Energy Research and Development Division
FINAL PROJECT REPORT

MODELING TOOL TO ASSESS AND MITIGATE THE EFFECTS OF SMALL HYDROPOWER ON STREAM FISHES IN CHANGING CALIFORNIA CLIMATE

Prepared for: California Energy Commission
Prepared by: University of California, Davis

JUNE 2016
CEC-500-2016-043

PREPARED BY:

Primary Author(s):
Lisa C. Thompson
D. Patrick Kilduff
Samuel Sandoval Solis
Sooyeon Yi
Alyssa N. Obester

Wildlife, Fish, and Conservation Biology Department
University of California Davis
1 Shields Avenue
Davis, CA 9566
Phone: 530-754-5732 | Fax: 530-752-4154
http://www.ucdavis.edu

Contract Number: 500-11-033

Prepared for:

California Energy Commission

Lillian Mirviss
Joe O'Hagan
Contract Manager

Aleecia Gutierrez
Office Manager
Energy Generation Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warranty, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

ACKNOWLEDGEMENTS

The authors would like to thank Ken Krich, Research Coordinator and Assistant Director, California Institute for Energy and Environment (CIEE), Eric Lee, CIEE Research Administrator, Lillian Mirviss, California Energy Commission Contract Manager, and retired California Energy Commission Contract Manager Joseph O'Hagan, for their support and assistance at all stages of this project.

The authors thank David Purkey, Charles Young, Jack Sieber, Marisa Escobar, and other staff at the Stockholm Environment for sharing their ideas for this project and for their encouragement to develop the Middle-Ware software. They thank Josue Medellin-Azuara, UC Davis, for sharing his ideas for this project, Victoria Whitworth for applying her fine editorial skills to the project proposal, and Christopher Mosser for his assistance in obtaining the SALMOD model runs and outputs from earlier hydrology and fishery modeling efforts that lead to the current project.

The authors thank Ed Cheslak of Pacific Gas and Electric for providing access to PG&E controlled areas of Butte Creek, and Timothy Sagraves of Sagraves Environmental for generously showing them around the upper Butte Creek watershed and offering invaluable assistance during the temperature logger installation and retrieval.

The authors are grateful to Allen Harthorn and Michael Smith of Friends of Butte Creek for their assistance on their field trips to Butte Creek, and for showing the modelers the real live spring-run Chinook salmon.

The authors are indebted to the stakeholders who participated in the three initial workshops and the final workshop, for sharing their time, expertise, and management experience as the authors sought to design models that would be most useful to develop water management options: Ed Cheslak (Pacific Gas and Electric), Marisa Escobar (SEI-US), Anna Ewing (California Department of Fish and Wildlife), David Hanson (Sacramento Municipal Utility District), Allen Hawthorn (Friends of Butte Creek), Sean Hoobler (California Department of Fish and Wildlife), Beth Lawson (California Department of Fish and Wildlife), Michael Maher (California State Water Resources Control Board), Tracy McReynolds (California Department of Fish and Wildlife), Susan Monheit (California State Water Resources Control Board), Darold Parry (Sacramento Municipal Utility District), David Purkey (SEI-US), Catalina Reyes (Pacific Gas and Electric), Chris Shutes (California Sportfishing Protection Alliance), Michael Smith (Friends of Butte Creek), Dan Teeter (US Forest Service), Gretchen Umlauf (NOAA Fisheries), Amber Villalobos (California State Water Resources Control Board), and Jeff Wetzel (California State Water Resources Control Board).

Finally, the authors thank the UC Davis, CIEE, and California Energy Commission administrative staff who have supported and facilitated their efforts.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Modeling Tool to Assess and Mitigate the Effects of Small Hydropower on Stream Fishes in Changing California Climate is the final report for Exploratory Studies of Potential Environmental Issues with Alternative Energy Futures for California project (contract number 500-11-033) conducted by the University of California Davis. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

When the source of a table, figure, or photo is not otherwise credited, it is the work of the author.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

Proponents of hydroelectric power generation in California frequently find themselves in conflict with proponents of fish over water allocation, yet the impacts of hydropower production and effectiveness of mitigation strategies are often unclear. Meanwhile, California's mandate to increase the amount of renewable energy sources and reduce greenhouse gas emissions has led to incentives to increase the production of energy from small hydropower as part of California's Renewable Portfolio Standard. In this project the authors developed and tested a fish habitat suitability model to assess the impacts and mitigation potential of small hydropower facilities. The model was designed to function seamlessly within an integrated modeling framework that includes (1) a watershed hydrology and water management model, (2) a fish habitat suitability model, and (3) software to link and control the other software components. The models are designed to be easily modified for different watersheds and fish populations, so they may be used to assess environmental effects of numerous small hydropower projects in more than one watershed simultaneously. The analytical (model) framework from this project lays the groundwork for future efforts to assess trade-offs between water use providing freshwater habitat for native fish populations, and the cost-efficient provision of water to small hydropower installations. The anticipated future impact of this project is that small hydropower producers will be able to more efficiently mitigate effects on California stream fishes, minimizing unnecessary curtailment of hydropower production while increasing the share of renewable energy in California's energy mix.

Keywords: Hydropower, model, fish, hydrology, software development, water management

Please use the following citation for this report:

Thompson, Lisa C.; D. Patrick Kilduff; Samuel Sandoval Solis; Sooyeon Yi; Alyssa N. Obester. (University of California Davis). 2015. *Modeling Tool to Assess and Mitigate the Effects of Small Hydropower on Stream Fishes in Changing California Climate.* California Energy Commission. Publication number: CEC-500-2016-043.

TABLE OF CONTENTS

Acknowledgements ..... **i**

PREFACE ..... **ii**

ABSTRACT ..... **iii**

TABLE OF CONTENTS ..... **iv**

EXECUTIVE SUMMARY **1**

Introduction 1

Project Purpose 1

Project Results 2

Project Benefits 2

CHAPTER 1: Introduction **3**

1.1 Small Hydropower 3

1.2 Issue and Purpose of Current Project 5

1.3 Current State of Knowledge 6

1.4 Approach and Scope 8

1.5 Goals and Objectives 9

1.6 Principal Tasks 9

1.6.1 Project Administration 9

1.6.2 Fish Model Development 9

CHAPTER 2: Model Development **11**

2.1 Comparison of Salmod Model to Other Fish Population Dynamics and Habitat Models 11

2.2 Model Structure and Functions 19

2.2.1 Model Processes and Nested Loops 19

2.2.2 Model Functions and their Role in the Simulation 21

2.2.3 Model Population Dynamics Accounting Framework 26

2.3 Model Output 26

2.3.1 Output Data Files 26

2.3.2 Evaluation of Model Performance 29
2.4 Model/Software Availability 29
CHAPTER 3: Model Integration With Master_WEAPhish Middle-Ware 30
3.1 Model integration 30
3.2 Middle-Ware Structure 32
3.2.1 Master_WEAPhish Set Up 32
3.2.2 Master_WEAPhish Structure 32
3.3 Middle-Ware Functions 32
3.3.1 Master_WEAPhish Set Up 32
3.3.2 Climate Scenarios, General Circulation Models, and Water Management Actions 33
3.3.3 Master_WEAPhish Operations 33
3.4 Model Outputs 33
3.5 Middle-Ware/Software Availability 36
CHAPTER 4: Outreach 37
4.1 Stakeholder Meetings 37
4.2 Stakeholder Feedback 38
4.2.1 Butte Creek 38
4.2.2 South Fork American River (Slab Creek) 39
4.2.3 North Fork American River (Clementine Dam) 39
4.3 Final Workshop 39
CHAPTER 5: Field Data Collection 40
5.1 Site Visits and Temperature Logger Installation 40
5.2 Water Temperature Data 44
CHAPTER 6: Discussion 46
6.1 Major Outcomes of Project 46
6.1.1 New Model Framework Centered on WEAP 46
6.1.2 WEAPhish Fish Population Dynamics and Habitat Model 46
6.1.3 Master_WEAPhish Middle-Ware Software 46

6.2 Benefits to Californians 46

6.3 Future Work 47

GLOSSARY 49

REFERENCES 50

APPENDIX A: WEAPhish User's Manual: A guide to installing and running a habitat-based, fish population model, v. 0.1 ..... A-1

APPENDIX B: User's Manual for Middle Ware [Master_WEAPhish] B-1

APPENDIX C: Final Workshop Presentation C-1

LIST OF FIGURES

Figure 1: Small Hydropower Facility on Butte Creek, California (Centerville Powerhouse) 4

Figure 2: Small Hydropower Facility on the South Fork American River (Slab Creek Dam) 4

Figure 3: Analytical Frameworks 6

Figure 4: Central Valley Watersheds in WEAP Application 7

Figure 5: Fish Mortality-Habitat Temperature Relationship 8

Figure 6: Annual Freshwater Fish Population Processes over Space and Time 20

Figure 7: WEAPhish Model Processes and Nested Loops 21

Figure 8: Screenshots of WEAPhish (fish_main.py) Run From Command Line 22

Figure 9: Screenshot of Python Code to Call Loads 23

Figure 10: Screenshot of Folder with WEAPhish Input Data Files 23

Figure 11: Screenshot of Functions Called 24

Figure 12: Screenshot of Fish_main.py Code 25

Figure 13: Sample Output for Physical Habitat 27

Figure 14: Sample Output for Fish Abundance 28

Figure 15: Overview of Model Integration 30

Figure 16: Schematic of Data Flow Between WEAP and WEAPhish Via the Middle-Ware 31

Figure 17: Timing of Data Flow between WEAP and WEAPhish via the Middle-Ware 31

Figure 18: Main Spreadsheet of the Master_WEAPhish Middle-Ware 32

Figure 19: Overview of Middle-Ware Controls of WEAP and WEAPhish Models 34

Figure 20: WEAPhish Python Screen Running from Master_WEAPhish Interface 34

Figure 21: Output Files From WEAP..... 35

Figure 22: Folder of WEAP Output Files 35

Figure 23: Installation of Temperature Loggers 40

Figure 24: Installation of Temperature Loggers 41

Figure 25: Temperature Monitoring Site 41

Figure 26: De Sabla Forebay, Part of Butte Creek's Hydropower Infrastructure 42

Figure 27: Butte Head Dam on Upper Butte Creek, on October 14, 2013 42

Figure 28: Temperature Monitoring Site 43

Figure 29: Butte Creek Sites Where Water Temperature was Monitored in 2013 44

Figure 30: Air Temperature and Stream Temperature Monitoring Results 45

LIST OF TABLES

Table 1: Comparison of Models' Characteristics, Purpose, Spatial Scale, and Temporal Resolution 12

Table 2: Comparison of Models' Premise, Parameter Estimation, Population Dynamics, and Statistical Approach..... 14

Table 3: Comparison of Models' Biophysical Linkages, Ocean Effects, and Human Interactions 17

Table 4: Comparison of Models' Output Data and Software 18

Table 5: Participants in Stakeholder Workshops..... 37

EXECUTIVE SUMMARY

Introduction

Hydroelectric power is currently the largest source of renewable power in the United States, providing more than 54 percent of the nation's total renewable energy supplies (US Department of Energy 2013). Because of changing climate and finite energy resources, there continues to be interest in renewable energy sources including hydropower (Oud, 2002). Most suitable sites for large-scale hydropower, however, have already been developed, and proposals for new, large hydroelectric power projects would not likely garner public support. As a result, small hydroelectric projects, those generating less than 30 megawatts of power, are being explored as potential renewable sources of energy (Paish 2002, Kane 2005, Schwartz et al. 2005, Hall et al. 2006, Navigant Consulting, Inc. 2006, Kosnik 2010, Capik et al. 2012).

Although much information exists about the environmental and ecological impacts associated with large-scale hydropower, little is known about the consequences associated with small hydroelectric projects (Frey and Linke 2002). California's 2005 Energy Policy Act (EPAct) provides incentives for new hydropower development that could be used to encourage developing additional hydropower capacity in California (Navigant Consulting, Inc. 2006). Meanwhile, California's mandate to increase the amount of renewable energy sources and reduce greenhouse gas emissions has led to incentives to increase producing electricity from small hydropower as part of California's Renewable Portfolio Standard. However, this may come with costs to native fish species whose ranges have already been severely restricted by human impacts (Lackey et al. 2006).

Supporters of hydroelectric power generation in California frequently find themselves in conflict with supporters of fish over water allocation, yet the impacts of hydropower production and effectiveness of mitigation strategies are often unclear. As a result, hydropower producers are forced to aggressively explore different water management options designed to maintain sufficient water supply while generating electricity. Complicating an already complex dilemma, climate change may alter the quantity and timing of water availability in coming decades (Maurer et al. 2007), potentially heightening conflicts between electricity generation and sufficient water for maintaining fish populations (Hayhoe et al. 2004). Adding to the environmental challenges, there is currently no general integrated analytical framework for exploring trade-offs between competing use of water by small hydropower and fish, nor one that considers climate change forecasts from global general circulation models. Such uncertainties could cause unnecessary curtailment of small hydropower production because of environmental concerns.

Project Purpose

This exploratory two-year project built and tested a model designed to function seamlessly within an integrated modeling framework that includes (1) a watershed hydrology and water management model, and (2) a fish habitat suitability model. The researchers also had the opportunity to collaborate with co-authors Sandoval Solis and Sooyeon Yi to add a third

element to the model - to develop Middle-Ware software to connect and control both the watershed hydrology and water management model, and the fish habitat suitability model.

Project Results

The researchers developed and successfully tested a fish habitat suitability model optimized to assess the impacts and mitigation potential of small hydropower facilities. The model functions seamlessly within an integrated modeling framework that includes (1) a watershed hydrology and water management model (WEAP), and (2) a fish habitat suitability model (WEAPhish), and (3) a Middle-Ware software (Master_WEAPhish) to link and control the other two components. The models are designed to be easily modified for different watersheds and fish populations, and can be used to assess environmental effects of numerous small hydropower projects in more than one watershed simultaneously.

Project Benefits

The analytical (model) framework from this project lays the groundwork for future efforts to assess trade-offs between water use providing freshwater habitat for native fish populations, and the cost-efficient provision of water to small hydropower installations. Expectations are: 1) improved information regarding environmental impacts that allow the hydropower sector to develop plausible estimates of the economic implications of various management options; 2) regulatory decision-makers can address a key environmental barrier to small hydropower production by avoiding unnecessary curtailment of production due to uncertainty and resultant possibility of unfounded environmental concerns; and 3) quantifying the cost of compromise will foster a more productive water management dialogue.

This model will be able to assist small hydropower producers to efficiently mitigate effects on California stream fishes, and minimize unnecessary curtailment of hydropower production while increasing renewable energy to California's energy mix. Power producers and agencies will gain knowledge on what fish-related performance indicators should be monitored at small hydropower facilities to improve design and water management protocols of new facilities.

