st Ave.) resulted in several reaches of the creek going dry. The reaches that are predicted to dry up are:

- From 80th Ave to just above 64th Ave
- From 48th Ave to just above 16th Ave
- From 3rd Ave to Main St in Union Gap

Groundwater seeps at 101st Ave, 64th Ave, and 16th Ave are predicted to be very small (0.02 to 0.22 cfs) and would only flow a short distance downstream before infiltrating back to groundwater through the creek streambed.

Wide Hollow Creek is predicted to remain perennial below the gravity drop at the Union Gap mill (in the former East Spring Creek watershed). This is mainly due to the amount of groundwater return in this reach as well as the flow from East Spring Creek.

Pre-development representation

None of the above scenario simulations for Wide Hollow Creek represents true pre-development (or "natural") conditions for the creek. Pre-development conditions would consider what Wide Hollow Creek looked like before human activities affected the water quantity, water quality, channel shape and routing, and riparian of the creek.

If a TMDL evaluation (clean-up study) for Wide Hollow Creek is desired, a pre-development reference condition might need to be established so that human use allowances could be evaluated against a reference condition. For example, in regards to temperature and DO human use allowances, a reference scenario (which best represents pre-development conditions) would have to be compared to scenarios with human activities to see if human activities are causing more than a:

- 0.3°C increase in temperature above pre-development temperature levels (human activities are not allowed to cause more than a 0. 3°C temperature increase above pre-development levels that go above the maximum temperature criterion, in this case, 17.5°C 7-DADMax).
- 0.2 mg/L decrease in DO below pre-development DO levels (human activities are not allowed to cause more than a 0. 2 mg /L decrease in DO below pre-development DO levels that go below the minimum DO criterion, in this case, 8.0 mg/L).

Developing a pre-development reference scenario for Wide Hollow Creek poses a difficult challenge for several reasons, including:

- Groundwater is the major source of summer-time flow to Wide Hollow Creek when irrigation water is removed. Pre-development conditions would have to consider the amount of groundwater flow recharging the creek prior to human activities in the basin. Of the scenarios above, scenario #5 may best represent pre-development conditions in Wide Hollow Creek from the standpoint of water quantity in the creek. However, scenario #5 predicts that reducing the amount of groundwater recharge to 23% of the current recharge will result in parts of the creek going dry. This prediction does corroborate with historical evidence that indicates parts of Wide Hollow Creek were intermittent prior to agricultural development.

- The need to consider the water quality of any groundwater sources. For example, currently, groundwater has a nitrate concentration around 5 mg/L which is probably due to human inputs of nitrate. What would the pre-development groundwater nitrate levels be? Lower nitrate levels might be expected to reduce algal productivity and thereby affect the DO and pH levels in the creek.

- The need to consider how to handle pre-development channel shape and routing. The weight of evidence suggests Wide Hollow Creek joined Bachelor Creek as a tributary to Ahtanum Creek in pre-development times, and did not flow into the East Spring Creek drainage. A true pre-development reference condition may have to consider re-routing Wide Hollow Creek back to its original configuration as a tributary to Bachelor Creek and Ahtanum Creek.

In summary, often there is a clear pre-development or natural condition that can be ascertained for a stream that provides a clear direction to strive for in implementing a TMDL to restore a waterway's functions. However, Wide Hollow Creek does not present a clear pre-development condition.

