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Primer for Identifying Cold-Water Refuges to Protect and Restore Thermal Diversity in Riverine Landscapes

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Primer for Identifying Cold-Water Refuges to Protect and Restore Thermal Diversity in Riverine Landscapes

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Executive Summary

In 2003, EPA issued Region 10 guidance for Pacific Northwest state and tribal temperature water quality standards. This document was the culmination of a multi-agency, multi-disciplinary effort to develop a temperature standard for the protection of salmon, steelhead, bull trout, and redband and Lahontan cutthroat trout (collectively termed coldwater salmonids). Since its release, Oregon and Washington have adopted the temperature standard for their waters designated for protection of coldwater salmonids. One of the unique aspects of the temperature standard, which strived to integrate the physical nature of rivers and streams and the biological requirements of coldwater salmonids, is the requirement to protect and restore cold-water refuges. This requirement is incorporated into the temperature criterion for the protection of migration corridors in the Willamette, Columbia, and Snake rivers. The intent of this provision is the recognition that some coldwater salmonids migrate through waters during thermally stressful months of summer and most likely are able to do so by using features in the rivers that provide cold water spatially or temporally. The challenge is to ensure that these features are identified, protected, and restored in order for these waters to meet the temperature standard. This primer is intended to assist Region 10 states, tribes, and local watershed groups in meeting this goal and thereby further the protection and restoration of coldwater salmonids. It provides an up-to-date summary with easily referenced information and illustrations on the scientific advances and management applications of research on cold-water refuges and can be used as a 'roadmap' for identifying cold-water refuges and learning more about processes that create thermal diversity in riverine landscapes. The specific objectives are to

1. Define *cold-water refuge* in scientific and management contexts,
2. Outline an approach for identifying cold-water refuges to address water quality standards,
3. Classify and characterize the types and physical processes that create cold-water refuges,
4. Review methods and tools for identifying cold-water refuges in small streams to large rivers, and
5. Describe ecological perspectives and on-the-ground approaches for protecting and restoring thermal diversity in rivers.

1. Introduction

1.1. Why are cold-water refuges important?

Cold-water refuges in rivers and streams have physiological and ecological significance because temperature is the driving factor that determines the metabolic rates of cold-blooded animals, such as fish and the organisms on which they feed. Because fish and invertebrates have specific ranges of thermal tolerance, increases in water temperature as a result of human modification of the natural thermal regime may require fish and invertebrates to move to areas that are more thermally suitable. [91, 39, 27, 61, 19, 77, 155, 184]

In order to protect the beneficial uses of rivers and streams, which include promoting a favorable environment for salmon and trout, cold-water refuges require specific consideration in the regulation of water quality through standards developed by state and federal agencies. [128, 120, 185]

1.2. Science and management needs

The social and economic importance of wild salmon and trout in the Pacific Northwest and their dramatic decline over the last century has brought the issue of water temperature to the forefront in fisheries science and management because of its significance as a habitat requirement under current conditions and in the broader context of climate change. [89, 137, 152, 182, 15, 153]

Although scientific understanding of fish and their fundamental physiological responses to elevated water temperature was well developed in a laboratory setting prior to the 1990s, application of this understanding in the field to address management needs has been and remains a significant challenge. This is due to the difficulty of replicating spatially and temporally complex thermal environments in the laboratory and relating observations of domesticated fish to the behavior of wild fish in natural environments. The need for science and applications of relevant technology has driven rapid advances in the last 15 years in identifying and predicting both the physical drivers of thermal heterogeneity in streams and the responses of aquatic organisms to these patterns.

1.3. Purpose and intended audience

The purpose of this primer is to provide an overview of cold-water refuges in river systems for the protection of salmon and trout. The primer provides instruction on what cold-water refuges are, how to identify them, how they function, and how they can be protected and restored. The following sections include the latest resources and references to assist in this work and are specifically designed to support state and tribal water quality standards for temperature. This primer is an outgrowth of the Environmental Protection Agency Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. [82]

EPA's temperature guidance was the culmination of a multi-agency, multi-disciplinary effort to develop a temperature standard for the protection of coldwater salmonids. Since its release, Oregon and Washington have adopted the temperature standard. One of the unique aspects of the temperature standard, which strived to integrate the physical nature of rivers and streams and the biological requirements of coldwater fish, is the requirement to protect and restore cold-water refuges.

The challenge is to ensure that these features are identified, protected, and restored in order for these waters to meet the temperature standard. This primer is intended to assist Region 10 states, tribes, and local watershed groups in meeting this goal and thereby further the protection and restoration of salmon and trout populations.

1.4. How to use this primer

This document is organized to provide information concisely and in a manner that facilitates navigation forward or backward as a handbook without requiring the reader to progress sequentially through each section to find information. The figures and table are numbered so that they can be associated with their corresponding sections and references in the main text. Detailed annotations and textual clarification are included with each figure and table so that they can be interpreted independently from the main text. To facilitate the flow and readability of the text, references are cited at the end of the paragraph to which they refer and are indicated with a corresponding number in the list of references.

Section 2 provides an overview of important ecological concepts in a management context. **Sections 3** and **4** provide step-by-step instruction for identifying cold-water refuges to address water quality standards. **Sections 5**, **6**, and **7** outline the scientific underpinnings and methodological approaches for understanding and identifying the processes that create and maintain cold-water refuges for the purposes of protection and restoration. Detailed information on any one topic is best acquired through the cited references that range from broad in scope to very specific.

Additional materials are provided in the appendices, including streaming video of scientific presentations on cold-water refuges and summaries and maps of remotely sensed stream temperature data, which are available online and on request from the authors.

1.5. Objectives

The primer has the following objectives:

- Define ‘cold-water refuge’ in scientific and management contexts.
- Outline an approach for identifying cold-water refuges to address water quality standards.
- Classify and characterize the types and physical processes that create cold-water refuges.
- Review methods and tools for identifying cold-water refuges in small streams to large rivers.
- Describe ecological perspectives and on-the-ground approaches for protecting and restoring thermal diversity in rivers.