CHAPTER 1: Introduction

1.1 Small Hydropower

For finite energy resources and a changing climate, there has been increasing interest in developing and using renewable sources of energy (Oud 2002). Hydroelectric power is currently the largest source of renewable power in the United States, providing more than 54 percent of the nation's total renewable energy supply (US Department of Energy 2013). However, most suitable sites for large-scale hydropower have already been developed, and the proposition of new, large hydroelectric power projects would likely be politically infeasible. As a result, small hydroelectric projects, those generating less than thirty megawatts of power, are beginning to be explored as potential renewable sources of energy (Paish 2002, Kane 2005, Hall et al. 2006, Navigant Consulting, Inc. 2006, Schwartz and Shahidehpour 2006, Kosnik 2010, Capik et al. 2012). In recent years there has also been considerable international interest in small hydropower development (Santos et al. 2006, Punys and Pelikan 2007, Panic et al. 2013, Sharma et al. 2013).

Construction of hydroelectric projects in the United States peaked in the early and mid-20th century, with the building of iconic sites such as the Hoover and Grand Coulee Dams. The construction of these dams aided development in the western United States, providing flood control and a reliable source of water for drinking and irrigation. In the 1970's attitudes towards dams and their environmental impacts began to change, brought on by controversial cases like the Tennessee Valley Authority vs. Hill as well as several dam failures (Gleick 1992). Knowledge about the negative biological, physical, and chemical impacts associated with the construction of dams increased (Young et al. 2011), and recently, the practice of dam removal has become more widespread. However, balancing the demands of numerous stakeholders reliant on the water supply provided by rivers and used by dams has proven to be difficult, and removing dams is not always attainable.

Although much information exists about the environmental and ecological impacts associated with large-scale hydropower, little is known about the consequences associated with small hydroelectric projects (Frey and Linke 2002). A thorough literature review through seven prominent databases (Google Scholar, Web of Science, Aquatic Sciences and Fisheries Abstracts, American Society of Civil Engineers Database, Water Resource Abstracts) returned little evidence of research on the environmental effects of small hydropower, in spite of the growing interest in small hydropower displayed in the literature (e.g., Paish 2002, Hall et al. 2006, Capik et al. 2012). While it is a relatively common belief that smaller hydroelectric projects are more benign, renewable, and ultimately less environmentally harmful and costly than large projects, there is no evidence to support this claim (Abassi 2010). Conversely, existing research suggests that on a per kilowatt basis, small hydropower is no less environmentally harmful than its larger counterparts (Abassi 2010). The impacts of these projects are likely to vary on a project specific basis, with varying degrees of harm. Regardless, further research is needed on the

specific impacts of small hydropower systems in order to minimize future economic and environmental costs (Figure 1, Figure 2).

Figure 1: Small Hydropower Facility on Butte Creek, California (Centerville Powerhouse)

Figure 2: Small Hydropower Facility on the South Fork American River (Slab Creek Dam)

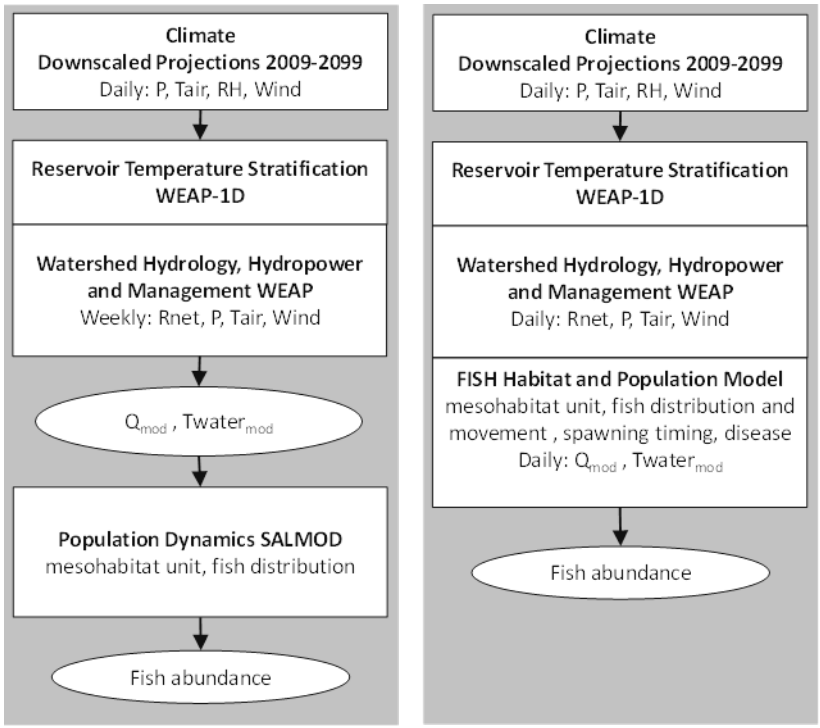
1.2 Issue and Purpose of Current Project

California's 2005 Energy Policy Act (EPAct) provides incentives for new hydropower development that could be used to encourage development of additional hydropower capacity in California (Navigant Consulting, Inc. 2006). Meanwhile, California's mandate to increase the contribution of renewable energy sources and reduce greenhouse gas emissions has led to incentives to increase the production of energy from small hydropower as part of California's Renewable Portfolio Standard. However, this may come with costs to native fish species whose ranges have already been severely restricted by human impacts (Lackey et al. 2006). Proponents of hydroelectric power generation in California frequently find themselves in conflict with proponents of fish over water allocation, yet the impacts of hydropower production and effectiveness of mitigation strategies are often unclear. As a result, hydropower producers are forced to aggressively explore different water management options designed to maintain sufficient water supply for generation within the context of changing social values favoring fish. Complicating an already complex dilemma, climate change may alter the quantity and timing of water availability in coming decades (Maurer et al. 2007), potentially heightening conflicts (Hayhoe et al. 2004). Adding to the environmental challenges, there is currently no general integrated analytical framework for the exploration of trade-offs between competing use of water by small hydropower and fish, nor one that takes into consideration climate change forecasts from global general circulation models. Such uncertainties could cause unnecessary curtailment of small hydropower production due to environmental concerns.

These issues were addressed by developing and testing the feasibility of a fish habitat suitability model optimized to assess the impacts and mitigation potential of small hydropower facilities. The purpose of this exploratory two-year project was to build and test a model designed to function seamlessly within an integrated modeling framework that includes 1) a watershed hydrology and water management model, and (2) a fish habitat suitability model. Part way through the project the researchers encountered the opportunity to collaborate with co-authors Sandoval Solis and Yi to (3) develop a Middle-Ware software to connect and control both the watershed hydrology and water management model, and the fish habitat suitability model. Because the models are designed to be easily modified for different watersheds and fish populations, they may be used to assess environmental effects of numerous small hydropower projects in more than one watershed simultaneously.

The analytical framework from this project (Figure 3) lays the groundwork for future efforts to assess trade-offs between water use providing freshwater habitat for native fish populations, and the cost-efficient provision of water to small hydropower installations. Expectations are that: 1) Improved information regarding environmental impacts will allow the hydropower sector to develop plausible estimates of the economic implications of various management options; 2) Regulatory decision-makers will be able to address a key environmental barrier to small hydropower production by avoiding unnecessary curtailment of production due to uncertainty and resultant possibility of unfounded environmental concerns; and 3) Quantifying the cost of compromise will foster a more productive water management dialogue.

Figure 3: Analytical Frameworks



Left: Assemblage of analytical framework, model coupling and data transfer, used to model future conditions for spring-run Chinook salmon in Butte Creek. P=precipitation, Tair=air temperature, RH=relative humidity, Qobs=observed streamflow, Twater obs=observed water temperature, Rnet=net radiation, Qmod=modeled streamflow, Twater mod= modeled water temperature.

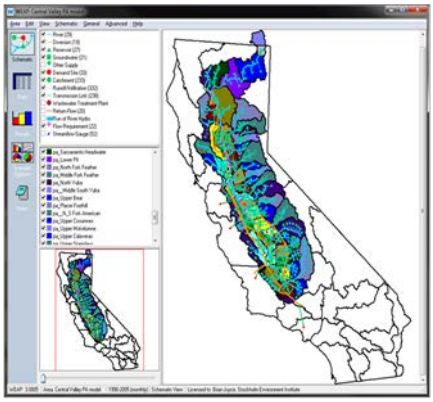
Right: Proposed analytical framework, showing integration of WEAP with the proposed fish model (improved capabilities including habitat-induced movement of fish, spawning timing, and stress-related disease dynamics, and would run on a shorter time step closer to that of hydropower operations).

1.3 Current State of Knowledge

This project expands on previous work by Dr. Lisa Thompson and colleagues. In 1998, Dr. David Purkey and colleagues began development of the Water Evaluation and Planning (WEAP, http://www.weap21.org/) system (Sieber and Purkey 2011), coupling the simulation of physical hydrology and the management of water infrastructure (Yates et al. 2005a,b). WEAP simulates potential changes in snow accumulation and melt, streamflow and water temperature in response to climate inputs under a given water management regime (Null et al. 2010, Purkey et al. 2007; Yates et al. 2005a; Yates et al. 2009; Young et al. 2009). The results of watershed process modeling are linked to user-defined priority-based water allocation routines that simulate the managed elements of a water system. For a full description of the model, the reader is referred to Yates et al. (2005a) and Young et al. (2009) where the algorithms for each hydrologic component are described, and to the WEAP User Guide (Sieber and Purkey 2011; http://www.weap21.org/downloads/WEAP_User_Guide.pdf).

Beginning in 2007, WEAP was coupled with a fish population dynamics model, developed by USGS, SALMOD (Bartholow et al. 1993), to estimate the impacts of different water management strategies on salmonids (Thompson et al. 2012), using future climate sequences derived from multiple General Circulation Models and carbon emissions scenarios. These past activities illustrate the approach the researchers have taken in the current project. The site of this project, Butte Creek, near Chico, California, exemplifies the type of conflict this project addresses, being habitat for spring-run Chinook salmon, a species listed as threatened and sensitive to increased water temperatures, and the site of economically driven operation of a hydropower system (Thompson et al. 2012). WEAP was linked to a salmon life-cycle and population dynamics model to assess local effects of climate change on salmon under management strategies ranging from changing operations of current infrastructure to building new infrastructure. The integrated framework was used to highlight how changing existing management could counteract climate change effects with only some small loss of power generation (Escobar et al. In prep). In addition, at the scale of the Central Valley, a WEAP application has been developed to support the California Department of Water Resources (DWR) Water Plan Update (WPU) and the US Bureau of Reclamation (USBR) Central Valley Integrated Resources Plan (IRP) processes (Figure 4) and was available to provide hydrological inputs to a new fish model.

Figure 4: Central Valley Watersheds in WEAP Application



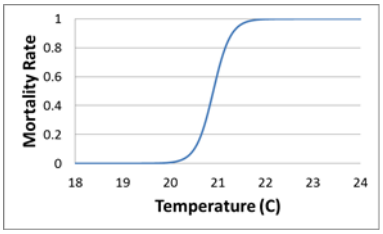
Watersheds in the WEAP application for the Central Valley, developed to support the California Department of Water Resources Water Plan Update (WPU) and the US Bureau of Reclamation Central Valley Integrated Resource Plan (IRP). The WEAP application has been calibrated to represent all of the key elements of the water systems in the Sacramento, San Joaquin, and Tulare Lake Hydrologic Regions.

During the effort to assess trade-offs between hydropower production and salmonid population viability based on the integration of WEAP and SALMOD (Thompson et al. 2012), five significant drawbacks of SALMOD were discovered:

- Any changes to the program had to be done by USGS scientists (e.g., increasing the maximum number of habitat units). At present the software is still available as a free download but the FORTRAN computer programming source code is unavailable, and the program is no longer being supported by the USGS.

- SALMOD does not allow for the simulation of habitat-induced (temperature, flow, salinity) migration of salmonids to and movement within the stream habitat (Goniea et al. 2006, Strange 2010), the potential for disease-related stresses within the spawning grounds (Holt et al. 1975), or metapopulation dynamics between fish populations in different watersheds (Lindley et al. 2007).
- SALMOD runs on a weekly time scale, much longer than the timeframe over which hydropower-related flow fluctuations typically occur (e.g., Young et al. 2011).
- Output data from WEAP had to be transferred to SALMOD semi-manually by converting the output file to a new input file, one run or scenario at a time.
- SALMOD requires life history inputs for all life stages of fish and detailed habitat data, but peer-reviewers of the authors' integrated modeling paper (Thompson et al. 2012) argued that a much simpler model focused on temperature thresholds (Figure 5) would have produced the same conclusions and management recommendations.

Figure 5: Fish Mortality-Habitat Temperature Relationship



Fish mortality-habitat temperature curve (dose-response model) for adult spring-run Chinook salmon in Butte Creek. As temperature increases beyond a threshold level there is an increase in the proportion of the fish population dying at each time step (Thompson et al. 2012).

1.4 Approach and Scope

Using the insights gained from the Butte Creek project, a major effort was made under the current project to develop a new fish habitat suitability model that addresses the issues noted above and also integrates seamlessly with the existing WEAP framework. The integrated model framework removes the need to manually transfer data files between the two models, and should improve the speed of model runs. The researchers used a multidisciplinary approach to develop the integrated modeling framework that includes 1) a watershed hydrology and water management model, 2) a fish habitat suitability model, and (3) a Middle-Ware software to connect and control both the watershed hydrology and water management model, and the fish habitat suitability model. The approach included consultation with key stakeholder groups early in the project. The researchers communicated with stakeholders, including state policymakers, resource agencies (CDFW, NMFS, CEC), and environmental groups, prior to commencing the modeling efforts, through three focus group meetings, to refine the model design. Near the end of the project the researchers delivered findings through a workshop and webinar for stakeholders. The findings will also be presented through conferences, journal

articles, policy briefs, and the University of California Cooperative Extension (UCCE) California Fish Website. The resulting habitat suitability model will be freely available through the University of California as open source code.

1.5 Goals and Objectives

The goal was to provide proof of concept that a fish habitat suitability modeling tool can be developed. To reach this goal there were three objectives:

- Develop and assess a fish habitat suitability model to forecast the effects of small hydropower on native fishes in California streams.
- Link the new model to the existing WEAP hydrological model.
- Communicate with stakeholders regarding plans, and inform them of results.

1.6 Principal Tasks

There were eight major tasks involved in the development of the fish habitat suitability modeling tool, of which steps 1 through 6 were to be accomplished in the current project, and steps 7 and 8 were planned to be completed in a future project:

1.6.1 Project Administration

Plan and conduct meetings with stakeholders to determine hydropower operations and fish population and habitat goals.