Conclusions

Ecology's results for the 2013-14 Wide Hollow Creek Study for Aquatic Life support the following conclusions:

- This study determined a complete water balance for Wide Hollow Creek, including groundwater sources, so all source constituents could be accounted for in the creek during the Ecology study year (July 2013 through June 2014).
- Currently, Wide Hollow Creek has three streamflow regimes: non-irrigation baseflow, irrigation season flow, and intermittent streamflow from the upper watershed during runoff conditions. During the Ecology study year there were no sustained runoff conditions.
- During the irrigation season of the study year, irrigation water sources dominated the streamflow in Wide Hollow Creek, primarily from Congdon Orchards, the Yakima Valley Canal, and the Naches-Cowiche Canal. All the irrigation water was diverted from the Naches River, and watered Wide Hollow Creek from 101st Ave. downstream.
- During the non-irrigation season, groundwater sources dominated the streamflow in Wide Hollow Creek. The groundwater entered Wide Hollow Creek in discrete reaches where the creek intercepted the groundwater table (seepages) and where drainage networks of underground collection pipes (DIDs) directed groundwater to Wide Hollow Creek. Perennial flow from groundwater sources began below 64th Ave.
- During the study year, Wide Hollow Creek had higher flow in the summer irrigation season than in the winter non-irrigation season. Wide Hollow Creek carried excess irrigation water (during irrigation season).
- During the study year, the travel time of water in the creek during the irrigation season was quick, taking about a day to flow from 101st Ave. to the mouth. The travel time of the water during the non-irrigation season was slower, taking several days to flow from 64th Ave. to the mouth.
- Wide Hollow Creek did not always meet Washington State water quality criteria for water temperature, DO and pH, during the study year. Water temperatures were elevated above criteria from June through September, and DO was sometimes too low during the irrigation and non-irrigation seasons.
- Riparian shade provided a benefit to water quality in the creek by reducing stream temperature and reducing light availability for algal productivity. Algal productivity in the creek was mostly limited by light availability (shade, water depth and water clarity). During the study, nutrients levels were too high to limit algal productivity in the creek.
- Ecology calibrated a QUAL2Kw water quality model to simulate the observed water temperature, DO and pH levels in Wide Hollow Creek. Using the calibrated model, Ecology simulated the irrigation season with reduced irrigation water which resulted in degraded water quality – increased temperature, lower DO, and higher pH. Simulating reduced shade over the creek also increased water temperature. Additionally, simulating the streamflow in the creek back to an estimated pre-development level resulted in parts of the creek drying up.

- Ecology found evidence of salmonid species utilizing reaches in Wide Hollow Creek. Fish surveys showed that the current conditions support limited cold-water aquatic life species in the creek, although this seemed to be true primarily in the East Spring Creek part of the watershed. The dominant fish species in Wide Hollow Creek above Union Gap were temperature tolerant indigenous non-salmon species, including speckled dace and redside shiners, although a few rainbow trout were found near Kissel Park and 3rd Ave.
- Ecology sampled the substrate and habitat at several sites in Wide Hollow Creek and compared them to other reference sites in streams of the Columbia Basin that had minimal or no impact from human activities. In comparison, Wide Hollow Creek sites had higher percent sands/fines in the substrate, more embeddedness of the substrate, lower Benthic Index of Biotic Integrity (B-IBI) scores, with an absence of stoneflies or species classified as pollution sensitive and a higher proportion of non-insect species. In comparison, these metrics suggest the habitat in Wide Hollow Creek is less suitable for supporting Salmonid Spawning, Rearing and Migration use.

Discussion

This study evaluated water quality (aquatic life criteria) in Wide Hollow Creek, in particular, the seasonal characteristics of water temperature, DO, and pH levels, which may affect the life cycles of aquatic life in the creek.

Ecology's study describes the creek's hydrology and water quality as it is currently managed. Ecology also calibrated a water quality model to predict what the creek's hydrology and water quality would look like under different management conditions, including some changes that may mimic pre-development conditions.

Ecology currently designates the aquatic life use within Wide Hollow Creek as supporting Salmonid Spawning, Rearing and Migration. The key identifying characteristic of this use is salmon or trout spawning and emergence that only occurs outside of the summer season (September 16 to June 14) as well as rearing and migration by salmonids throughout the year. Ecology made this assignment by default, and not by an individual assessment of the creek itself.