2. What is a cold-water refuge?

2.1. Scientific definitions

The terms *refugium*, *refugia*, and *refuge* have been used widely in the scientific literature, but they have different connotations and denotations and require clarification in order to avoid confusion. In the field of biogeography, refugia (plural for *refugium* in Latin) are distinct geographic areas, or 'islands' in a figurative sense, in which flora and fauna have been able to survive in isolation from surrounding unfavorable environmental conditions. For example, glacial refugia are areas in which plants and animals were able survive during the Pleistocene Epoch (the Great Ice Age). Fire refugia are areas of various sizes ranging from a microhabitat to a portion of a landscape that is not burned in wildfire. An important aspect of refugia in a biogeographical sense is that they are considered *refugia* only if they are occupied by species that were already present in an area, as opposed to areas of retreat used by migratory species.[176, 233, 205, 53, 52, 2]

In community ecology, *refugium* and *refuge* generally refer to areas occupied by organisms to avoid predation and competition, or human impacts, such as angling, harvest, or land use.[233, 52, 2, 55]

Aquatic ecologists also apply the concept of refuge in regard to species interactions, but more frequently, *refugia* and *refuges* are used to identify local-scale areas or 'shelters' in which organisms are protected from unfavorable physical conditions, such as streamflow, flood-related disturbance, and temperature. Aquatic organisms may take refuge in warm water in winter or cold water in summer, depending on ambient conditions and the thermal tolerances of the species.[97, 130, 192, 101, 64, 206, 174, 177, 56, 144, 158, 107, 12, 181, 164, 5, 55, 87]

Applications of the concept of refuges in aquatic systems have not always been explicit regarding scale. As we will elaborate in **Section 5**, thermal refuges can be understood to operate at spatial scales ranging from microhabitats to entire river basins. Regardless of scale, refuges will always be defined as discrete patches within some larger spatial context.

2.2. Proposed terminology

To avoid possible confusion about (1) the biogeographical definition of *refugia* and (2) the spelling of its singular form *refugium*, this primer uses *refuge* and *refuges*, which may be either cold or warm in relation to surrounding water and are collectively termed *thermal refuges*. For example, a thermal refuge in the winter is a place that is warmer than the surrounding water (i.e., a "warm-water" refuge). Conversely, a thermal refuge in the summer is a place that is colder than the surrounding water (i.e., a "cold-water" refuge). This primer focuses on cold-water refuges as pertains to water quality standards and the effects of elevated water temperature on salmonids (see **Section 1.3**).

2.3. Management and policy

Due to the inherent physical and ecological complexity of cold-water refuges, explicit terminology is required in order to minimize varying interpretations. [235, 128, 37]

The EPA has determined that "Critical aspects of the natural thermal regime that should be protected and restored include the spatial extent of cold-water refugia (generally defined as waters that are 2°C colder than the surrounding water), the diurnal temperature variation, the seasonal temperature variation (i.e., number of days at or near the maximum temperature), and shifts in the annual temperature pattern." [82]

Based on EPA guidance, the Oregon Department of Environmental Quality developed a more specific definition: "*Cold-Water Refugia* means those portions of a water body where or times during the diel temperature cycle when the water temperature is at least 2°C colder than the daily maximum temperature of the adjacent well-mixed flow of the water body." (OAR 340-041-0002 [10]). [170, 36, 46, 171]
http://www.deq.state.or.us/wq/standards/temperature.htm

2.4. Conceptual framework

Fish are capable of detecting differences in temperature of <0.1°C and respond to these fine-scale differences in both space and time by moving to areas that are more favorable. Movement by an organism to occupy more favorable thermal environments is termed *behavioral thermoregulation*. Observations of fish using cold-water refuges in the Pacific Northwest provided direct evidence of thermal effects on salmon and trout and raised awareness of the importance of these habitats. Understanding how fish respond to cold-water refuges requires information on the ecological context, spatial and temporal variability, and physical typology of the refuge itself. [142, 163, 248, 230, 77, 201, 202, 149]

2.4.1. Ecological context

The upper and lower limits of all environmental conditions within which a species can persist have been described as a multidimensional space or "fundamental niche" for that species. Although abstract in a theoretical sense, the idea of the fundamental niche is important because it provides an avenue for understanding the multiple factors at play in determining the capacity of a species to perform in the natural environment (**Figure 2.4.1.1**). [118, 235, 204]

For example, there are physical and biological tradeoffs for a fish that moves to a cold-water refuge. Although the water temperature may be favorable, conditions may be less than optimal for dissolved oxygen, depth, cover, and isolation from the mainstem. Feeding and species interactions, such as predation and competition, all affect the favorability of a cold-water refuge and may be compromised in order for the fish to maintain immediate physiological homeostasis (**Figures 2.4.1.2, 2.4.1.3**, and **2.4.1.4**). [142, 197, 32, 48, 80, 75, 134, 78, 243, 65, 94, 38, 157]

For the purposes of this primer, a refuge is first defined in relation to temperature. To be effective in providing the conditions necessary for persistence within an otherwise hostile matrix, a refuge also must meet all minimal habitat requirements for a given species. Evaluations of thermal refuge effectiveness will require consideration of accessibility, chemical environment, and other trade-offs that may be associated with predation risk or foraging efficiency within refuges (**Figure 2.4.1.5**). Guidance on evaluation of these factors is beyond the scope of this primer, but we urge users to collect supplemental data on other factors that may influence refuge effectiveness to help advance the state of the science (see **Figure 2.4.1.5** for examples of these supplemental data).