1.6.2 Fish Model Development

- Literature review to determine life-stage and run-specific functional relationships and critical thresholds for each freshwater stage to be included in the model, e.g., mortality rate as a function of water temperature (Fig. 4), egg survival and development rates, and critical temperature and flow requirements for volitional migration for adults.
- Development of model for integration into the WEAP framework. Input from WEAP was temperature and flow.
- Calibrate model using historic data as possible.
- Conduct sensitivity analysis (feasibility test) to determine how robust model results are.
- Conduct site visits to representative small hydropower facilities. Collect detailed water temperature data upstream and downstream of a representative small hydropower facility for use in model development and calibration.
- Plan and conduct workshop near end of project to present the model to stakeholders.
- Prepare final report, web pages, and papers. Make presentation at conference.
- Use the integrated analytical framework to model the potential impacts of climate change using data generated by a suite of climate models for multiple future emissions scenarios.

- Use the integrated analytical framework to assess trade-offs between water use to provide freshwater habitat for native fish populations, and the cost-efficient provision of water to small hydropower installation for energy production.

CHAPTER 2:
Model Development

As described briefly in Chapter 1, the third task for this project was developing the fish population dynamics and fish habitat model. This involved comparing the previously used SALMOD model with other fish population and habitat models that have been described in the literature. Following this review, the task involved the development of a new model for integration into the WEAP framework, after consultation with stakeholders in watersheds where the new model might be deployed (see Chapter 4). In this this chapter, the authors review the SALMOD model in comparison with other relevant models and describe the development of the new WEAPhish model.

2.1 Comparison of Salmod Model to Other Fish Population Dynamics and Habitat Models

The researchers compared the features of the SALMOD model, which had previously been used for Butte Creek spring-run Chinook, with those of six other fish population and habitat models: Shiraz (Battin et al. 2007), OBAN (Scheurelle et al. 2006), Ecosystem Diagnostic and Testing (Lestelle et al. 2004), Unit Characteristic Method (Cramer and Ackerman 2009), Ripple "POP" module (Dietrich and Ligon 2008), and EPA stream network (Liebowitz and White 2009). The models were compared based on the following attributes: characteristics, purpose, spatial scale, and temporal resolution (Table 1); premise, parameter estimation, population dynamics, and statistical approach (Table 2); biophysical linkages, ocean effects, and human interactions (Table 3); and output data and software (Table 4).

Based on a review of existing fish population dynamics and habitat models, and the discussion with stakeholders at the three stakeholder workshops held early in this project (see Chapter 4, Outreach for details on these discussions), the design for the new WEAPhish model was developed. WEAPhish uses spatially and temporally explicit temperature and flow data for the selected study stream to model single-species demographic processes of stream fishes (currently implemented for an anadromous salmon). The model's name reflects efforts to integrate it with the water resource planning software WEAP, Water Evaluation and Planning system, developed by SEI.

WEAPhish is a Python implementation of the USGS SALMOD model (Bartholow et al. 1993, 2002). This path was chosen because, in part, there was a desire to continue past investigations based on SALMOD, which is no longer supported by the USGS. This enabled comparison between WEAPhish results and existing SALMOD results from common model configurations, while allowing for future development to expand existing model functionality. WEAPhish was written in Python because the language has a relatively low-learning curve (www.python.org) and has excellent support for scientific computing and simulation (see http://www.scipy.org/).

Table 1: Comparison of Models' Characteristics, Purpose, Spatial Scale, and Temporal Resolution

Model	Characteristics	Purpose	Spatial scale	Temporal resolution
SALMOD	Realistic and Precise	Model cumulative effects of water temperature on salmon growth and mortality.	Mesohabitat units - based on channel structure and slope, modified by distribution of mocrohabitat (cover); Linear stream.	Weekly time step. Anadromous: Only tracks cohort from spawning to exiting system can't link generations and ocean survival.
Shiraz	Realistic and Precise	Incorporate effects of habitat change, hatchery operations, and harvest management on salmon populations for use in recovery planning.	Broad as watershed to fine as stream reach. Once defined all assumed equal size with respect to fish movement.	Annual - allows for several several stage transitions to occur within a year.
OBAN	Realistic and Precise	Evaluate how environmental and anthropogenic factors influence salmon population vital rates (e.g., survival) using Bayesian approach to evaluate alternative hypotheses on population productivity and capacity.	Specific to life-stage, spawning grounds, juvenile rearing habitat, ocean for post-smolting juveniles.	Annual time-step.
Ecosystem Diagnostic and Testing	Realistic and Precise	Evaluated the effect of quality and quantity habitat salmon population performance and prioritize restoration and preservation actions within watersheds.	Stream reach.	Annual time step.

Model	Characteristics	Purpose	Spatial scale	Temporal resolution
Unit Characteristic Method	Realistic and Precise	Estimate stream carrying capacity of salmonids and how human activities influence stream productivity.	Channel unit (pool, riffle, glide).	Not applicable (N/A).
Ripple "POP" module	Realistic and Precise	Evaluate the role of habitat on salmon populations.	Habitat - channel reaches, with information on the riffle, run, pool and cascade within each.	Sub-year stages.
EPA stream network	General and Realistic	Evaluate the influence of stream connectivity on the movement and productivity of salmon populations	High resolution in freshwater, but includes influence of ocean basin scale environmental conditions during ocean phase.	Annual.

Table 2: Comparison of Models' Premise, Parameter Estimation, Population Dynamics, and Statistical Approach

Model	Premise	Parameter estimation	Population dynamics	Deterministic vs. Stochastic
SALMOD	Egg and fish mortality and growth are directly related to timing and magnitude of streamflow and temperature	External	Tracks spatially distinct cohorts from eggs to downstream migrants. Tabulates various causes of mortality for all cohorts by life stage (adults, spawners, egg and juveniles).	Deterministic
Shiraz	The physical environment (habitat) drive fish population dynamics in each segment of river at each life stage	Externally derived functional relations	Beverton-Holt model drives survival within each habitat unit.	Stochastic
OBAN	Estimates population productivity and system capacity for each life-stage, based on available population data, which can be fit to using up to 5 environmental data sets	Bayesian estimates	Stage-structured with a Beverton-Holt transition function. 6 freshwater stages and 3 ocean stages.	Statistical

Model	Premise	Parameter estimation	Population dynamics	Deterministic vs. Stochastic
Ecosystem Diagnostic and Testing	Process to rate quantity and quality of habitat for a species. Biological capacity and productivity of fish is a function of environmental conditions relative to "ideal" conditions	External or expert value	Beverton-Holt function for each species, life stage and habitat.	Deterministic
Unit Characteristic Method	Habitat-based approach to understand the influence of particular habitat features on the productivity and capacity of salmon populations in a stream	External or expert value	Carrying capacity a spatially explicit function of suitable habitat for each life-stage.	Deterministic
Ripple "POP" module	Physical environmental conditions dictate the distribution and abundance of salmonid life stages in a watershed	External or expert value	Capacity from "HAB" is a function of the total reach area times the sum of sub-reach specific habitat area, habitat usability and species density.	Deterministic

Model	Premise	Parameter estimation	Population dynamics	Deterministic vs. Stochastic
EPA stream network	The relative influence of stream network topology on fish movement and dynamics can be assessed by investigating many possible alternative (simulated) stream networks and associated salmon populations	External estimates (several characterized by probability distributions)	Stochastic life-cycle model.	Stochastic

Table 3: Comparison of Models' Biophysical Linkages, Ocean Effects, and Human Interactions

Model	Linking physical habitat and salmon	Ocean	Human interactions (fishing, dams, habitat change)
SALMOD	Within each mesohabitat unit (run, riffle, pool) temperature and flow drive growth, movement and survival of each cohort for all life stages.	No	Flow and temperature and capacity drive growth, mortality and movement.
Shiraz	Habitat model: habitat indicators (physical characteristics) and stochastic variables (micro-habitat: Water temperature and flow) relate to productivity and survival.	Yes	Harvest, Hatchery, Habitat (Land use and Landscape processes) and Hydropower.
OBAN	Fits population indices to environmental data or indices. Demographic rates and environmental conditions assumed common to each stage, but distinct across stages.	Yes	Incorporates covariates for anthropogenic drivers: fishing, entrainment, flow reductions for agriculture, hatchery, Delta Cross Channel gate position.
Ecosystem Diagnostic and Testing	Develops species independent 'view' of environmental conditions that influence salmon survival at each stream reach.	Yes	Four environmental scenarios: (1) current habitat condition with ocean harvest, (2) current habitat without ocean harvest, (3) historical habitat, reconstructed, and (4) ''degraded'' habitat.
Unit Characteristic Method	Does not examine influence of temperature. Assumes fish density more closely linked to channel unit type than micro-habitat features like velocity, depth and cover.	N/A	Habitat alterations (e.g., restoration activities), harvest rate changes, influence of hatchery fish on system carrying capacity.
Ripple "POP" module	Physical environment from watershed and geology to microhabitat (riffle, run, pool or cascade) drives capacity, movement and survival of each stage.	Yes	Fish passage, restoration, harvest.
EPA stream network	If juvenile abundance in a segment exceeds reach specific capacity, the "excess" fish move to other reaches - with mortality a function of distance moved to find suitable habitat.	Yes[1]	Fishing, hatchery (coastal OR no dams).

Source: Current project.

[1] AL drives PDO that influences salmon survival in the ocean.

Table 4: Comparison of Models' Output Data and Software

Model	Output Data	Software
SALMOD	Number of eggs/fish. Mean length and weight. Percent egg development. Number of redds. Number of in vivo eggs/female. Life stage and class of cohort. Effective incubation area.	Written in FORTRAN with C++ GUI. Windows only. Currently being re-written in R.
Shiraz	4 criteria of viable salmon populations: 1) abundance, 2) productivity, 3) spatial structure, and 4) diversity.	Microsoft VBA - Excel
OBAN	Posterior estimates of population parameters; fit of model and accompanying annual time series of population metrics.	AD Model Builder
Ecosystem Diagnostic and Testing	Population abundance, productivity, capacity and diversity. Also prioritizes reaches for restoration and preservation.	Have not found explicit reference to underlying programming language.
Unit Characteristic Method	Predicted smolt capacity in each basin examined; quantifies habitat variability among systems; variability of capacity of reaches in each system; sensitivity to habitat factors.	Have not found explicit reference to underlying programming language.
Ripple "POP" module	Static spatial patterns of long-term average abundance for each life stage. Time series of total abundance for each life stage.	C++
EPA stream network	Spawner density, percent unoccupied reaches, percent recolonization, average extinction rate, spawner change from initial to last generation.	R

The researchers then set about building and implementing the age, stage, habitat, and fish abundance model to include time-, location-, and life stage-specific growth, mortality, movement, maturation, and reproductive processes driven by the underlying physical habitat and associated relationships between physical habitat conditions and demographic processes. The WEAPhish model incorporates fish population dynamic processes (movement, growth, and mortality) driven by the physical habitat modeled using input data and user defined

relationships (i.e., weekly flow, temperature, and useable habitat for each stream habitat unit and each fish life stage).

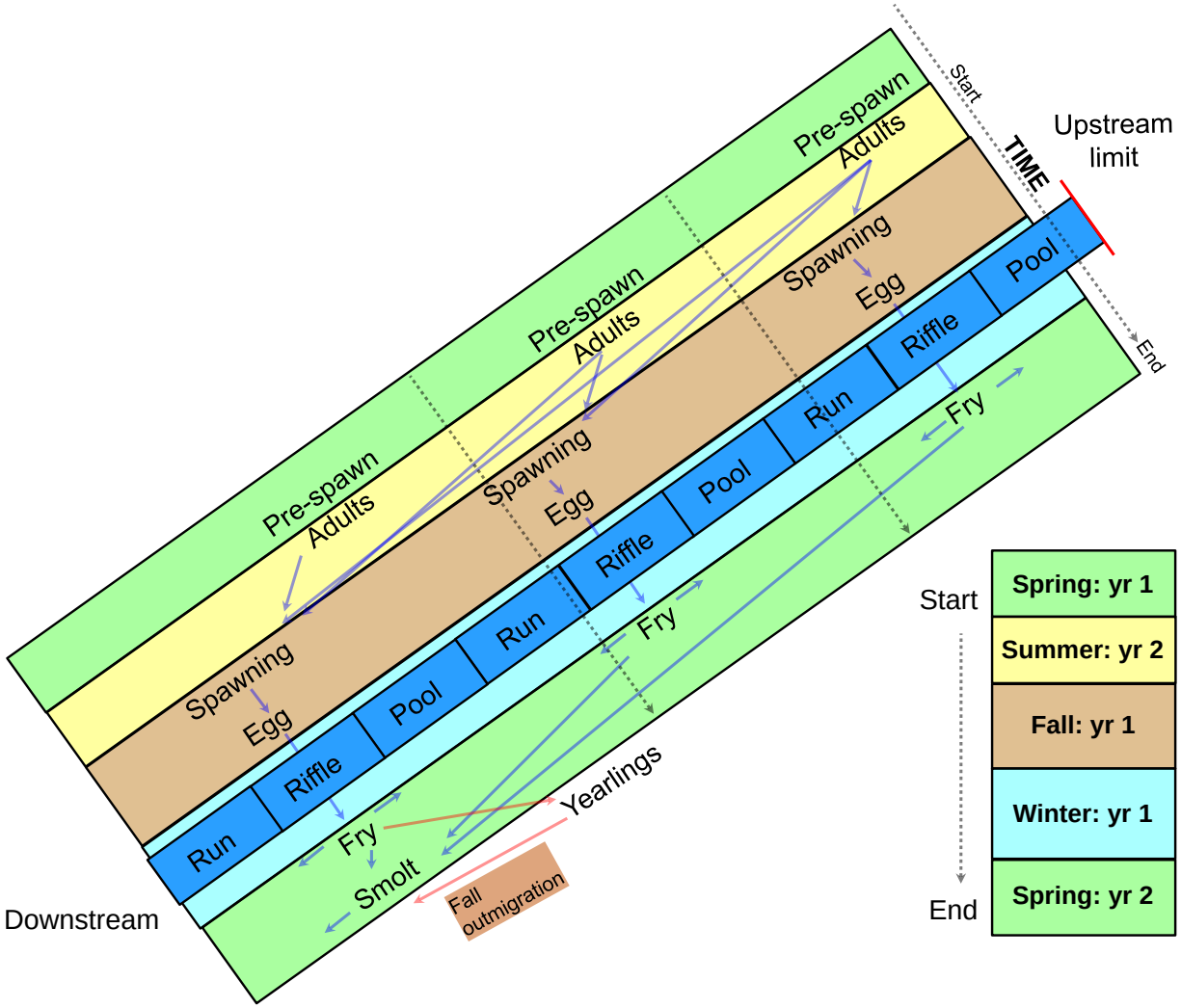
2.2 Model Structure and Functions

This section describes the WEAPhish model structure, set-up, and model processes. Please note that the structure and operation of the WEAPhish model are covered in detail in the user's manual (see Appendix A).