One of the goals of this study was to determine if the current water quality of Wide Hollow Creek supports its current *aquatic life use* (Salmon Spawning, Rearing, and Migration). This study attempted to answer that question by evaluating whether the creek's water quality met the temperature, DO, and pH *aquatic life criteria* established for Salmonid Spawning, Rearing and Migration use.

Ecology evaluated the aquatic life criteria for current conditions (study year) and simulated conditions, such as reduced irrigation water inflow and estimated pre-development flow:

- Study-year conditions did not always meet the aquatic life criteria for water temperature and DO, although the temperature criteria were met for much of the time outside of the summer season. Fish surveys showed that the current conditions support limited cold-water aquatic life species in the creek, although this seemed to be primarily true in the East Spring Creek part of the watershed. The dominant fish species in Wide Hollow Creek above Union Gap were temperature-tolerant indigenous non-salmon species, including speckled dace and redside shiner, although a few rainbow trout were found near Kissel Park and 3rd Ave.
- Simulating reduced irrigation flow to Wide Hollow Creek predicts that water temperature, DO and pH levels in Wide Hollow Creek, particularly above Union Gap, will get worse in the summer, and less supportive of a Salmonid Spawning, Rearing and Migration use.
- Simulating pre-development flow conditions in Wide Hollow Creek predicts that parts of the creek will go dry, suggesting that parts of Wide Hollow Creek may have been naturally intermittent, and not conducive to a Salmonid Spawning, Rearing and Migration use.

Today the flow regime in the creek (with irrigation water) supports limited cold-water aquatic life species from 64th Ave. to the mouth. The added irrigation water during the irrigation season helps to support the limited population of cold-water aquatic life species by providing perennial flow which favorably moderates stream temperature, DO, and pH levels.

In the future, if there is a desire to restore Wide Hollow Creek to a pre-development condition, it would make sense to change the aquatic life use designation for parts of the creek, since it will no longer support a Salmon Spawning, Rearing and Migration use, at least above Union Gap.

Reasons for restoring to a pre-development condition may include the desire to:

- Move the channel of the creek to a new location or back to its original location, disconnected from the East Spring Creek watershed,
- Use irrigation water more efficiently which would reduce excess irrigation water being discharged to the creek. Pressurizing the Yakima Valley and Naches-Cowiche canals could significantly reduce the amount of excess irrigation water reaching Wide Hollow Creek during the irrigation season.
- Support the aquatic life use in the Naches River, recognizing that there is a competing trade-off when moving Naches River water out-of-basin. Leaving more water in the Naches River might:
    - Benefit the aquatic life in the Naches River basin.
    - Help improve water temperature in the lower Naches River.

Recommendations

For managing Wide Hollow Creek "As is"

The following recommendations are made in consideration of managing the creek "as is", recognizing that the creek currently functions as a modified system due to the application of out-of-basin irrigation water. The results of this 2013-2014 study suggest that the current modified system does provide some adequate conditions for a limited Salmonid Spawning Rearing and Migration use (cold-water aquatic life habitat and function) in parts of the creek.

Actions which might protect the current aquatic life use (a limited Salmonid Spawning, Rearing and Migration use) include:

- Continued addition of Naches River irrigation water will dilute the heavily concentrated groundwater backbone of Wide Hollow Creek, and moderate water temperature, DO, and pH levels.
- Implementing a temperature TMDL on the Naches River may provide delivery of cooler irrigation water to Wide Hollow Creek.
- Implementing a DO and pH TMDL on the Naches River may provide delivery of cleaner irrigation water to Wide Hollow Creek (less detritus and nutrients).
- Shading or piping the Yakima Valley Canal and the Naches Cowiche Canal could provide cooler irrigation water to Wide Hollow Creek and also would inhibit growth of algae in the canals (eliminating the need for algaecides in the canal), and reduce organic matter to the creek.
- Creating more appropriate and functional riparian areas that create more shade and stabilize the banks of the creek may provide for cooler water temperature.
- Reducing the DID and stormwater sources to Wide Hollow would improve water quality in the creek. Even though this study did not have the opportunity to fully characterize the stormwater aspects of these sources, they do contribute to poorer water quality in the creek (see Table 12). Having stormwater basins that infiltrate DID and stormwater flow instead of discharging directly to the creek would be preferable for other water quality concerns as well (bacteria and toxics), especially during storm runoff events.
- Improving groundwater water quality. For example, the non-irrigation season has groundwater nitrate around 5 mg/L which is probably because of human inputs of nitrate. DO and pH levels may be improved if groundwater sources had lower nitrate concentrations.
- Identifying unknown discharges to the creek, some identified as spikes in the observed flow record (see Appendix I), should be investigated and regulated as necessary.