2.4.2. Spatial and temporal variability

Changes in the size and persistence of cold-water refuges have corresponding effects at various spatial and temporal scales and levels of biological organization for a given fish species (**Figure 2.4.2.1**). Moreover, the favorableness of a given cold-water refuge varies depending on the degree of isolation between refuge habitats and the distance to other habitats required for survival and growth (**Figures 2.4.2.2** and **2.4.2.3**). [211, 193, 66, 74, 103, 72]

Fish may use cold-water refuges at various temporal and spatial scales. This particular aspect of the thermal ecology of fish is poorly understood due, in part, to the difficulty of quantifying the dimensions of cold-water refuges that can be constantly changing in space and time (**Figure 2.4.2.4**). The literature on cold-water refuges primarily addresses spatial heterogeneity in water temperature as opposed to temporal variability. Although this primer focuses more on spatial patterns, it is important to stress that more information is needed on how coldwater fish use both spatial and temporal variability in water temperature to survive in thermally stressful environments (**Figure 2.4.2.5**). Improved technology for tracking movements of fish, as discussed in **Section 6.4.3**, has great potential for addressing problems of spatial and temporal scale and behavioral thermoregulation by fish. [163, 86, 188, 230]

2.4.3. Physical typology

Hydrologic processes that create cold-water refuges may be broadly defined as either point sources (e.g., tributaries and groundwater seeps) or as non-point sources (e.g., ‘gaining’ or ‘losing’ reaches). Direct measurement of gaining or losing reaches requires the use of mini-piezometers installed in the streambed, or highly precise stream gaging. Indirect methods also are effective for identifying potential gaining and losing reaches and are easier to apply over large areas because indirect methods do not involve installing equipment in the field. These indirect methods can be used to identify floodplain features, channel morphology, and thermal patterns that are associated with groundwater/streamwater exchange (see **Sections 5** and **6**) (**Figures 2.4.3.1** and **2.4.3.2**). [42, 60, 187, 109, 17, 58, 51, 186]

3. A ‘road map’ for identifying cold-water refuges to address water quality standards

3.1. Approach

The process of identifying cold-water refuges in riverine landscapes and using this information to address management objectives is complex. However, the process can be divided into a series of steps to make the task more manageable. This section outlines these steps in general terms and provides a framework for addressing EPA Region 10 temperature water quality guidance to protect and restore cold-water refuges. This framework also provides a ‘road map’ for navigating to subsequent sections of the handbook with more detailed information, references, and illustrations.

3.2. Spatial scale

Step 1. Define the spatial context of interest in terms of resolution and extent.

The resolution is the scale (also described as ‘grain’ in the ecological literature) at which cold-water refuges are quantified, whereas the extent is the geographic area (e.g., basin size or length of stream) over which an assessment of cold-water refuges is conducted.

The resolution and extent may not be defined explicitly in the objectives that call for an assessment of cold-water refuges. Therefore, it may be necessary to review, and perhaps revise, the overall goals of a project in order to focus the questions regarding the spatial characteristics of the cold-water refuges of interest. Information for a given extent may be needed on cold-water refuges at several different resolutions.

Section 5 of this primer provides information to assist the user on selecting the appropriate spatial scale(s) of interest in an assessment of cold-water refuges (e.g., basins and subbasins, segments, reaches, channel units, and microhabitats). **Table 5.1.1** lists these scales and provides dimensions in space (length and area) and time (months, decades, etc.) that typically are associated with processes that create cold-water refuges. Note that the actual dimensions of streams and rivers vary depending on stream size (i.e., Strahler order; see **Section 3.4**).

3.3. Temporal scale

Step 2. Define the temporal context of interest in terms of resolution and extent.

The temporal resolution of a temperature measurement is defined as the interval in time between measurements in seconds, minutes, hours, days, weeks, or other predefined intervals. The temporal extent is the length of time over which temperature measurements are collected. For evaluating stream temperature, typical extents range from months and years to decades, or greater, depending on the frequency of the natural and human disturbances of interest.

The concept of temporal scale as applied to cold-water refuges is abstract, so it helps to think in terms of different sampling methods. For example, measuring temperatures in a stream with a hand-held thermometer typically has a temporal resolution of seconds, based on the time it takes to obtain a reading. The temporal extent of this method typically is on the order of minutes. The temporal resolution of a digital temperature data logger is the interval at which the logger is programmed to record measurements, and the temporal extent is the duration of the deployment.

The various methods discussed in **Section 6** have different capabilities in terms of temporal resolution and extent. An assessment of cold-water refuges may require data at multiple temporal resolutions.

3.4. Stream size and accessibility

Step 3. Evaluate the range of stream sizes that will be encountered in the river segment of interest.

Methods for identifying cold-water refuges vary with respect to their effectiveness in streams of different sizes and their accessibility by foot, boat, or car (**Section 6**). Knowing the approximate stream sizes likely to be encountered will help guide planning efforts for conducting surveys of cold-water refuges. Stream size is measured in terms of discharge, which is a function of wetted width, depth, and water velocity. Discharge and/or channel widths can be visually estimated from remotely sensed imagery or obtained from on-line data repositories (USGS gaging station data:
http://or.water.usgs.gov/,
http://waterdata.usgs.gov/nwis,
http://or.water.usgs.gov/projs_dir/will_tmdl/main_stem_bth.html).

3.5. Toolbox

Step 4. Select the appropriate tools based on the scales of interest, logistical constraints, and available resources.

A variety of tools exist for identifying cold-water refuges and the areas in which they are likely to occur (**Section 6**). As a general rule, maps, models, and imagery are most effective for evaluating where cold-water refuges are likely to occur at medium to large spatial scales, whereas methods for measuring cold-water refuges directly are more appropriate at medium to small spatial scales.

The order of methods presented below highlights the importance of using publically available data prior to conducting fieldwork. Even when resources exist for data collection in the field, *a priori* evaluation of maps, models, existing data, and airborne/satellite imagery ensures that resources will be used efficiently.

3.5.1. Maps

When the spatial extent of an area of interest is large, maps are an essential screening tool for focusing field data collection. Maps of ecoregions, geology, and topography provide readily accessible information on potential locations of cold-water refuges at basin, subbasin, segment, and reach scales (**Sections 5.1**, **5.2**, **5.3**, **5.4**, and **6.1**). Historical maps may provide an important temporal context (**Section 7.4**). These maps depict channel locations and morphology prior to human alteration and could illustrate areas where cold-water refuges have been lost and potentially could be restored (**Section 7.5**).