2.2.1 Model Processes and Nested Loops

Prior to running the model for a particular fish population and stream habitat, the model must be set up. The user will need to define the physical habitat structure (e.g., number of habitat units), define the relationships between stream habitat and demographic rates (e.g., weighted usable area, temperature-related growth, temperature-related mortality), and initialize the age, stage, and spatially explicit abundance. In the case of the current WEAPhish model, the habitat and relationships were based on Butte Creek spring-run Chinook (Figure 6), following the example of Thompson et al. (2012). This process needs to be coordinated with the development of a watershed-specific WEAP model. Inputs to both the WEAP model and the WEAPhish model can be entered into the spreadsheets of the Master_WEAPhish Middle-Ware file, described in detail in Chapter 3.

Figure 6: Annual Freshwater Fish Population Processes over Space and Time



Annual freshwater population processes over space and time, showing the example of spring-run Chinook salmon. The spatial "axis" runs from upper right to lower left, and the time "axis" runs from upper center to middle right. Adults return from the ocean in spring of year 1, transition to holding adult in summer (yellow), with a preference for pool habitat, then spawning adults (brown) with a preference for riffle habitat. Eggs and early stage fry are in riffles during fall and winter, then fry begin to move out into pools and runs in spring. In fall of the second year, smolts move downstream and leave the stream habitat in order to migrate to the ocean.

Following model set-up, a simulation can begin. The WEAPhish model is launched from Master_WEAPhish (or the Python command line). At the beginning of the simulation the WEAPhish model is initialized, then begins running for the requested number of simulation years (Figure 7).

Figure 7: WEAPhish Model Processes and Nested Loops

Beginning of simulation:

Load input data, set model parameters, initialize data structures, define simulation type and time range

Each simulation year:

Seed the stream with fish, based on their observed distribution and habitat use

Each time step:

Each process at stream computational unit level:

Compute biomass, add additional fish (e.g., hatchery supplementation), spawn (during spawning season), and return moving fish from the "virtual stream" to new their stream computational unit

Each cohort of fish within a computational unit:

Calculate mortality of juveniles and adults based on temperature, density, and base rates, calculate growth and determine new size class, determine seasonal, flow (i.e., freshet), and density dependent movement and mortality.

Tabulate simulation results

2.2.2 Model Functions and their Role in the Simulation

The following major modules (scripts) are used to model fish population demographic processes in the full simulation: fish_main.py, loads_functions.py, loads.py, and continuous_sim (many arguments). The detailed role of each module is as follows.fish_main.py – This is the "outer-most" script of WEAPhish and it provides the overview calls. It is called from the command line (Figure 8) or from the Master_WEAPhish spreadsheet. It calls loads (via a Python import statement) then runs continuous_sim().

Figure 8: Screenshots of WEAPhish (fish_main.py) Run From Command Line

```
bc_2010_2011 — bash — 143×24
Patricks-MacBook-Pro-2:bc_2010_2019 patrickkilduff$ cd ~/Dropbox/fish_model_runs/bc_2010_2011/
Patricks-MacBook-Pro-2:bc_2010_2011 patrickkilduff$ time ipython ~/weaphish/fishmain/fish_main.py
START FISH MAIN
FLOW DATA LOADED
FRESHET DATA IN MEMORY
TEMP DATA LOADED
WUA AND CAPACITY DATA LOADED IN MEMORY
LOADED DATA IN FUNCTIONS, PROCEED FISH_MAIN
SHOULD HAVE DERIVED FOLDER LOADED WITH LOTS OF DATA
TIME STEP 0
TIME STEP 1
TIME STEP 2
TIME STEP 3
TIME STEP 4
TIME STEP 5
TIME STEP 6
TIME STEP 7
TIME STEP 8
TIME STEP 9
TIME STEP 10
TIME STEP 11
TIME STEP 12
TIME STEP 13
TIME STEP 14
```

```
TIME STEP 100
TIME STEP 101
TIME STEP 102
TIME STEP 103
Continuous simulation has run
model run completed. it took 2:11:05.443707
2015-03-22 17:08:50.201423

real    131m8.237s
user    82m56.236s
sys     0m27.560s
Patricks-MacBook-Pro-2:bc_2010_2011 patrickkilduff$
```

loads.py – This script is implemented via an import statement in fish_main.py (Figure 9). It sets up the stream habitat, defined by stream temperature, flow, and weighted usable area. It is used to define stage-specific carrying capacity of fish in each stream unit (e.g., each pool, riffle, and run in the system) during each weekly time step of the model simulation period. loads.py sets fixed parameters, at least to a default value. It reads multiple input files: species.txt, stream.txt, control_options.txt, control_process.txt, relations.txt, spawn.txt, flows.txt, temp.txt, wua.txt, wua_stage_scalars.txt (Figure 10, 11). Note: These input files may be obtained by WEAPhish when running from the Python command line, or through inputs to spreadsheets in the Master_WEAPhish Middle-ware when WEAPhish is being controlled by the Middle-Ware. loads.py defines and specifies the dimensions of the "internal" data structures. It defines stage-based carrying capacity for each stream segment based on weighted usable area (WUA). It created and applies interpolation functions based on biological and biophysical relationships from relations.txt. In all, loads.py contains over 400 lines of code.

Figure 9: Screenshot of Python Code to Call Loads

```
from loads.loads import *
from functions.functions import *
```

Figure 10: Screenshot of Folder with WEAPhish Input Data Files

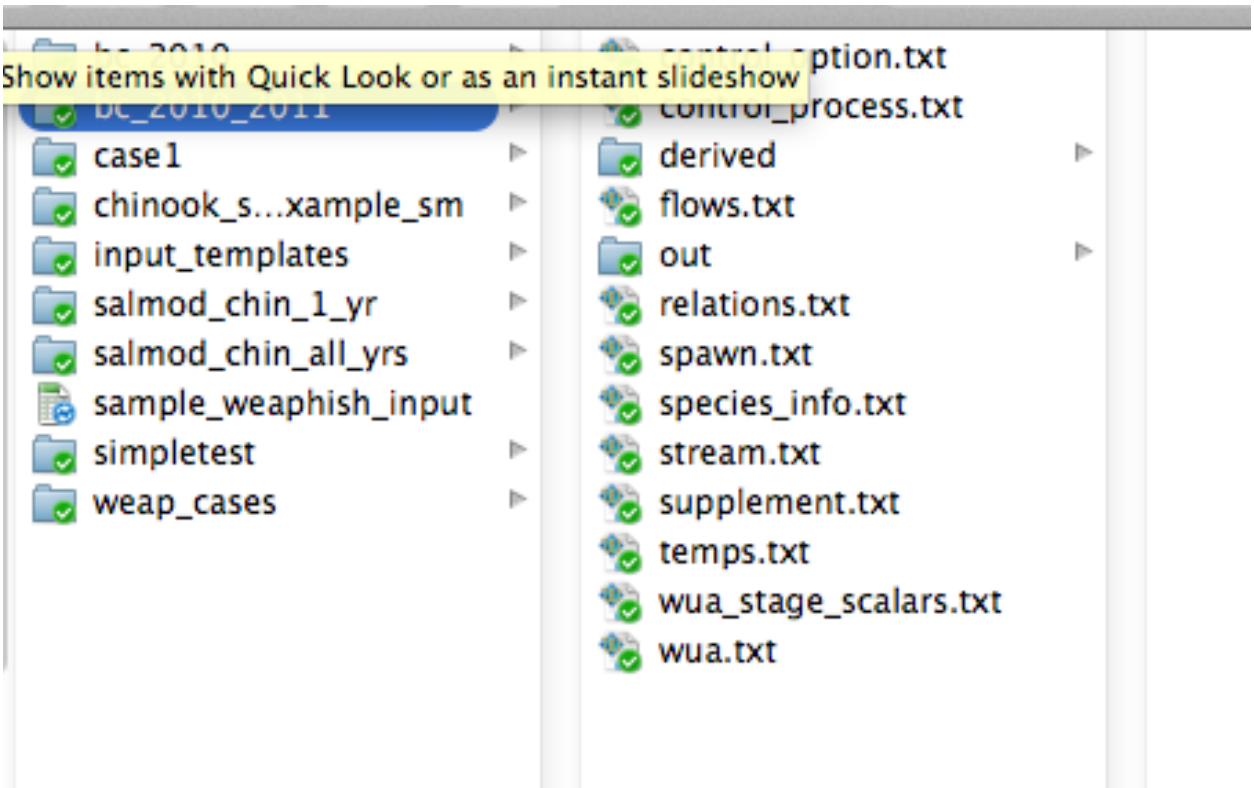
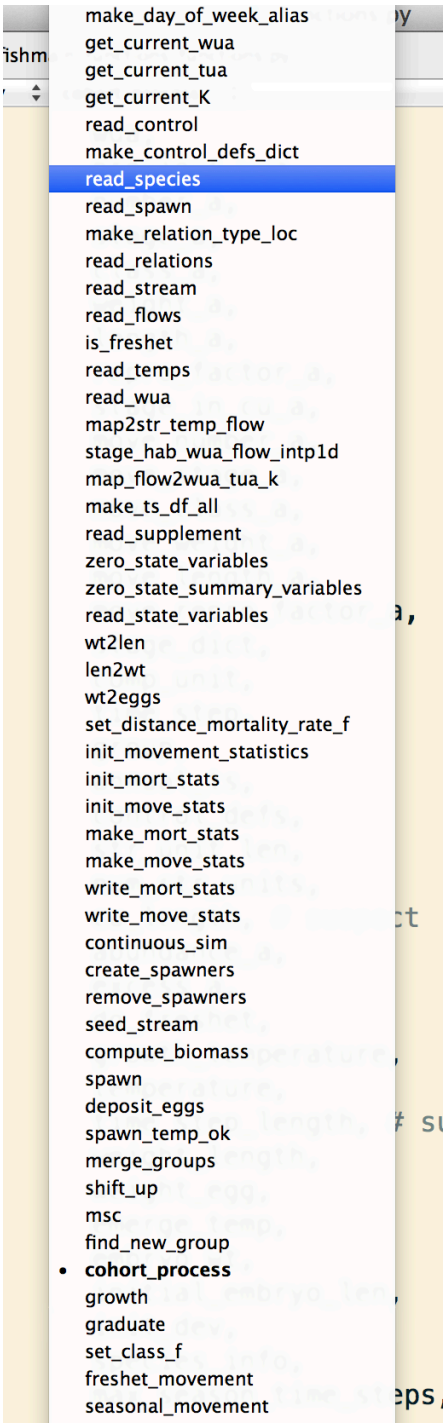


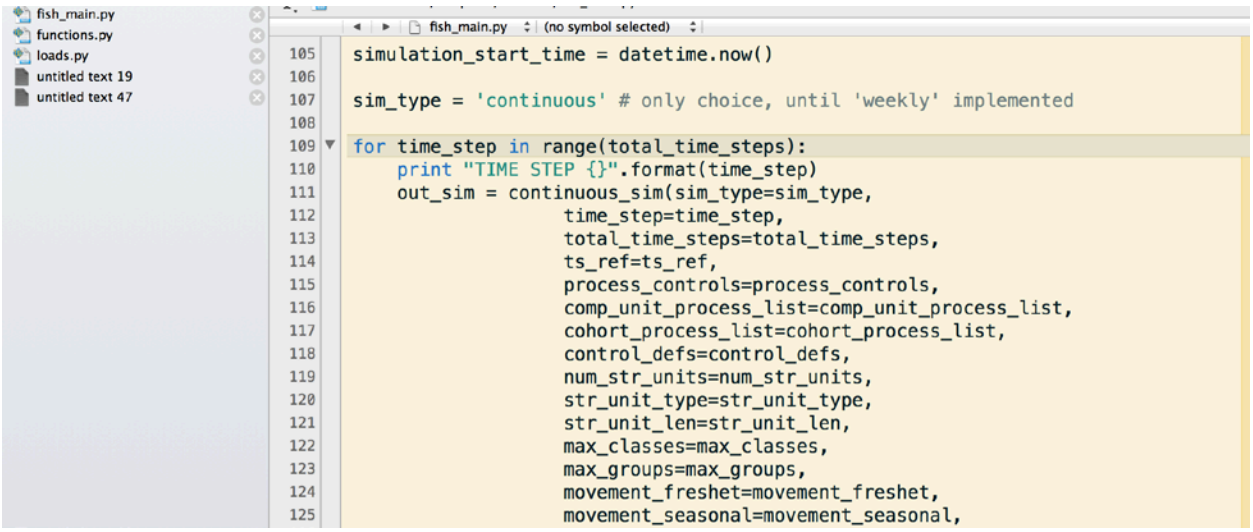
Figure 11: Screenshot of Functions Called



functions.py – This script contains all definitions of the demographic functions (growth, spawn, mortality, movement, etc.), data loading functions, and support functions for running simulations. continuous_sim (many arguments) – This function is called at each time step and sets, updates, and reports on the current status of the fish population and stream conditions

(Figure 12). It "seeds/supplements" fish into the stream and sets the initial simulation conditions. It obtains current flow, temperature, habitat data, and stage-specific carrying capacity. For each time step, continuous_sim() runs each demographic process and records changes in fish population state. This includes processes that operate on the entire cohort: "seeding" fish, calculating biomass, spawning, and accounting for fish movement. This also includes processes that operate on each cohort of fish present in each computational unit: mortality (base, temperature-based, density-based, in vivo egg, and redd superimposition), growth, and movement (forced by flow, habitat constraint, or seasonal migration) as well as accounting processes such as tracking the "graduation" of fish to new life stages and size classes. For each of these processes, continuous_sim() does the fish accounting, then records and summarizes relevant data.

Figure 12: Screenshot of Fish_main.py Code



At the level of the computational unit there are additional processes involved in simulating the fish population dynamics, including the following:

- supplement/seed - Allocates fish to the stream based on available habitat. Currently only adults can be seeded (works for Butte Creek example case). Adding juveniles is straight forward.
- move-in - After movement, this moves fish from a "virtual" stream to their new computational unit.
- Biomass - Sums biomass of each stage for a computational unit.
- spawn - Directs spawning of fish based on annual model time steps when spawning occurs.

Furthermore, at the level of the cohort there are additional processes involved in simulating the fish population dynamics.

- habitat_move, freshet_move*, seasonal_move - Moves fish based on habitat carrying capacity, strength of current flow to previous flows, or seasonal migrations.
- mortality - Applies base, temperature, density mortality and does the accounting. Also accounts for in vivo mortality of eggs due to death of adult/spawning females.
- growth - Calculates and accounts for temperature-based growth. Growth is not density-dependent.
- catastrophe - Allows for user input of the occurrence of catastrophic events.
- graduate - Advances the life stage and size class of a cohort.
- carry - Tracks the number of eggs in females during the spawning season.
- collapse (msc) - A convenience/efficiency function. "Collapses" or lumps cohorts of same stage and class (juveniles only) when there are too many cohorts in a computational unit.
- mature (yellow) - For non-anadromous models, this converts adults in to spawners. This is not needed for Butte Creek, but is available for use in other watersheds.