As mentioned before, the course of action of maintaining the creek "as is" should also come with the recognition that this there are trade-offs for keeping Wide Hollow Creek as an artificial system. In the future, if a management decision is made to restore Wide Hollow to a pre-development condition, the following recommendations are made:

For restoring Wide Hollow Creek to a "Pre-development condition"

This study predicts that *restoration* to a pre-development condition would decrease cold-water aquatic life habitat and function for the parts of Wide Hollow Creek above Union Gap.

The following recommendations are made for actions initiated if Wide Hollow Creek is restored to a pre-development condition:

- Complete a study that would establish a new aquatic life use for Wide Hollow Creek. These studies are called Use Attainability Analyses (UAA). The new aquatic life use would take into account what is attainable as far as water quality and habitat in a pre-development condition. The predicted hydrology and water quality would inform what kind of aquatic life species are expected to survive in a pre-development condition. As described in model scenarios from this study, the creek would not support a Salmon Spawning, Rearing and Migration use.
- Restore appropriate function of pre-development channels or wetlands in the watershed.
- Reduce the DID and stormwater sources to a pre-development Wide Hollow Creek in order to improve water quality in the creek. Discharge stormwater and DID water to stormwater infiltration basins instead of discharging directly.
- Protect and improve groundwater water quality so that the groundwater seeps that still discharge to Wide Hollow Creek would benefit the new aquatic life species expected in a pre-development condition.

This report also recommends:

For the intermittent reaches in upper Wide Hollow Creek (above 101st Ave)

The upper reaches of Wide Hollow Creek (above 101st Ave) do not have the perennial flow or the natural stream processes that are required to support the beneficial use of Salmonid Spawning, Rearing, and Migration. These reaches are intermittent year-to-year, and historically were intermittent as well, as drawn on the 1899 USGS map. These reaches may briefly have had perennial flow during the time period when the Yakima-Tieton Irrigation District system was not piped or pressurized, but they are again intermittent, appearing to run only during runoff events in some years. The upper watershed did not have a sustained runoff during the Ecology study year (July 2013 through June 2014).

The upper reaches of Wide Hollow Creek and Cottonwood Creek (above Dazet Rd) are on the list of impaired waters because of low DO levels that were measured in 2004-06.

A review of the data from that time period showed that measurements were taken when there was extremely low flow (a trickle of less than 0.2 cfs) of water in the stream channels. The water samples also had high specific conductivity indicating groundwater source. The emerging groundwater would be expected to have low DO levels as well.

Because the upper parts of Wide Hollow Creek were dry during the study year, Ecology was unable to confirm any low DO levels. As described above, these reaches are not expected to support any Salmon Spawning, Rearing and Migration use; therefore. Ecology recommends:

- Removal of the 303(d) DO listings for Wide Hollow Creek and Cottonwood Creek above Dazet Road (where Cottonwood Creek and Wide Hollow Creek join)

Even though flow from the upper watershed is intermittent, protecting the quality of upstream water sources in the upper watershed (above 101st Ave), for the times when there is runoff, would be beneficial to aquatic life in Wide Hollow Creek and waters downstream. Projects that protect or restore any natural hydrology and natural stream function in the drainages in the upper watershed should be encouraged.