Maps are effective for identifying potential locations of cold-water refuges in large rivers (i.e., non-wadeable streams) that are difficult to sample exhaustively in the field, and in remote areas that are inaccessible by car or boat.

3.5.2. Modeling

During the initial phase of identifying cold-water refuges, various models and data may be used to fine-tune map-based predictions of potential cold-water refuge locations. Spatially explicit stream temperature models have been developed by natural resource agencies for many rivers throughout the Pacific Northwest (**Section 6.2**).

Model output consists of longitudinal profiles and maps depicting variability in stream temperature at relatively high spatial resolutions (<1 km) for entire river segments tens of kilometers in length. Cold-water refuges detected in stream temperature models at basin, subbasin, segment, and reach scales include tributary inputs, effects of riparian shading, and groundwater/surface-water interactions (**Sections 5.2**, **5.3**, and **5.4**).

3.5.3. Remote sensing

Airborne and satellite imaging (Section 6.3) can be an invaluable tool for predicting where cold-water refuges are likely to occur under present conditions and where they may have occurred historically and where they potentially could be restored (Sections 7.4 and 7.5). These tools are most useful for identifying features associated with cold-water refuges at segment, reach, and channel unit scales (Sections 5.3, 5.4, and 5.5). In medium- and large-sized rivers, aerial photographs also can be used to identify riverine features associated with cold-water refuges at the microhabitat scale (Section 5.6). When available, thermal infrared imagery collected from an aircraft or on the ground provides a means to locate and map cold-water areas with a high degree of precision (Section 6.3.3). A limitation of imagery is that it can be used effectively only in river systems in which the view of the stream channel and floodplain is not obstructed by trees.

3.5.4. Direct measurement

If the spatial extent of the area of interest is small or involves small stream sizes, it may be appropriate to forgo maps, models, and airborne/satellite imagery and proceed directly to measuring cold-water refuges in the field (Section 6.4). An example of this situation would be in headwater streams, for which (1) available maps are too coarse in scale to detect channel characteristics and (2) aerial views of the stream are obscured by riparian vegetation. In most cases, direct measurement is used only after a thorough investigation of maps, imagery, models, and existing field data.

Appropriate spatial and temporal scales for direct measurement of cold-water refuges vary among methods. For example, stationary temperature data loggers can be deployed throughout entire basins and throughout segments to create maps of broad-scale patterns of stream temperature (Section 6.1). However, stationary data loggers typically cannot be deployed at densities high enough to detect cold-water refuges at reach, channel unit, and microhabitat scales. Hand-held thermocouples and towed digital temperature data loggers can be used to identify cold-water anomalies at segment, reach, channel unit, and microhabitat scales (Sections 5.3, 5.4, 5.5, and 5.6), but these techniques do not provide a synoptic assessment, or ‘snapshot’, of thermal patterns.

3.6. Assessment

Step 5. Identify and map cold-water refuges with respect to their typology.

Assessment involves map-, model-, image-, and field-based identification (Section 6) of existing cold-water refuges as well as the locations where they may have occurred prior to human alteration of the riverine landscape. Cold-water refuges are classified and characterized as described in Section 5.

3.7. Data compilation and documentation

Step 6. Generate tables and maps.

Cold-water refuges are coded by type (**Section 2.4.3**), hierarchical level (**Sections 5.2**, **5.3**, **5.4**, **5.5**, and **5.6**), location by river kilometer (referenced to the USGS National Hydrography Dataset), method of assessment (**Sections 6.1**, **6.2**, **6.3**, and **6.4**), data source (i.e., if publically available maps, data, models, and imagery are used), and time and date of measurement.

3.8. Evaluation and implementation

Step 7. Evaluate the distribution of cold-water refuges with respect to EPA Region 10 temperature water quality guidance.

The current distribution, including size, frequency, and spacing of cold-water refuges, provides (1) information needed to protect existing habitats, (2) clues to the historical distribution of such habitats that can be used as a baseline for determining targets for restoration, and (3) evidence to help evaluate the sufficiency of these habitats for supporting successful migration and/or rearing of juvenile and adult salmonids (**Section 7**). An example of a process by which managers can use this combined information to make informed management decisions for protecting and restoring cold-water refuges is provided in **Section 7** (see **Figure 7.1.1**).

4. Application to EPA guidance on migration corridors for salmon and trout

4.1. Background

The EPA recommends a 7-day average daily maximum water temperature of 20°C in portions of rivers through which salmon and trout migrate during maximum summer temperatures. This recommendation includes the provision to protect and restore cold-water refuges where they currently exist and where they may have occurred historically prior to human alteration of the landscape (see **Section 2.3** for the definition of a cold-water refuge based on EPA guidance). [82]

The following steps are provided to assist states and tribes in identifying cold-water refuges in migration corridors for salmon and trout. The lower Willamette River in Oregon is used as an example because it is designated by the Oregon Department of Environmental Quality as a migration corridor for salmon and trout. This use also occurs in the lower parts of other rivers in the Pacific Northwest (e.g., John Day River, Columbia River, and Snake River; see website below). The lower Willamette River contains a wide range of channel forms and sizes and provides an illustration of how the following steps may be applied in other river systems of similar size and complexity.
http://www.deq.state.or.us/wq/rules/div041tblsfigs.htm#t2

Details regarding the lower Willamette River are provided only as an example; adaptations of this approach by states and tribes will be required to meet their specific needs, objectives, and budget constraints. The Willamette River has been studied extensively and therefore has the benefit of a wealth of data from remote sensing and intensive investigation in the field. Many of these techniques may not be available to resource managers in less-studied basins; however, low-cost approaches using publically available data and Internet resources also are effective for identifying areas of potential thermal heterogeneity. These low-cost techniques are illustrated and described in **Sections 5** and **6**.