2.2.3 Model Population Dynamics Accounting Framework

WEAPhish has an accounting framework with accounting functions that compute and track data to be stored or referenced permanently, annually, for each weekly time-step, or for each spatial computational level focusing on the allocation of life-stage and size class specific mortality rates based on temperature, density, movement, and other causes. This builds on the fish population dynamic process controls to ensure that when each population dynamic process (e.g., growth, movement, mortality, maturation, and reproduction) runs the model will properly account for each addition, loss, movement, or transition of each of the many cohorts present in the model at any given time and location.

2.3 Model Output

2.3.1 Output Data Files

WEAPhish output data are stored in text (*.txt) files, giving users the option to use the software of their choice to visualize the data. Below a few example plots of output data produced using open-source software R (www.r-project.org) and the open source IDE RStudio (www.rstudio.com) that summarize output of different example WEAPhish runs are provided.

The following plot (Figure 13) shows an example of how the physical habitat changes with time and how that impacts the available fish habitat. Each plot below displays one model year of data (May 2010 to May 2011). The top plot shows changes in WUA for all stages, the middle and bottom plots show the mean and min/max temperature (red) and flow (blue) data. In early 2011, a high flow event (spike in bottom plot) resulted in a temporary reduction in usable stream habitat for all stages in the top plot (a dip in all lines). From the previous plot, this corresponds to a realized loss of habitat only for egg and fry stages, as the other stages are not present in the stream.

Figure 13: Sample Output for Physical Habitat

Annual time series data. The top plot shows the weighted usable area over time for the different fish life stages (note that some stages have the same WUA data). The middle plot shows the temperature; the mean temperature is the dark red line and the light red shaded area denotes the high and low temperature values in the stream. The bottom plot shows flow; the mean flow is the dark blue line and the light blue shaded area denotes the high and low flow values in the stream.

Figure 14 shows a time series plot of fish abundance (Numbers) over time (one model year from May 2010 to May 2011) for each stage. This plot uses the ggplot2 R package (http://ggplot2.org/) and employs the 'faceting' approach to produce a 'stack' of time series plots for each stage in a single column. These plots show the time evolution from one generation to the next – adult

males and females in the top two plots spawn and die in September and early October, but produce new eggs – as well as the growth based transition from one stage to the next (new eggs grow into eggs, which grow into small fry, etc.). Note that the y-axis varies for each of the plots.

Figure 14: Sample Output for Fish Abundance

Annual time series data. Abundance of each stage plotted versus time, from the top plot down, showing adult females, adult males, eggs (1), eggs (2), fry (1), fry (2), and fingerlings.

2.3.2 Evaluation of Model Performance

While WEAPhish has not fully calibrated to historical data for Butte Creek, the model produces results that appear realistic and very similar to those obtained from the fully calibrated SALMOD model (Thompson et al. 2012). WEAPhish indicated a realistic response of habitat availability in response to a flow spike (Figure 13) and also shows realistic transitions between life stages, and cumulative mortality (across life stages) in response to flow and temperature factors (Figure 14).

2.4 Model/Software Availability

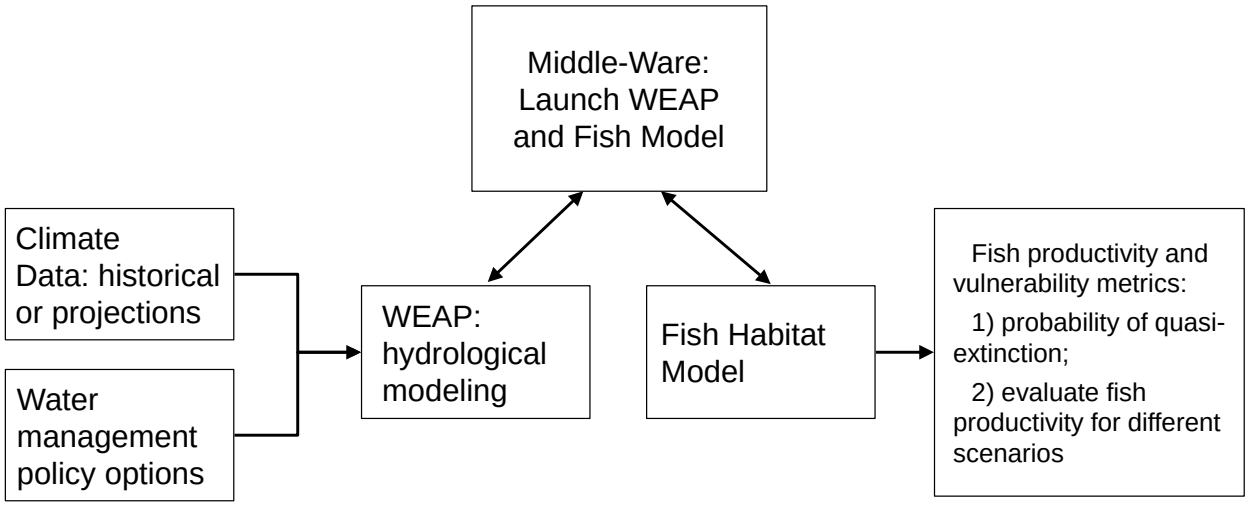
WEAPhish will be available from the author Patrick Kilduff at dpkilduff@ucdavis.edu. Once the model is peer-reviewed, users will be able to download the model from a source code repository (either BitBucket or GitHub). The authors will endeavor to make the repository location known through the peer-review publication, and also through their professional websites.

CHAPTER 3:
Model Integration With Master_WEAPhish Middle-Ware

3.1 Model integration

The Middle-Ware, called Master_WEAPhish, was developed to link the WEAPhish fish population and habitat simulation model to the Water Evaluation And Planning (WEAP) watershed modeling software for integrated water resource planning (Figure 15), developed and supported by the Stockholm Environment Institute (SEI) (Yates et al. 2005a, b). The WEAPhish model requires spatially explicit flow and temperature over the entire study period, and this information typically comes from integrated water planning models. SEI's WEAP software provides a platform for investigating multiple demands for water based on climate data – both retrospective and prospective. An important goal of the authors' ongoing work is to ensure that the fish model works seamlessly with WEAP, thus enabling concurrent analysis of water requirements for fish, hydropower, and other end uses.

Figure 15: Overview of Model Integration

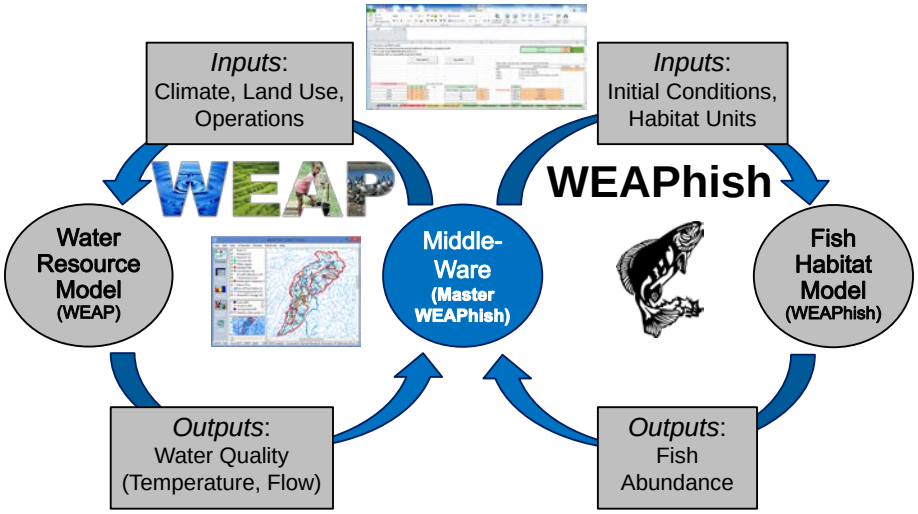


Integration of the WEAP hydrological model with the WEAPhish fish population and habitat model, by the Master_WEAPhish Middle-Ware. Inputs to WEAP include historical or projected climate data, and water management policy options. Outputs from WEAPhish include fish productivity and survival.

The authors note that the task of actually integrating the two models was outside the deliverables for the current project. However, completing the integration with WEAP at this stage offered a greater value for the grant funds available because the fish model will be readily available to be implemented in small hydropower assessments, rather than simply ready for integration with the WEAP platform in a subsequent grant.

While both the WEAP and WEAPhish models can be run independently, in their linked configuration the Master_WEAPhish Middle-Ware launches and controls both models, provides their inputs and receives their output files for storage (Figure 16).

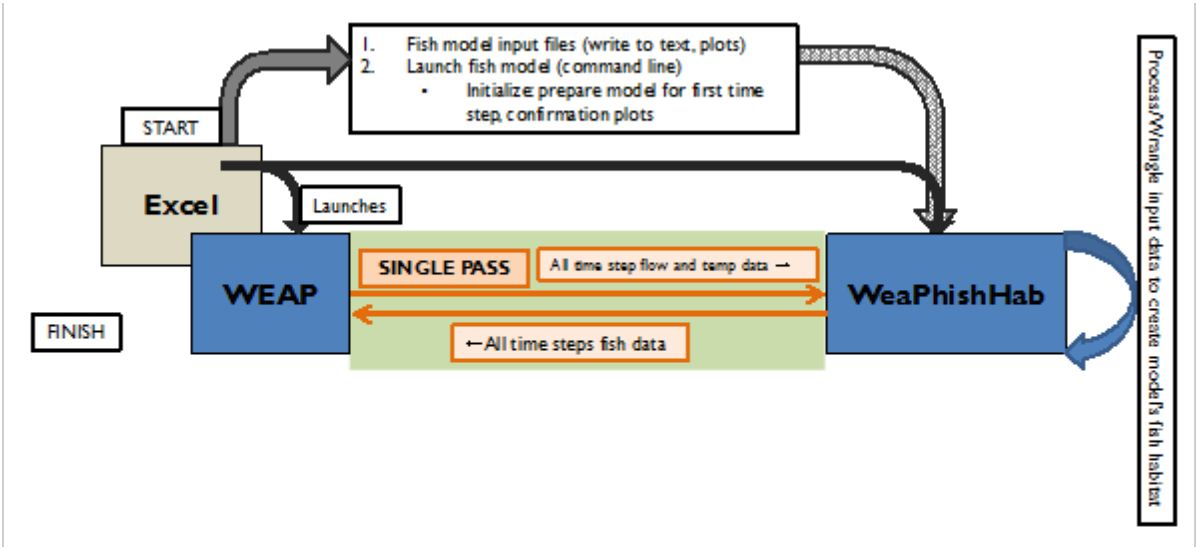
Figure 16: Schematic of Data Flow Between WEAP and WEAPhish Via the Middle-Ware



Middle-Ware connection between WEAP and WEAPhish, and inputs and outputs of each model.

In their current linked configuration, both WEAP and WEAPhish run on a daily timestep, but data are exchanged between the two models only after a pre-determined number of years have run in each model (Figure 17).

Figure 17: Timing of Data Flow between WEAP and WEAPhish via the Middle-Ware



Middle-Ware linkage between WEAP and WEAPhish, for the current linkage structure, whereby data are transferred once from WEAP to WEAPhish, after all years of the WEAP simulation have run.

3.2 Middle-Ware Structure

This section gives an overview of the Master_WEAPhish Middle-Ware set up, structure, and model processes. Please note that the structure and operation of the Master_WEAPhish Middle-Ware are covered in detail in the user's manual (see Appendix B).

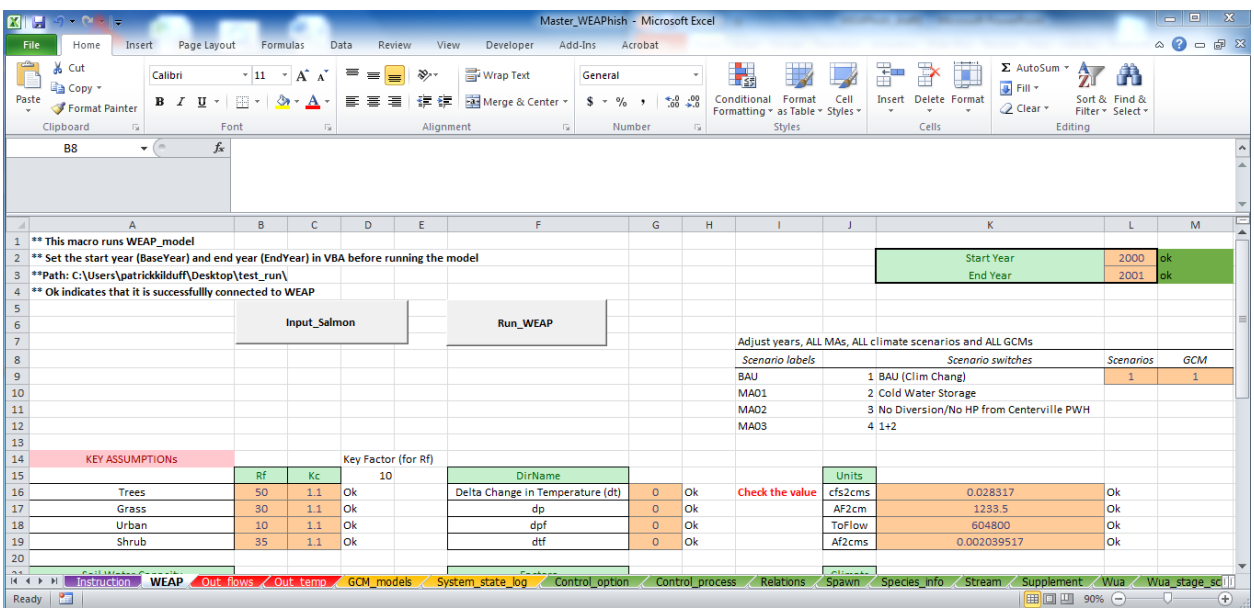
3.2.1 Master_WEAPhish Set Up

The Master_WEAPhish Middle-Ware is scripted in Visual Basic for Applications (VBA) in Excel. It is located in directory C:\WEAPhish, and the Excel file should be saved as an "Excel Macro-Enabled Workbook" at all times. Macros should be enabled before attempting to run Master_WEAPhish. The software WEAP, Anaconda, and Python 2.7 should also be installed.

3.2.2 Master_WEAPhish Structure

The Master_WEAPhish Middle-Ware consists of an Excel Workbook with a substantial number of tabs (spreadsheets). These include: Instructions, main WEAP tab, output flow and temperature, GCM models, system state log, and green tabs corresponding to the WEAPhish txt input files (Figure 18).

Figure 18: Main Spreadsheet of the Master_WEAPhish Middle-Ware



The WEAP tab spreadsheet of the Master_WEAPhish Middle-Ware, including the macro buttons to run WEAP (Run_WEAP) and WEAPhish (Input_Salmon). Input cells for the start year and end year are shown in the top right of the spreadsheet. Climate change scenarios and water management adaptations are shown center-right. Other cells contain other inputs to the WEAP model.