References

Adams, K., 2010. Quality Assurance Monitoring Plan: Ambient Biological Monitoring in Rivers and Streams: Benthic Macroinvertebrates and Periphyton. Washington State Department of Ecology, Olympia, WA. Publication 10-03-109.
https://apps.ecology.wa.gov/publications/SummaryPages/1003109.html

Bohn, G., 2015. Mid-Yakima River Basin Bacteria Total Maximum Daily Load Water Quality Improvement Report - DRAFT. Publication 15-10-028. Washington State Department of Ecology, Olympia, Washington.
https://apps.ecology.wa.gov/publications/SummaryPages/1510028.html

Bothwell, M. L., 1985. Phosphorus limitation of lotic periphyton growth rates: An intersite comparison using continuous-flow troughs (Thompson River system, British Columbia) 1. Limnology and oceanography, 30(3), 527-542.

Carroll, J., 2013, Wide Hollow Creek Water Quality Study for Aquatic Life Use. Quality Assurance Project Plan. Temperature, Dissolved Oxygen and pH. Washington State Department of Ecology. Olympia WA. Publication 13-03-116.
https://apps.ecology.wa.gov/publications/SummaryPages/1303116.html

CFHMP, 2012. Ahtanum-Wide Hollow Comprehensive Flood Hazard Management Plan. Yakima County Water Resources Division Management Division.
https://www.yakimacounty.us/317/Comprehensive-Flood-Hazard-Management-Pl

Chapra, S.C., 1997. Surface Water-Quality Modeling. McGraw-Hill, New York, N.Y.

Chapra, S.C., Pelletier, G.J. and Tao, H., 2008. QUAL2K: A Modeling Framework for Simulating River and Stream Water Quality, Version 2.11: Documentation and Users Manual. Civil and Environmental Engineering Dept., Tufts University, Medford, MA.,

Daubenmire, R.F., 1970. Steppe Vegetation of Washington. Washington Agricultural Experiment Station. Technical Bulletin No. 62.

Dugger, D., 2013. Quality Assurance Project Plan: Mid-Yakima River Tributaries Temperature Study. Washington State Department of Ecology, Yakima, WA. Publication 13-03-114.
https://apps.ecology.wa.gov/publications/SummaryPages/1303114.html

Easterbrooks, John A., 2016. Personal communication by email on 2-11-2016. Washington Department of Fish and Wildlife, Yakima, WA.

Ecology, 2015. TTools for ArcGIS. Washington State Department of Ecology, Olympia, WA.
www.ecy.wa.gov/programs/eap/models.html

EPA, 1985. Rates, Constants, and Kinetics Formulations in Surface Water Quality Modeling (Second Edition). Publication EPA/600/3-85-040. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA 30613.

Farnsworth, L., 1872. Original subdivision notes and map of the United States General Land Office survey. On file with the US Department of the Interior, Bureau of Land Management for Oregon/Washington. Cadastral Survey Records. Portland, OR.

Foxworthy, B.L., 1962. Geology and Groundwater Resources of the Ahtanum Valley, Yakima County, Washington. Geologic Survey Water-Supply Paper 1598. Washington DC, US Government Printing Office.

Haring, D., 2001. Habitat Limiting Factors. Yakima River Watershed, Water Resource Inventory Areas 37-39. Final Report. Washington State Conservation Commission, Olympia, WA.

Harvester, Perry, 2013. Personal communication. Washington Department of Fish and Wildlife, Yakima, WA.

Hill, B., F. McCormick, B. Harvey, S. Johnson, M. Warren and C. Elonen, 2009. Microbial enzyme activity, nutrient uptake and nutrient limitation in forested streams. Freshwater Biology (2010) vol 55, 1005-1019. Published 2009.