4.2. Spatial and temporal scales

Steps 1 and 2

The spatial and temporal extents of inquiry are set by EPA guidance and by the State water quality standard that refer to migration corridors for salmon and trout during the warmest two months of summer. The lower 80 km of the Willamette River is designated as a migration corridor for salmon and trout in the summer. Thus, the spatial and temporal extents of this assessment are 80 km and two months (July–August), respectively. For a river segment this long, quantifying cold-refuges at a very fine spatial resolution may not be logistically feasible. Therefore, an entire pool or riffle (channel unit), or a portion thereof (microhabitat: e.g., 10 m^2), is an appropriate scale at which to examine cold-water refuges in this river segment. Cold-water refuges smaller than the stated resolution would not be considered in the assessment.

An appropriate temporal resolution for examining cold-water refuges in the lower Willamette River is 1 day, in which a potential metric of interest is daily maximum water temperature. Because the stated temporal resolution is 1 day, cold-water refuges would be considered only in the assessment if their daily maximum temperature is 2°C less than the surrounding waters (see **Section 2.4.2** for guidance on how the spatial boundaries of a cold-water refuge are defined).

4.3. Stream size and accessibility

Step 3

The lower Willamette River segment is a large, floodplain river with stream widths greater than 100 m and depths greater than 3 m. The river segment is not wadeable but is navigable by boat; access by car to specific riverbank locations is limited by adequate roads and private land. Aerial photography available from Google© Earth (http://earth.google.com) or other high-resolution sources can be an invaluable tool for evaluating stream size (i.e., width) and the accessibility of specific river reaches from roads. Because water depth is more difficult to evaluate from aerial photography, it is recommended that reconnaissance be conducted on foot or by boat before surveys of cold-water refuges are conducted.

4.4. Toolbox

Step 4

Maps, models, and imagery are appropriate tools (**Sections 6.1**, **6.2**, and **6.3**) for an initial assessment of cold-water refuges at segment, reach, and channel unit scales in the lower Willamette River (**Sections 5.3**, **5.4**, and **5.5**).

Methods for *in situ* identification of cold-water refuges could include (1) surveys by boat with hand-held thermocouples and towed digital temperature data loggers, (2) deployment of stationary data loggers, and (3) tracking of fish with temperature-sensitive tags and data loggers (**Section 6.4**).

4.5. Assessment

Step 5

The Oregon Department of Environmental Quality used airborne thermal infrared remote sensing and temperature models to develop total maximum daily loads (TMDLs) for temperature in the Willamette River. Thermal infrared images can be used to help identify cold-water refuges associated with river confluences and thermal heterogeneity at segment, reach, and channel unit scales. The TMDL models provide information on cold-water refuges at segment and reach scales.
http://www.deq.state.or.us/wq/tmdls/tmdls.htm
http://or.water.usgs.gov/proj/will_temp/

Maps and imagery for the lower Willamette River are publically available over a range of spatial scales and can be used to assess landscape features associated with zones of potential and historical groundwater/surface-water interactions. These areas are where cold-water refuges are likely to occur at segment, reach, and channel unit scales (**Section 7.4**).

Direct measurement of cold-water refuges in the lower Willamette River is best accomplished by deploying stationary data loggers at point locations based on patterns observed in maps, models, and imagery to target areas likely to contain cold-water refuges. Data loggers may be used to confirm the locations of cold-water refuges and to monitor variability in their size seasonally and with different flow conditions. If resources are not sufficient to deploy stationary data loggers at a density commensurate with the spatial resolution and extent of interest, additional surveys with towed data loggers may be required to quantify thermal patterns in gaps between data loggers.

4.6. Data compilation and documentation

Step 6

Generate tables and maps as outlined in **Section 3.7**.

4.7. Evaluation and implementation

Step 7

Evaluate the distribution of cold-water refuges to address EPA Region 10 guidance and Oregon Department of Environmental Quality water quality standards for the lower Willamette River as outlined in **Section 3.8**.

5. Classification and characterization

5.1. Hierarchical organization

This section builds on the simple typology introduced in **Section 2.4.3** by discussing the various processes that are associated with creating point and non-point cold-water refuges at different spatial scales.

Landscapes, watersheds, and streams are organized hierarchically in space and time, and this structure provides a useful framework for classifying and characterizing cold-water refuges (**Table 5.1.1**). For the purposes of this primer, the EPA level-II and -IV ecoregions provide the landscape context of geology, physiography, vegetation, climate, soils, land use, and hydrology (**Figure 5.1.1**). Subsequent levels in the hierarchy include basins, subbasins, segments, reaches, channel units (pool/riffle), and microhabitats, which form the templates upon which cold-water refuges and the processes that create them are shaped. [90, 172, 175, 70, 79, 223, 146, 186]

5.2. Basin and subbasin

Understanding cold-water refuges at lower levels in the hierarchy requires knowledge of the basin-scale context. For example, cold-water refuges at the basin and subbasin level are often driven by elevation, topography, geology, channel slope, and interactions with surface and subsurface hydrology. Hydrologic landscapes and ecoregions integrate these patterns and make it possible to draw conclusions about which basins and subbasins will be cooler than others (**Figure 5.2.1**). Patterns of vegetation, soils, and land use provide additional clues about the thermal potential of watersheds. [194, 244, 11, 218, 246, 125, 126, 157, 164, 40, 219, 242]

5.3. Segment

Cold-water refuges at scales of 0.5–1 km in small rivers and 5–10 km in large rivers occur at confluences where large tributaries (Strahler order >4) enter the mainstem and where bounded alluvial valley segments (BAVS) 'funnel' cooler subsurface water upward into the stream channel (**Figure 5.3.1**). Abrupt changes in channel slope also are potential indicators of thermal heterogeneity associated with downwelling and upwelling zones at the valley-segment level. [16, 159, 183, 20, 21, 132, 14, 23, 33, 81, 99, 113, 34, 131, 238]