3.3 Middle-Ware Functions

3.3.1 Master_WEAPhish Set Up

The main WEAP tab contains the macro buttons to launch WEAP and WEAPhish (Figure 18). The spreadsheet also contains cells indicating the start year and end year of the model run, and

sets of cells for choosing the General Circulation Model and the potential water management actions.

3.3.2 Climate Scenarios, General Circulation Models, and Water Management Actions

The salmon population dynamics model used by Thompson et al. (2012), SALMOD, provided a detail accounting of how physical environmental conditions influence salmon spawning, incubation, and juvenile survival, movement and growth in freshwater, but did not include ocean survival, and assumed that the same number of adult salmon returned to spawn each year. Salmon survival, growth and movement was driven by predicted stream temperature (habitat quality and quantity) in SALMOD, with the physical habitat modeled using the WEAP model. WEAP used the downscaled climate data for the A2 (bad for salmon) and B1 (not as bad for salmon) climate scenarios under several different water management adaptations (Thompson et al. 2012). The water management adaptations included 1) business as usual (BAU) and, alternatively, 2) eliminating "the diversion of water from Butte Creek at the Centerville diversion dam during the critical July-September holding period, with all flow in the creek released into the SRCS summer holding reaches." These two water management scenarios represented the status quo (BAU) and the management strategy that lead to the greatest improvement in time to extinction in Thompson et al. (2012). The key result from Thompson et al. (2012) was that survival during the pre-spawning stages is predicted to decline precipitously throughout the remainder of this century under many of the emissions and water management scenarios investigated.

In the current model configuration, WEAP is set up to run the same two emissions scenarios (A2 and B1) and six GCMs, for a total of twelve combinations, as were run by Thompson et al. (2012). In addition, WEAP can run four management options: (1) BAU (climate change with no water management adaptations), (2) Cold Water Storage (cold water is stored in reservoirs for use for fish in mid-summer), (3) No Diversion (no diversion of water to Centerville Powerhouse for hydropower generation), and (4) a combination of Cold Water Storage and No Diversion.

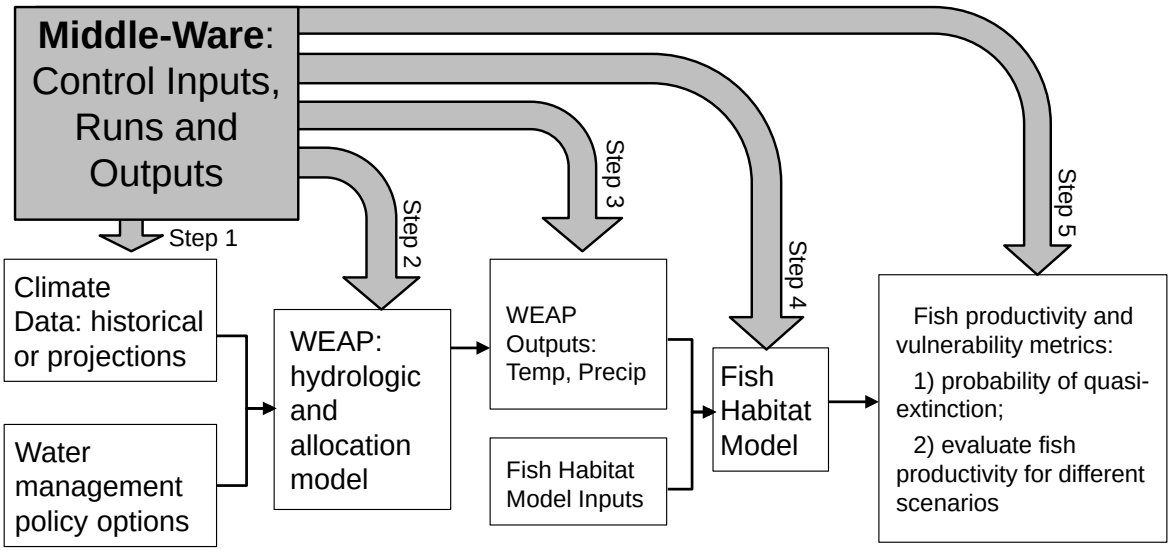
3.3.3 Master_WEAPhish Operations

To run WEAP and WEAPhish, the user clicks on the chosen macro button to launch the model. Master_WEAPhish will control the inputs, runs, and outputs (Figure 19). The WEAPhish Python screen will be visible from the Master_WEAPhish Excel screen (Figure 20).

3.4 Model Outputs

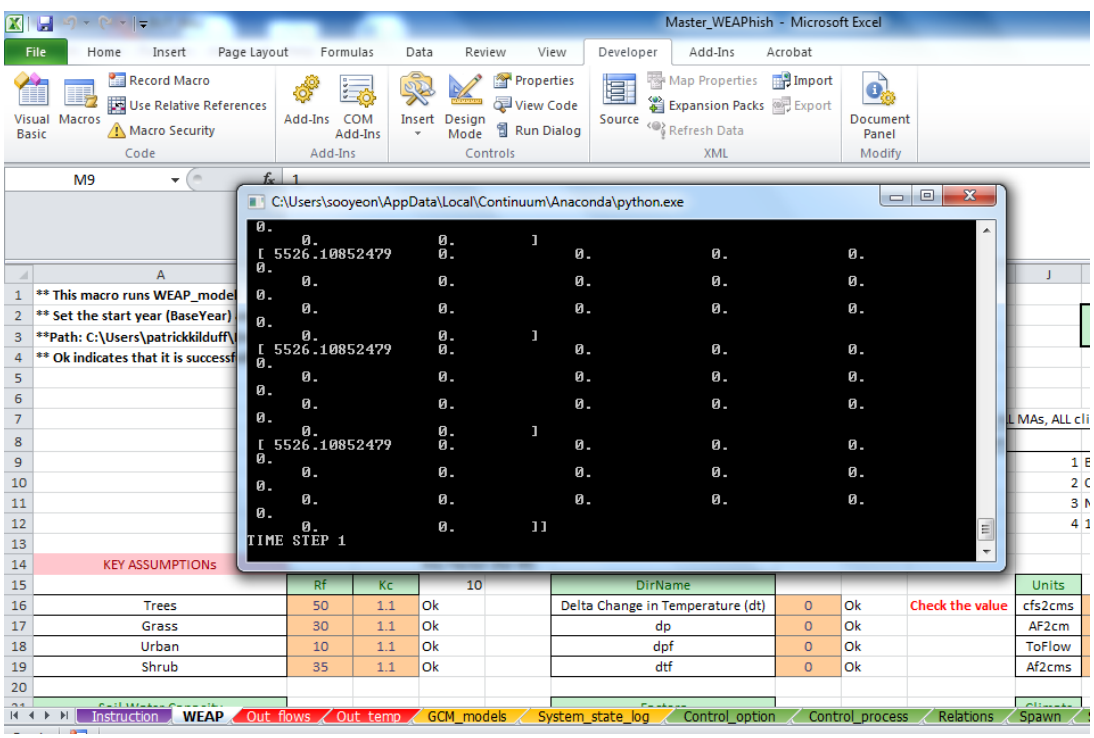
Water flow and water temperature outputs from WEAP will be visible in the Out_flows and Out_temp tab sheets (Figure 21). Output data will be placed into a separate Excel file for each model run (Figure 22). Given that there are currently two climate scenarios, six GCMs, and four water management options, there would be a total of 48 output files for flow and for temperature.

Figure 19: Overview of Middle-Ware Controls of WEAP and WEAPhish Models



Steps in the control of the WEAP hydrological model and WEAPhish fish population and habitat model, by the Master_WEAPhish Middle-Ware.

Figure 20: WEAPhish Python Screen Running from Master_WEAPhish Interface



WEAPhish fish population and habitat model, running after launch from Master_WEAPhish Middle-Ware.

Figure 21: Output Files From WEAP

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	5/25/1999	40	40	40	40	40	40	40	40	40	40	40	40
2	6/1/1999	40	40	40	40	40	40	40	40	40	40	40	40
3	6/8/1999	40	40	40	40	40	40	40	40	40	40	40	40
4	6/15/1999	40	40	40	40	40	40	40	40	40	40	40	40
5	6/22/1999	40	40	40	40	40	40	40	40	40	40	40	40
6	6/29/1999	40	40	40	40	40	40	40	40	40	40	40	40
7	7/6/1999	40	40	40	40	40	40	40	40	40	40	40	40
8	7/13/1999	40.023	40.023	40.023	40.023	40.023	40.023	40.023	40.023	40.023	40.023	40.023	40.023
9	7/20/1999	40	40	40	40	40	40	40	40	40	40	40	40
10	7/27/1999	40.001	40.001	40.001	40.001	40.001	40.001	40.001	40.001	40.001	40.001	40.001	40.001
11	8/3/1999	36.219	36.219	36.219	36.219	36.219	36.219	36.219	36.219	36.219	36.219	36.219	36.219
12	8/10/1999	32.424	32.424	32.424	32.424	32.424	32.424	32.424	32.424	32.424	32.424	32.424	32.424
13	8/17/1999	29.006	29.006	29.006	29.006	29.006	29.006	29.006	29.006	29.006	29.006	29.006	29.006
14	8/24/1999	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05	26.05
15	8/31/1999	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3	23.3
16	9/7/1999	20.899	20.899	20.899	20.899	20.899	20.899	20.899	20.899	20.899	20.899	20.899	20.899
17	9/14/1999	18.651	18.651	18.651	18.651	18.651	18.651	18.651	18.651	18.651	18.651	18.651	18.651
18	9/21/1999	16.648	16.648	16.648	16.648	16.648	16.648	16.648	16.648	16.648	16.648	16.648	16.648
19	9/28/1999	14.759	14.759	14.759	14.759	14.759	14.759	14.759	14.759	14.759	14.759	14.759	14.759
20	10/5/1999	401.77	401.77	401.77	401.77	401.77	401.77	401.77	401.77	401.77	401.77	401.77	401.77
21	10/12/1999	409.39	409.39	409.39	409.39	409.39	409.39	409.39	409.39	409.39	409.39	409.39	409.39
22	10/19/1999	56.264	56.264	56.264	56.264	56.264	56.264	56.264	56.264	56.264	56.264	56.264	56.264

WEAP | Out_flows | Out_temp | GCM_models | System_state_log | Control_option | Control

Out_flows spreadsheet in Master_WEAPhish showing water flow data output from WEAP. The adjacent spreadsheet, Out_temp, would contain water temperature output from WEAP.

Figure 22: Folder of WEAP Output Files

Name	Date modified
BAU_T_sresA2_cnrmcm3	3/17/2015 12:50 PM
BAU_Q_sresA2_cnrmcm3	3/17/2015 12:50 PM
BAU_System_state_log_sresA2_cnrmcm3	3/17/2015 12:50 PM
BAU_T_sresA2_ncarpcm1	3/17/2015 12:49 PM
BAU_Q_sresA2_ncarpcm1	3/17/2015 12:49 PM
BAU_System_state_log_sresA2_ncarpcm1	3/17/2015 12:49 PM
BAU_Q_sresA2_ncarccsm3	3/17/2015 12:48 PM
BAU_System_state_log_sresA2_ncarccsm3	3/17/2015 12:48 PM
BAU_T_sresA2_ncarccsm3	3/17/2015 12:48 PM
BAU_Q_sresA2_mpiecham5	3/17/2015 12:47 PM
BAU_System_state_log_sresA2_mpiecham5	3/17/2015 12:47 PM
BAU_T_sresA2_mpiecham5	3/17/2015 12:47 PM
BAU_Q_sresA2_miroc32med	3/17/2015 12:46 PM
BAU_System_state_log_sresA2_miroc32med	3/17/2015 12:46 PM
BAU_T_sresA2_miroc32med	3/17/2015 12:46 PM
BAU_T_sresA2_gfdlcm21	3/17/2015 12:45 PM
BAU_Q_sresA2_gfdlcm21	3/17/2015 12:45 PM
BAU_System_state_log_sresA2_gfdlcm21	3/17/2015 12:45 PM
BAU_System_state_log__date	3/16/2015 4:54 PM
Empty_file	3/2/2015 5:04 PM

Folder indicating the nomenclature used to name WEAP output files (T = temperature, Q = flow, System = system state log) for different climate scenario and General Circulation Model combinations. The folder shown contains only files from Business As Usual (BAU) water management model runs.

3.5 Middle-Ware/Software Availability

For further information about Master_WEAPhish or User's Manual, contact the following:

- Sooyeon Yi - scyi@ucdavis.edu
- Samuel Sandoval - samsandoval@ucdavis.edu

CHAPTER 4: Outreach

As noted in Chapter 1, the second task for this project was to plan and conduct meetings with stakeholders to determine hydropower operations and fish population and habitat goals, and the fifth task was to plan and conduct a workshop near the end of the project to present the model to stakeholders.

4.1 Stakeholder Meetings

UC Davis researchers met with agency and utility stakeholder groups to discuss plans to develop the fish habitat and population model (Table 5). Participants were aware that the researchers would use their feedback to help the research team to design the most appropriate model to 1) assess trade-offs between water use by native fish and for cost-efficient operations of small hydropower for energy production and 2) evaluate potential effects of climate change using data from climate models with future emissions scenarios. By meeting with groups from three different watersheds, the authors hoped to obtain feedback on key aspects of each system's hydrology and ecology that allowed them to build a more useful and broadly applicable modeling tool.

Table 5: Participants in Stakeholder Workshops

Watershed	Hydropower Facility	Meeting Date	Agency	Name
Butte Creek	DeSabla Dam, Centerville Powerhouse	12 Sept 2013	CA State Water Resources Control Board	Amber Villalobos
Butte Creek	DeSabla Dam, Centerville Powerhouse	12 Sept 2013	CA State Water Resources Control Board	Jeff Wetzel
Butte Creek	DeSabla Dam, Centerville Powerhouse	12 Sept 2013	PG&E	Ed Cheslak
Butte Creek	DeSabla Dam, Centerville Powerhouse	12 Sept 2013	PG&E	Catalina Reyes
Butte Creek	DeSabla Dam, Centerville Powerhouse	12 Sept 2013	NOAA Fisheries	Gretchen Umlauf

Watershed	Hydropower Facility	Meeting Date	Agency	Name
South Fork American River	Slab Creek Dam, White Rock Powerhouse	18 Sept 2013	CA State Water Resources Control Board	Michael Maher
South Fork American River	Slab Creek Dam, White Rock Powerhouse	18 Sept 2013	CA State Water Resources Control Board	Susan Monheit
South Fork American River	Slab Creek Dam, White Rock Powerhouse	18 Sept 2013	SMUD	David Hanson
South Fork American River	Slab Creek Dam, White Rock Powerhouse	18 Sept 2013	SMUD	Darold Perry
North Fork American River	Clementine (North Fork) Dam	31 Oct 2013	Ca Dept. Fish and Wildlife	Anna Ewing
North Fork American River	Clementine (North Fork) Dam	31 Oct 2013	Ca Dept. Fish and Wildlife	Sean Hoobler
North Fork American River	Clementine (North Fork) Dam	31 Oct 2013	Ca Dept. Fish and Wildlife	Beth Lawson
North Fork American River	Clementine (North Fork) Dam	31 Oct 2013	US Forest Service	Dan Teater

Source: Current project.