Jayne, S.O., 1907. Irrigation in the Yakima Valley, Washington. U.S. Department of Agriculture, Office of Experiment Stations. Bulletin 188. Washington D.C. Government Printing Office.

Jensen C.A. and Olshausen B.A., 1901. Soil survey of the Yakima area Washington on field operations for 1901 United States Department of Agriculture Bureau Soils, 1902.

Johnson, A., K. Carmack, B. Era-Miller, B. Lubliner, S. Golding, and R. Coots, 2010. Yakima River Pesticides and PCBs Total Maximum Daily Load: Volume 1. Water Quality Study Findings. Washington State Department of Ecology, Olympia, WA. Publication 10-03-018. https://apps.ecology.wa.gov/publications/SummaryPages/1003018.html

Kendra, W., 1988. Quality of Water, Sediment, and Biota in Wide Hollow Creek, Washington. Washington State Department of Ecology, Olympia, WA. Publication 88-e26. https://apps.ecology.wa.gov/publications/SummaryPages/88e26.html

Michelsen T., 2011. Development of benthic SQVs for freshwater sediments in Washington, Oregon, and Idaho. Report to Washington Department of Ecology and Oregon Department of Environmental Quality. Ecology Publication 11-09-054. Prepared by Avocet Consulting. https://apps.ecology.wa.gov/publications/SummaryPages/1109054.html

NRCS, 2016. Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at https://websoilsurvey.nrcs.usda.gov/. Accessed June 2016.

Pelletier, G., 2015. Shade.xls: a tool for estimating shade from riparian vegetation. Washington State Department of Ecology, Olympia, WA. www.ecy.wa.gov/programs/eap/models.html

Pelletier, G. and S. Chapra, 2008. QUAL2Kw: a modeling framework for simulating river and stream water quality. User's Manual, Theory and documentation. www.ecy.wa.gov/programs/eap/models.html

Pfaff, C., 2002. Harvests of Plenty A History of the Yakima Irrigation Project, Washington. United States Department of the Interior Bureau of Reclamation Technical Service Center, Denver Colorado.

Richardson, E., 1867. Original subdivision notes and map of the United States General Land Office survey. On file with the US Department of the Interior, Bureau of Land Management for Oregon/Washington. Cadastral Survey Records. Portland, OR.

Rier, S. T., & Stevenson, R. J. (2006). Response of periphytic algae to gradients in nitrogen and phosphorus in streamside mesocosms. Hydrobiologia, 561(1), 131-147.

Snouwaert, E. and Stuart, T., 2015. North Fork Palouse River Dissolved Oxygen and pH Total Maximum Daily Load: Water Quality Improvement Report and Implementation Plan. Publication 15-10-029, October 2015. Washington State Department of Ecology, Olympia, WA. https://apps.ecology.wa.gov/publications/SummaryPages/1510029.html

Stohr, A., 2008. Standard Operating Procedures for the computer analysis of hemispherical digital images collected as part of a temperature Total Maximum Daily Load (TMDL) or Forests and Fish Unit technical study. Version 2.0. Washington State Department of Ecology, Olympia, WA. SOP Number EAP046. www.ecy.wa.gov/programs/eap/quality.html

Tarbutton, S., 2012. Mid-Yakima River Basin Fecal Coliform Bacteria Total Maximum Daily Load: Water Quality Study Findings. Washington State Department of Ecology, Olympia, WA. Publication 12-03-047.
https://apps.ecology.wa.gov/publications/SummaryPages/1203047.html

USGS, 1899. United State Department of the Interior, Geological Survey, Washington Ellensburg Quadrangle. Surveyed in 1899.

Vaccaro, J.J. and T.D. Olsen, 2007. Estimates of Ground-Water Recharge to the Yakima River Basin Aquifer System, Washington, for Predevelopment and Current Land-Use and Land-Cover Conditions. Scientific Investigations Report 2007-5007. U.S. Geological Survey, Reston, VA.