Hypolimnetic releases downstream of dams create segment-scale thermal discontinuities that are predictable based on the structure and timing of releases, whereas segment-scale changes in temperature related to sediment dynamics and differences in thermal loading (Kent Smith, Yoncalla.net, personal commun., September 10, 2009) are difficult to differentiate from other processes without developing process-based models (see **Section 6.2**) (**Figure 5.2.1**). [147]
http://www.yoncalla.net/Temperature_10.htm

5.4. Reach

Medium-sized tributaries (Strahler order: 3-4) with relatively constant, cool flow throughout the summer may create reach-scale cold-water refuges at confluences where the tributaries enter the mainstem. [10, 69, 98, 216]

Floodplain connectivity in alluvial valleys with high sinuosity, multiple subsurface pathways, and alluvial fans with glacial meltwater can create thermal diversity at a reach scale (**Figure 5.4.1**), but studies that have investigated how these areas may be used as cold-water refuges are rare. Reach-scale studies of fish and groundwater, hyporheic and surface-water exchange primarily have focused on spawning site selection by salmonids where upwelling creates warm-water refuges for eggs and fry in the winter. [7, 16, 145, 183, 160, 41, 140, 186]

Where the channel is confined laterally by steep valley walls, thermal heterogeneity may be associated with vertical as opposed to lateral exchange of hyporheic and surface water. These upwelling and downwelling zones may occur at discontinuities, or “steps”, in the longitudinal elevational profile of headwater streams at the reach and valley scale. Within bedrock-dominated reaches, thermal heterogeneity may be minimal due to a lack of vertical and lateral hyporheic exchange through the streambed and floodplain. Alluvial valleys are more likely to have reach-scale cold-water refuges formed by hyporheic processes, whereas bedrock canyons primarily may be limited to tributary sources (see **Section 5.3**). [127, 247, 238]

5.5. Channel unit

Cold-water refuges at the scale of pools and riffles are associated with small tributary confluences (Strahler order: 1-2), springbrooks (**Figure 5.5.1**), side channels (**Figure 5.5.2**), and wall-base channels (**Figure 5.5.3**) that occur in a wide variety of stream types throughout the Pacific Northwest. Cold-water patches also occur at smaller spatial scales (see **Section 5.6**) and are created by similar processes where groundwater and subsurface flow emerges from the streambank into the main stream channel. [178, 22, 78, 45, 1, 44, 6, 47, 213]

5.6. Microhabitat

Cold-water refuges and their use by salmonids at the microhabitat level are well described in the literature. Microhabitat cold-water refuges occur in thermally stratified pools and where bedform topography creates strong vertical hydraulic gradients. Alcoves and lateral seeps also are commonly found along riverbanks (**Figures 5.6.1** and **5.6.2**), but they may not be in locations that are easily accessible to fish. [28, 173, 151, 162, 166, 150, 29, 95, 104, 54, 8, 77, 96, 9, 79, 78, 106, 85, 222]

Shade from overhanging vegetation or steep valley walls can affect cold-water refuges at the microhabitat scale by preventing warming. [78, 214, 127, 200, 249, 161, 251]

6. Identification and prediction

6.1. Maps

Publicly available paper and digital maps are useful for determining the landscape context and hydrologic characteristics of rivers prior to identifying cold-water refuges at segment, reach, and channel unit scales. [172, 43, 175, 244, 246]
http://www.epa.gov/wed/pages/ecoregions/level_iv.htm
http://water.usgs.gov/GIS/metadata/usgswrd/XML/hlrus.xml

The Oregon Department of Environmental Quality has created 1:100,000-scale fish use designation maps that provide assessments of habitat for coldwater fish based on field surveys (**Figure 6.1.1**). [210]
http://www.deq.state.or.us/wq/rules/div041tblsfigs.htm#t2

Although these maps are not based directly on temperature, the spatial patterns of cold-water areas correspond remarkably well with large-scale database records of actual stream temperature (**Figure 6.1.2**).

USGS 1:24,000-scale topographic quadrangles and the 30- and 10-m digital elevation models derived from these maps have been used very effectively to identify segment- and even reach-level patterns of hyporheic exchange corresponding to cool-water areas (**Figures 5.3.1** and **6.1.3**). [16, 169, 14]

6.2. Modeling

A wide variety of process-based and statistical models have been developed to predict stream temperature at basin, segment, and reach levels (**Figure 6.2.1**). These tools have become more accessible to resource managers as geographic information system (GIS) software has improved and the available pool of employees with programming experience has increased. [25, 13, 136, 122, 71, 35, 93, 195, 92, 169, 3, 62, 4, 63, 123, 198]

6.3. Remote sensing

The availability of high-quality, high-resolution satellite imagery has increased dramatically in the last decade through Internet mapping services, which provide a spatial resolution that is sufficient even for detecting cold-water areas, such as springbrooks in small rivers (**Figure 6.3.1**):

TerraServer: http://www.terraserver.com
Google© Earth: http://earth.google.com
Google© Maps: http://maps.google.com

6.3.1. Aerial photography

High-resolution color digital orthophotography is now available for most of the Pacific Northwest and Oregon.