4.2 Stakeholder Feedback

The main points arising from each of the three workshops were as follows:

4.2.1 Butte Creek

- Important to consider trade-offs between hydropower costs and fish.
- Daily time step for hydrology and, possibly, fish.
- Model habitat and life-cycle complexity similar to SALMOD.
- Model survival and growth during ocean and downstream of Butte Creek.

- Ensure hydrology reflects predicted changes in seasonality of snowpack and rain.

4.2.2 South Fork American River (Slab Creek)

- New habitat class: Cascade (steep; little gravel substrate for spawning, egg rearing).
- Warm and cool water species are present along the temperature river gradient (therefore desirable to have a model that can handle multiple species).
- Tributaries act as sources of fish.

4.2.3 North Fork American River (Clementine Dam)

At the start of the project there was a pending proposal to add hydropower generation to Clementine (North Fork) Dam; this proposal has since been withdrawn. The researchers met with stakeholders from the North Fork American River on October 31, 2013. This meeting was delayed because several participants were called away to fire duty on the Yosemite Rim Fire and American Fire.

- Habitat upstream of the dam is of interest.
- If hydropower facility installed, potential for impingement and entrainment.
- Interest in adding a Reservoir habitat class (with thermal refuge in summer) to allow modeling of potential use of this habitat by rainbow trout.

4.3 Final Workshop

On March 25, 2015 the authors held a workshop to update the original workshop participants on their progress with the models and linkage. The event was titled: Workshop for UC Davis Fish Population and Habitat Model "WEAPhish", and "Master_WEAPhish" Middle-Ware Link to WEAP. Since some people were not able to attend in person, a webinar option was also offered. The webinar video and audio were recorded, and the webinar is available to view online at the California Fish Website. The link is:

http://calfish.ucdavis.edu/Research_Projects/?uid=11&ds=557

The powerpoint slides of all the workshop presenters are compiled as a PDF file in Appendix C.

CHAPTER 5:
Field Data Collection

The fourth task for this project was to conduct site visits to representative small hydropower facilities and to collect detailed water temperature data upstream and downstream of a representative small hydropower facility for use in model development and calibration.

Temperature loggers were installed at several key locations in Butte Creek in the summer of 2013. The aim was to collect a more detailed and comprehensive set of water temperature than had previously been acquired in order to facilitate and improve future calibrations of the WEAP temperature sub-module for use with the new WEAPhish model.

5.1 Site Visits and Temperature Logger Installation

Air and water temperature loggers were deployed in early July 2013, and left running continuously through mid-October, 2013 (Figures 23, 24, 25, 26, 27, 28). The researchers collected the field gear in early October, rather than late September, as originally planned, in order to coordinate with PG&E's field crew for access to sites in PG&E-controlled areas of Butte Creek. Temperatures were measured and logged at 15-minute intervals, using Onset™ Hobo Water Temp Pro loggers.

Figure 23: Installation of Temperature Loggers

Alyssa Obester indicates air temperature logger location at Butte Head Dam location on Upper Butte Creek.

Figure 24: Installation of Temperature Loggers

Patrick Kilduff and Lisa Thompson attach water temperature logger to chain at Forks of the Butte location on Upper Butte Creek.

Source: Alyssa Obester.

Figure 25: Temperature Monitoring Site

Temperature monitoring site at Forks of the Butte (S5) site on Upper Butte Creek.

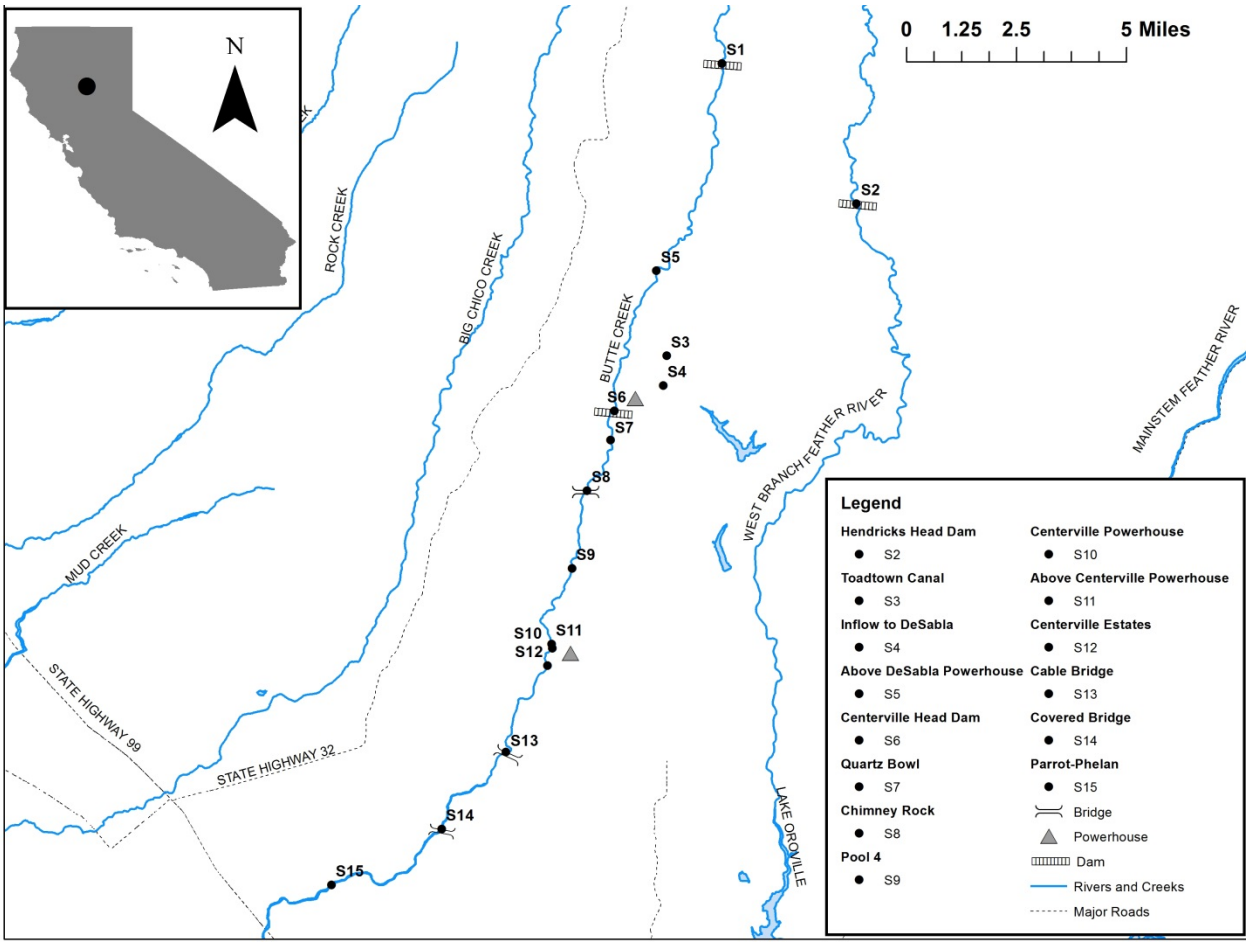
Figure 26: De Sabla Forebay, Part of Butte Creek's Hydropower Infrastructure

Figure 27: Butte Head Dam on Upper Butte Creek, on October 14, 2013

Figure 28: Temperature Monitoring Site

Temperature monitoring site at Butte Head Dam on upper Butte Creek, on October 14, 2013.

Figure 29: Butte Creek Sites Where Water Temperature was Monitored in 2013



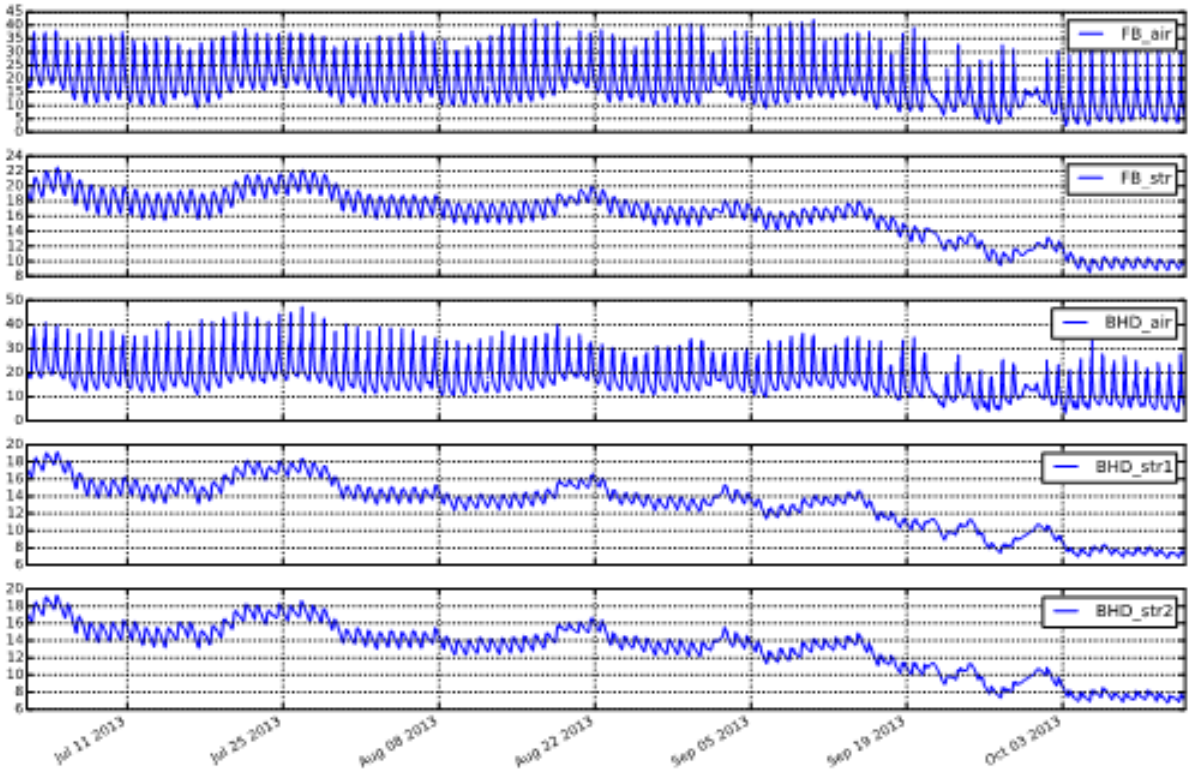
Sites monitored for water temperature along Butte Creek by the current study and by Pacific Gas and Electric in 2013. Inset map shows location of study area within California.

Source: Alyssa Obester.

5.2 Water Temperature Data

Air temperature and stream temperature monitoring results are presented from July – October, 2013 for Butte Creek sites (1) Forks of the Butte (FB_air and FB_str [stream]), and (2) Butte Head Dam (BHD_air, BHD_str1, BHD_str2) (Figure 30).

Figure 30: Air Temperature and Stream Temperature Monitoring Results



Air temperature and stream temperature monitoring results from July – October, 2013 for Butte Creek sites (1) Forks of the Butte (FB_air and FB_str [stream]), and (2) Butte Head Dam (BHD_air, BHD_str1, BHD_str2). Temperatures are plotted in degrees Celsius and were measured at 15-minute intervals.

CHAPTER 6: Discussion

6.1 Major Outcomes of Project

6.1.1 New Model Framework Centered on WEAP

The integrated framework begins with the WEAP system. The Stockholm Environment Institute-US Office (SEI) provided the team with their current WEAP model for Butte Creek to use a point of departure for the integration of the fish model.

6.1.2 WEAPhish Fish Population Dynamics and Habitat Model

The new component of the framework is a fish habitat suitability model, WEAPhish. The model code was written in the programming language Python, a language compatible with WEAP (Sieber and Purkey 2011). Suitable habitat quantity was calculated as a function of water temperature and flow released from upstream reservoirs associated with small hydro facilities (simulated using WEAP), as well as the spatial distribution of available spawning, holding, and rearing habitat. The researchers also sought to quantify factors such as flow, flow pulses (magnitude, frequency, ramping rate, seasonal and daily timing) that are known to affect fish (Young et al. 2011). The temperature-mortality relationship routine developed for Butte Creek spring-run Chinook salmon was used (Figure 3), modified based on local temperature and fish data. Temperature has proven to be the key habitat variable for mid-summer survival of California coldwater fishes (Thompson et al. 2006, Thompson et al. in press) and is likely to be increasingly important in smaller, low-volume streams under climate change (Thompson et al. 2012). The fish habitat suitability model WEAPhish predicts the amount of habitat available for fish, and the potential fish density. Ultimately, the goal will be to identify water management strategies that maintain suitable habitat to support freshwater-dependent lifestages; e.g., spring-run Chinook adults or summer egg survival of winter-run Chinook.

6.1.3 Master_WEAPhish Middle-Ware Software

Going beyond the original scope of work, the new fish model has been integrated within WEAP to simulate the fate of salmonid populations, resulting in a fish component that can be readily modified for multiple populations and watersheds. The project has resulted in a product with potential use on a broad geographic scale. While the researchers examined three streams with representative small hydro facilities prior to model development, the model has been designed to be generalizable to other streams.

6.2 Benefits to Californians

The feasibility of a fish habitat suitability model optimized was developed and tested to assess the impacts and mitigation potential of small hydropower facilities. The model has been designed to function seamlessly within an integrated modeling framework that includes 1) a watershed hydrology and water management model, and (2) a fish habitat suitability model, and (3) a Middle-Ware software to link and control the other two components. The models are designed to be easily modified for different watersheds and fish populations, so they may be

used to assess environmental effects of numerous small hydropower projects in more than one watershed simultaneously.

The analytical framework from this project lays the groundwork for future efforts to assess trade-offs between water use providing freshwater habitat for native fish populations and the cost-efficient provision of water to small hydropower installations. Expectations are that 1) Improved information regarding environmental impacts will allow the hydropower sector to develop plausible estimates of the economic implications of various management options; 2) Regulatory decision-makers will be able to address a key environmental barrier to small hydropower production by avoiding unnecessary curtailment of production due to uncertainty and resultant possibility of unfounded environmental concerns; and 3) Quantifying the cost of compromise will foster a more productive water management dialogue.

The anticipated future impact of this project will be that small hydropower producers will be able to more efficiently mitigate effects on California stream fishes, thereby also minimizing unnecessary curtailment of hydropower production while increasing the contribution of renewable energy portfolios to California's energy mix. Power producers and agencies will gain knowledge on what fish-related performance indicators should be monitored at small hydropower facilities in order to improve design and water management protocols of new facilities.