Wetzel, R. G., 1983. Limnology (Second Edition), CBS College Publishing. New York, NY.

Appendices

Appendices A-I are linked to this report as an "Appendices" file at:
https://apps.ecology.wa.gov/publications/SummaryPages/2003007.html

Appendix A. Groundwater Study

Appendix B. Bioassessment Study

Appendix C. Water Quality Study Data Summary

Appendix D. Water Quality Study Data Quality

Appendix E. Stream Heating Mechanisms

Appendix F. QUAL2Kw Model Inputs

Appendix G. QUAL2Kw Model Calibration

Appendix H. QUAL2Kw Model Sensitivity Analysis

Appendix I. Flow Spikes Fall 2013 - Wide Hollow Creek

Glossary, Acronyms, and Abbreviations

Anthropogenic: Human-caused.

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Designated uses: Those uses specified in Chapter 173-201A WAC (Water Quality Standards for Surface Waters of the State of Washington) for each water body or segment, regardless of whether or not the uses are currently attained.

Diatom: A major group of algae that possess a rigid siliceous cell wall.

Diel: Of, or pertaining to, a 24-hour period.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Diurnal: Of, or pertaining to, a day or each day; daily. (1) Occurring during the daytime only, as different from nocturnal or crepuscular, or (2) Daily; related to actions which are completed in the course of a calendar day, and which typically recur every calendar day (e.g., diurnal temperature rises during the day, and falls during the night).

Effective shade: The fraction of incoming solar shortwave radiation that is blocked from reaching the surface of a stream or other defined area.

Fecal coliform (FC): That portion of the coliform group of bacteria which is present in intestinal tracts and feces of warm-blooded animals as detected by the product of acid or gas from lactose in a suitable culture medium within 24 hours at 44.5 plus or minus 0.2 degrees Celsius. Fecal coliform bacteria are "indicator" organisms that suggest the possible presence of disease-causing organisms. Concentrations are measured in colony forming units per 100 milliliters of water (cfu/100 mL).

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Periphyton: A complex mixture of algae, cyanobacteria, heterotrophic microbes, and detritus that is attached to submerged surfaces.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Pollution: Contamination or other alteration of the physical, chemical, or biological properties of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or are likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Riparian: Relating to the banks along a natural course of water.

Salmonid: Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.

Stormwater: The portion of precipitation that does not naturally percolate into the ground or evaporate but instead runs off roads, pavement, and roofs during rainfall or snow melt. Stormwater can also come from hard or saturated grass surfaces such as lawns, pastures, playfields, and from gravel roads and parking lots.

Study year: July 2013 to June 2014 (for this study).

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and water courses within the jurisdiction of Washington State.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a Margin of Safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants.

These are water quality-limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

90th percentile: A statistical number obtained from a distribution of a data set, above which 10% of the data exists and below which 90% of the data exists.

Acronyms and Abbreviations

BMP	Best management practice
DID	Drainage improvement district
DO	Dissolved oxygen
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software
MEL	Manchester Environmental Laboratory
NPDES	(See Glossary above)
RM	River mile
RPD	Relative percent difference
RSD	Relative standard deviation
SOP	Standard operating procedures
TMDL	(See Glossary above)
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WQA	Water Quality Assessment
WRIA	Water Resource Inventory Area

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
cms	cubic meters per second, a unit of flow
ft	feet
g	gram, a unit of mass
kg	kilograms, a unit of mass equal to 1,000 grams
kg/d	kilograms per day
km	kilometer, a unit of length equal to 1,000 meters
m	meter
mg	milligram
mgd	million gallons per day
mg/d	milligrams per day
mg/L	milligrams per liter (parts per million)
mL	milliliters
NTU	nephelometric turbidity units
s.u.	standard units
ug/L	micrograms per liter (parts per billion)
umhos/cm	micromhos per centimeter
uS/cm	microsiemens per centimeter, a unit of conductivity