National Agriculture Imagery Program (NAIP):
http://165.221.201.14/NAIP.html

Oregon Imagery Explorer:
http://oregonexplorer.info/imagery

Even higher resolution (<1 m) airborne color imagery is becoming more affordable and has been used to map fine-scale channel features associated with channel complexity and subsurface flow paths. [241, 148]

Current methods for detecting groundwater with remote sensing are still in development but are likely to be increasingly used in the future. [31, 114, 18, 67, 68, 179]

6.3.2. LiDAR

Technology that uses airborne light detection and ranging (LiDAR) to map the elevation of the water surface and surrounding floodplain with sub-meter accuracy currently offers the greatest potential for identifying floodplain features associated with cold-water refuges and groundwater inputs at segment, reach, and channel unit scales. LiDAR that utilizes the blue-green portion of the electromagnetic spectrum is capable of mapping the streambed by penetrating the water. [156]

6.3.3. Thermal infrared imaging

Airborne thermal infrared (TIR) remote sensing has been used extensively throughout the Pacific Northwest to map cold-water refuges and thermal heterogeneity in rivers at channel unit to basin scales using helicopters and fixed-wing aircraft (**Figures 6.3.3.1**, 6.3.3.2, **6.3.3.3**, and **6.3.3.4**; **Appendix B**). In some cases, airborne TIR imagery has been related directly to field surveys of fish locations and cold-water refuges, but more work is needed in this area. Limitations of the approach are that (1) dense riparian canopy and overhanging streambanks can block the sensor's view of the water, and (2) in deep, slow-moving rivers, the surface temperature may not be indicative of the overall water temperature or of cold-water areas near the river bottom. [229, 227, 22, 230, 84, 83, 228, 138, 141, 225, 47, 63, 226, 105]

Recent advances in sensor technology have led to the development of relatively low-cost (about $2,000) hand-held TIR imagers that could be used for ground-based assessments of thermal heterogeneity in small, wadeable streams.
http://www.professionalequipment.com/flir-i7-infrared-camera-i7/thermal-infrared-camera/

6.4. Direct measurement

Techniques for locating cold-water refuges directly with hand-held sensors or probes that are towed through the river also have improved and become more accessible in the last decade with the improved accuracy of portable global positioning systems (GPS) and the small size and high storage capacity of digital temperature data loggers.

6.4.1. Thermocouples and probes

A fast-response, hand-held thermocouple mounted on a telescoping rod is one of the least expensive and most precise ways to detect thermal anomalies and map cold-water refuges in wadeable streams (**Figure 6.4.1.1**). Because the digital readout displays near instantaneous changes in temperature, the spatial extent of small- to medium-sized cold-water refuges can be mapped before ambient temperature has changed. [78, 1]

In large, deep rivers where a spatially continuous transect of water temperature, depth, conductivity, or resistivity is needed to detect groundwater inputs, a ‘profiling’ technique can be used (**Figure 6.4.1.2**). In this approach, the temperature sensor is towed behind a boat or on foot (i.e., in wadeable streams) (**Figure 6.4.1.3**); data logging of temperature (or conductivity, depth, etc.) and geographic coordinates occurs simultaneously. Localized decreases in temperature (i.e., ‘troughs’ in the longitudinal profile) indicate possible cold-water areas (**Figure 6.4.1.2**). [224, 217, 133, 14, 231, 50, 240, 199]

6.4.2. Stationary data loggers

Stationary data loggers include digital temperature data loggers and distributed fiber optic temperature sensing. Digital temperature data loggers have been used in fisheries and water quality monitoring since the 1990s and are useful for characterizing the temporal patterns of cold-water refuges once they have been located with other methods. Digital temperature data loggers are useful for quantifying spatial patterns in stream temperature at reach, segment, and watershed scales but are less effective for locating cold-water refuges at microhabitat and channel unit scales because of their small spatial ‘footprint’ (about 10 cm). Digital temperature data loggers can be deployed in spatially dense arrays (i.e., spaced at 1–2 m intervals) to evaluate thermal heterogeneity in small areas, but this approach typically is not extended over many kilometers due to the cost and logistical difficulties of deploying thousands of data loggers [73, 208, 209]

Recent developments in distributed temperature sensing (DTS) have made it possible to map spatial and temporal heterogeneity of groundwater, hyporheic, and surface-water interactions because the fiber optic cable can measure water temperature at a spatial resolution of less than 1 cm over multiple kilometers. Temperature measurements at this fine spatial resolution also are recorded at a very fine temporal resolution. A present disadvantage of the method is that the cable may not be able to withstand high water velocities and may break, making deployment in remote locations problematic. [57, 116]

6.4.3. Tagged fish

Methods for monitoring the internal temperature of fish in the wild also have dramatically improved, such that it is possible to log their temperatures continuously over time. This method, when combined with radio telemetry or passive integrated transponder (PIT) tags, offers an unprecedented view into the thermal ecology of fish in the natural environment. In order to determine whether fish are using cold-water refuges, other methods of direct measurement must be used to quantify the spatial and temporal variability of water temperatures available to the fish. [24, 188, 30, 220, 190, 215, 115]

7. Protection and restoration

7.1. Scientific guidance for policy decisions

To provide the science necessary for making policy decisions regarding cold-water refuges, a conceptual framework is needed that is consistent in terminology and provides a means to (1) quantitatively monitor the distribution of cold-water refuges in a spatially explicit manner, (2) prioritize areas for protection, and (3) restore the processes that create and maintain thermal diversity in riverine landscapes. An example of such a framework is provided in **Figure 7.1.1**. [168, 154, 189, 59, 196, 236]

7.2. The shifting mosaic of thermal landscapes

The fact that thermal landscapes are dynamic in time and space indicates that they can not be easily summarized in metrics that can be translated into water quality criteria. However, this challenge is not insurmountable and can be addressed by explicitly considering temporal dynamics as an integral part a functioning and resilient riverine landscape. [234, 183, 203, 108, 180, 102]

7.3. Ecological complexity

Given the complexity of human and natural systems that have reduced thermal diversity in river systems, restoration will require consideration of cold-water refuges within a broad context including (1) physical factors, such as riparian condition and hydrologic connectivity in the floodplain, (2) biological interactions with native and non-native species that may influence the effectiveness of cold-water refuges for coldwater fish, (3) effects on other aquatic species and life history stages, and (4) unanticipated human effects, such as climate change. [88, 232, 119, 239, 139, 167, 250, 191, 49]

7.4. Predictive modeling in space and time

Advances in qualitative and quantitative modeling to predict the locations of current cold-water refuges and prioritize areas for restoration will continue to make it easier for scientists to provide the kind of information that managers need in order to make informed decisions that are based on the best available science. [135, 169, 100, 138, 221, 207, 121]