6.3 Future Work

In future applications, beyond the scope of this proposal, the researchers intend to model the potential impacts of climate change using data generated by a suite of climate models, for multiple future scenarios (IPCC 2007). Downscaling to the river systems will be accomplished using the bias correction and spatial downscaling method (Maurer and Hidalgo 2008). The researchers will explicitly model trade-offs in water use between competing uses, and examine the costs (financial and reliability) to hydropower producers of providing adequate freshwater habitat for native fishes. The researchers will predict the quantity and quality (temperature) of water required for native fishes the changes in hydropower production and revenue if this water is provided to fish, for both current and future climate scenarios.

The researchers' ability to predict long-term population abundance of anadromous fish species such as salmon and steelhead is limited because they did not explicitly model the ocean phase or impacts of changing ocean productivity. The researchers chose to make this simplification because they were focused on water management in freshwater systems, and the management options available for wild salmonids do not currently include methods to increase ocean survival. However, in future the WEAPhish model could be modified to include an ocean component. This addition would also allow consideration of the effects of climate change on ocean conditions that may affect the salmon life cycle, in addition to the effects of climate change on the freshwater life cycle that are currently captured by WEAP and WEAPhish.

Currently the WEAP water allocation/operations rules for Butte Creek are based on the time of year (week of the water year), given the expectation that air and water temperatures are likely to be at their maximum in mid-summer. However, the WEAP water allocation/operations rules

could in theory be altered to include fish status part way through a model run. In order to accomplish this, WEAPhish and Master_WEAPhish would be modified to allow more frequent exchange of inputs and outputs. Currently the models run on a weekly time step, over a number of years, and exchange data at the end of a complete run of years. This is similar to the frequency of data exchange previously done manually between WEAP and SALMOD (Thompson et al. 2012). However, with the new Master_WEAPhish Middle-Ware, it should be possible to have the two models exchange inputs on a weekly basis. While this would likely result in considerably longer run times, it would allow exploration of the efficacy of more tightly coupled water management actions, for example by having WEAP water allocation rules that would respond to WEAPhish fish abundance or mortality rates in the previous time step.

Another avenue to advance the model framework is to connect WEAP and WEAPhish to other model components already incorporated within WEAP, or connected to WEAP in ways similar to the Master_WEAPhish Middle-Ware. These include models of hydropower generation, municipal water use, agricultural plant growth, agricultural land and water use and economic benefits, and waterfowl habitat and bioenergetics. This 5F Framework, in which the Fs are Fuels (hydropower), Fish, Farms, Faucets (municipal), and Fowl (waterfowl), could be used to examine water use trade-offs among all these valuable uses, in order to find water management actions that are most robust under climate change.

Water availability for small hydropower production is often the product of operations to meet multiple water use objectives. In future, it will be possible to model and track the shifts in the timing and amount of hydropower production, as a function of the priorities assigned to the competing (and sometimes complementary) demands of agricultural, waterfowl, fish, and municipal water uses. There are likely to be multiple pathways or arrangements to meet these various demands, with variable outcomes for hydropower reliability, production, timing, and flexibility. An integrated model framework will be of great value to hydropower managers, as they seek to identify and implement management options that optimize hydropower generation, and ultimately, to maximize ratepayer benefits.

GLOSSARY

Term	Definition
CDFW	California Department of Fish and Wildlife
DWR	California Department of Water Resources
Carrying capacity	The maximum number of organisms that can be sustained in a particular habitat, given the availability food, cover, etc..
Cohort	A group of fish born in the same year, also called a "year-class".
GCM	General Circulation Model, a global climate model.
In vivo eggs	Eggs that are carried within the body of a female fish, prior to spawning.
IRP	Central Valley Integrated Resources Plan
Middle-Ware	A piece of computer software designed to link the inputs and outputs of two or more separate computer models.
NMFS	National Marine Fisheries Service (NOAA Fisheries)
PG&E	Pacific Gas and Electric
Redd superimposition	A redd is nest for eggs that a female fish digs in the stream gravel. Superimposition occurs when a female fish digs a nest and in so doing, digs up eggs laid in a nest made by a previous female fish.
SEI	Stockholm Environment Institute
SMUD	Sacramento Municipal Utility District
UCCE	University of California Cooperative Extension
USBR	United States Bureau of Reclamation
USGS	United States Geological Survey
WEAP	Water Evaluation and Planning model system
WPU	Water Plan Update
WUA	Weighted Usable Area

REFERENCES

Abbasi T, Abbasi SA. 2011. Small hydro and the environmental implications of its extensive utilization. Renewable & Sustainable Energy Reviews 15(4): 2134-2143.

Bartholow JM, Laake JL, Stalnaker CB, Williamson S. 1993. A salmonid population model with emphasis on habitat limitations. Rivers 4(4): 265-279.

Battin J, Wiley MW, Ruckelshaus MH, Palmer RN, Korb E, Bartz KK, Imaki H. 2007. Projected impacts of climate change on salmon habitat restoration. Proceedings of the National Academy of Science. 104(16): 6720-6725.

Capik M, Yilmaz AO, Cavusoglu I. 2012. Hydropower for sustainable energy development in Turkey: The small hydropower case of the Eastern Black Sea Region. Renewable and Sustainable Energy Reviews 16(8): 6160-6172.

Cramer SP, Ackerman NK. 2009. Prediction of stream carrying capacity for steelhead: the Unit Characteristic method. In Pacific Salmon Environmental and Life History Models: Advancing Science for Sustainable Salmon in the Future, E. Eric Knudsen and J. Hal Michael, Jr., editors. American Fisheries Society Symposium 71. Bethesda, MD. 464 pp.

Dietrich WE, Ligon F. 2008. RIPPLE – A digital terrain-based model for linking salmon population dynamics to channel networks. Prepared by Stillwater Sciences, Berkeley, California.

Escobar M, et al. (In prep). Exploring the hydropower implications of water management adaptations to climate change to reduce the vulnerability of priority aquatic ecosystems.

Frey GW, Linke DM. 2002. Hydropower as a renewable and sustainable energy resource meeting global energy challenges in a reasonable way. Energy Policy 30(14): 1261-1265.

Gleick PH. 1992. Environmental consequences of hydroelectric development: The role of facility size and type. Energy 17(8): 735-747.

Goniea TM, Keefer ML, Bjornn TC, Peery CA, Bennett DH, Stuehrenberg LC. 2006. Behavioral thermoregulation and slowed migration by adult fall Chinook salmon in response to high Columbia River water temperatures. Transactions of the American Fisheries Society 135:408-419.

Hall DG, Reeves KS, Brizzee J, Lee RD, Carroll GR, Sommers GL. 2006. Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants. DOE-ID-11263.

Hayhoe K, Cayan D, Field CB, Frumhoff PC, Maurer EP, Miller NL, Moser SC, Schneider SH, Cahill KN, Cleland EE, Dale L, Drapek R, Hanemann RM, Kalkstein LS, Lenihan J, Lunch CK, Neilson RP, Sheridan SC, Verville JH. 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences 101(34):12422-12427.

Holt RA, Sanders JE, Zin JL, Pilcher KS. 1975. Relaxation of water temperature to Flexibacter columnaris infection in steelhead trout (Salmo gairdneri), coho (Oncorhynchus kisutch), and Chinook (O. tshawytscha) salmon. Journal of the Fisheries Research Board of Canada 32:1553-1559.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: synthesis report. IPCC, Geneva, Switzerland. 104 p., http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm

Kane M. 2005. California Small Hydropower and Ocean Wave Energy Resources. Staff Paper, California Energy Commission. CEC-500-2005-074.

Kosnik L. 2010. The potential for small scale hydropower development in the US. Energy Policy 38(10): 5512-5519.

Lackey RT, Lach DH, Duncan SL (eds). 2006. Salmon 2100: the future of wild Pacific salmon. American Fisheries Society, Bethesda, MD.

Lestelle LC, Mobrand LE, McConnaha WE. 2004. Information structure of ecosystem diagnosis and treatment (EDT) and habitat rating rules for Chinook salmon, coho salmon, and steelhead trout. Mobrand Biometrics. 29 pp.

Liebowitz SG, White D. 2009. Modelling the effect of stream network characteristics and juvenile movement on coho salmon. In Pacific Salmon Environmental and Life History Models: Advancing Science for Sustainable Salmon in the Future, E. Eric Knudsen and J. Hal Michael, Jr., editors. American Fisheries Society Symposium 71. Bethesda, MD. 464 pp.

Lindley ST, Schick RS, Mora E, Adams PB, Anderson JJ, Greene S, Hanson C, May BP, McEwan DR, MacFarlane RB, Swanson C, Williams JG. 2007. Framework for assessing viability of threatened and endangered Chinook salmon and steelhead in the Sacramento-San Joaquin basin. San Francisco Estuary and Watershed Science 5:1-26.

Maurer EP, Stewart IT, Bonfils C, Duffy PB, Cayan D. 2007. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. Journal of Geophysical Research-Atmospheres 112, D11118, 1-12.

Maurer EP, Hidalgo HG. 2008. Utility of daily vs. monthly large-scale climate data: an intercomparison of two statistical downscaling methods. Hydrology and Earth System Sciences 12(2): 551-563.

Navigant Consulting, Inc. 2006. Statewide Small Hydropower Resource Assessment. PIER final Project Report. Prepared For California Energy Commission Public Interest Energy Research Program. June 2006. CEC-500-2006-065. 67 p.

Null SE, Viers JH, Mount JF. 2010. Hydrologic Response and Watershed Sensitivity to Climate Warming in California's Sierra Nevada. Plos One 5(3).

Oud E. 2002. The evolving context for hydropower development. Energy Policy 30(14): 1215-1223.

Paish O. 2002. Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews 6(6): 537-556.

Panić M, Urošev M, Milanović Pešić A, Brankov J, Bjeljac Ž. 2013. Small hydropower plants in Serbia: Hydropower potential, current state and perspectives. Renewable and Sustainable Energy Reviews 23: 341-349.

Punys P, Pelikan B. 2007. Review of small hydropower in the new Member States and Candidate Countries in the context of the enlarged European Union. Renewable and Sustainable Energy Reviews 11(7): 1321-1360.

Purkey DR, Huber-Lee A, Yates DN, Hanemann M, Herrod-Julius S. 2007. Integrating a climate change assessment tool into stakeholder-driven water management decision-making processes in California. Water Resources Management. 21(1): 315-329.

Santos JM, Ferreira MT, Pinheiro AN, Bochechas JH. 2006. Effects of small hydropower plants on fish assemblages in medium-sized streams in central and northern Portugal. Aquatic Conservation: Marine and Freshwater Ecosystems 16(4): 373-388.

Scheuerell MD, Hilborn R, Ruckelshaus MH, Bartz KK, Lagueux KM, Haas AD, and Rawson K. 2006. Canadian Journal of Fisheries and Aquatic Sciences. 63: 1596-1607.

Schwartz FH, and Shahidehpour M. 2006. Small hydro as green power. EIC Climate Change Technology, 2006 IEEE (Institute of Electrical and Electronics Engineers). pp. 1-6.

Sharma NK, Tiwari PK, Sood YR. 2013. A comprehensive analysis of strategies, policies and development of hydropower in India: Special emphasis on small hydro power. Renewable and Sustainable Energy Reviews 18: 460-470.

Sieber JS, Purkey DR. 2011. WEAP Water Evaluation and Planning System – User Guide. Stockholm Environment Institute, US Center. 343 p. http://www.weap21.org/downloads/WEAP_User_Guide.pdf

Strange JS. 2010. Upper thermal limits to migration in adult Chinook salmon: Evidence from the Klamath River basin. Transactions of the American Fisheries Society 139:1091-1108.

Thompson LC, Forero L, Sado Y, Tate KW. 2006. Impact of environmental factors on fish distribution assessed in rangeland streams. California Agriculture. 60(4):200-206.

Thompson LC, Escobar MI, Mosser CM, Purkey DR, Yates D, Moyle PB. 2012. Water management adaptations to prevent loss of spring-run Chinook salmon in California under climate change. Journal of Water Resources Planning and Management 138(5): 465-478.

Thompson LC, Voss JL, Larsen RE, Tietje WD, Cooper RA, Moyle PB. 2012. Southern steelhead (Oncorhynchus mykiss), hard woody debris, and temperature in a California central coast watershed. Transactions of the American Fisheries Society 141(2):275-284.

United States Department of Energy. 2013. International Energy Statistics.

Yates D, Purkey D, Sieber J, Huber-Lee A, and Galbraith H. 2005a. WEAP21 - A demand-, priority-, and preference-driven water planning model Part 2: Aiding freshwater ecosystem service evaluation. Water International, 30(4): 501-512.

Yates D, Sieber J, Purkey D, and Huber-Lee A. 2005b. WEAP21 - A demand-, priority-, and preference-driven water planning model Part 1: Model characteristics. Water International., 30(4): 487-500.

Yates D, Purkey D, Sieber J, Huber-Lee A, Galbraith H, West J, Herrod-Julius S, Young C, Joyce B, and Rayej M. 2009. Climate driven water resources model of the Sacramento Basin, California. Journal of Water Resources Planning and Management, 135(5): 303-313.

Young CA, Escobar-Arias MI, Fernandes M, Joyce B, Kiparsky M, Mount JF, Mehta VK, Purkey D, Viers JH, and Yates D. 2009. Modeling the hydrology of climate change in California's Sierra Nevada for subwatershed scale adaptation. Journal of the American Water Resources Association 45(6): 1409-1423.

Young P, Cech, Jr JJ, Thompson LC. 2011. Hydropower-related pulsed-flow impacts on stream fishes: A brief review, conceptual model, knowledge gaps, and research needs. Reviews in Fish Biology and Fisheries. 21(4): 713-731.

APPENDIX A:
WEAPhish User's Manual: A Guide to Installing and Running a Habitat-Based Fish Population Model, v. 0.1

This appendix is available as a separate volume,
publication number CEC-500-2016-043-APA.

Please use the following citation for this appendix:

Kilduff, D. Patrick; Lisa C. Thompson; Samuel S. Sandoval; Sooyeon Yi. 2015. WEAPhish User's Manual: A guide to installing and running a habitat-based, fish population model, v. 0.1 beta. University of California Davis, March 31, 2015. 40 p.

APPENDIX B:
User's Manual for Middle Ware [Master_WEAPhish]

This appendix is available as a separate volume,
publication number CEC-500-2016-043-APB.

Please us the following citation for this appendix:

Yi, Sooyeon; Samuel S. Sandoval. 2015. User's Manual for Middle Ware [Master_WEAPhish]. University of California Davis, March 31, 2015. 6 p.

APPENDIX C:
Final Workshop Presentation

This appendix is available as a separate volume,
publication number CEC-500-2016-043-APC.

Please use the following citation for this appendix:

Thompson, Lisa C.; D. Patrick Kilduff; Samuel S. Sandoval; Sooyeon Yi. 2015. Fish Population & Habitat Model "WEAPhish", & "Master_WEAPhish" Middle-Ware Link to WEAP. Powerpoint presentation, pdf file. Sacramento, CA. 25 Mar 2015. 46 p.