Are current distributions of cold-water refuges sufficient to support migration and rearing of juvenile and adult salmonids within a given riverscape? If not, what improvements will be necessary in the size, frequency, or characteristics of refuges to achieve goals for salmonid management in the future? To answer these questions, approaches are needed to assess the suitability of current or future thermally diverse riverscapes for the successful completion of salmonid life histories. For example, combining field data collection, predictive modeling with validation, and landscape scenarios of alternative futures has much to offer for protecting and restoring cold-water refuges at scales from localized reaches to entire floodplain segments (**Figure 7.4.1**). By reconnecting the river with the floodplain and restoring riparian vegetation, potential hydrologic processes that create thermal heterogeneity may be restored. This integrated approach certainly will be required to address the challenges posed by climate change, which will put additional constraints on the capacity of rivers to maintain the processes that create thermal diversity. [143, 137, 124, 15, 117, 165]

7.5. Restoration as experimentation

To effectively restore the hydrologic processes that create thermal diversity, manipulation of entire riverine landscapes may be required, not just of distinct reaches or channel units. Hyporheic processes occur laterally, longitudinally, and vertically and do not have easily defined boundaries. Thus, active approaches to restoring these processes by installing instream structures and engineering new channels may be difficult to apply and test in the field. When passive restoration and reestablishment of riparian vegetation are not enough to reconnect the river with the floodplain, re-engineering may be used as an experiment, with monitoring in place to adapt the approach as needed. For example, the current Upper Middle Fork John Day Restoration Project being conducted by the Confederated Tribes of the Warm Springs Indian Reservation, the Bureau of Reclamation, and the U.S. Forest Service is one such program and provides a case study on restoring cold-water refuges (**Figures 7.5.1**, **7.5.2**, and **7.5.3**). [26, 129, 85, 110, 116, 111, 112]

7.6. Conclusion

A goal of this primer is to help bridge the gap between research and management of cold-water refuges through outreach and technology transfer. The many references to completed and on-going work in this area demonstrate that much of the research on cold-water refuges is closely tied to on-the-ground issues and questions brought up in discussions between scientists and managers. In providing a more complete view of cold-water refuges across a range of spatial and temporal scales, this document will lead to more discussions between scientists and managers about the complexity of river systems. Maintaining thermal diversity across multiple spatial scales—not just small-scale cold-water refuges in wadeable streams that are most easily detected—is essential for long-term viability of coldwater stream fish. This complexity, although daunting, reflects the potential capacity of riverine landscapes to recover thermal diversity through restoration and ultimately provide the habitats required for the long-term viability of coldwater fish. [212, 76, 245, 70, 237]

8. Figures and table

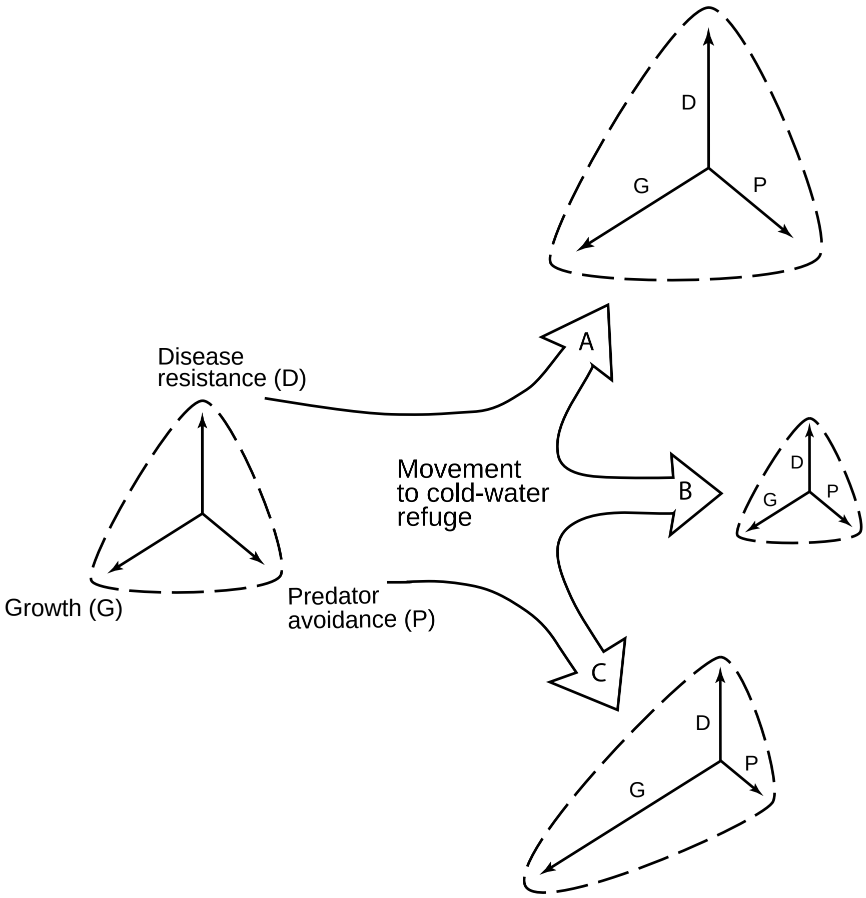

Figure 2.4.1.1. Performance capacity of fish in cold-water refuges (adapted from Schreck and Li, 1991). The performance phenotype (e.g., disease resistance [D], growth [G], and predator avoidance [P]; see triangle on left) of a fish is set by the genotype, which itself is the result of genetics, environment, history, and ontogeny. When a fish moves along arrows A, B, or C to a cold-water refuge, the performance vectors indicating the capacity to resist disease, avoid predators, and grow (see vectors D, P, and G) may increase or decrease, creating a new realized performance capacity based on the unique physical and biological conditions of the cold-water refuge. For example, cold-water areas may increase (A) or decrease (B) all performance capacities equally, or more often than not there will be tradeoffs (C) where the capacity for growth increases, disease resistance is unaffected, but predator avoidance decreases, or any combination thereof.

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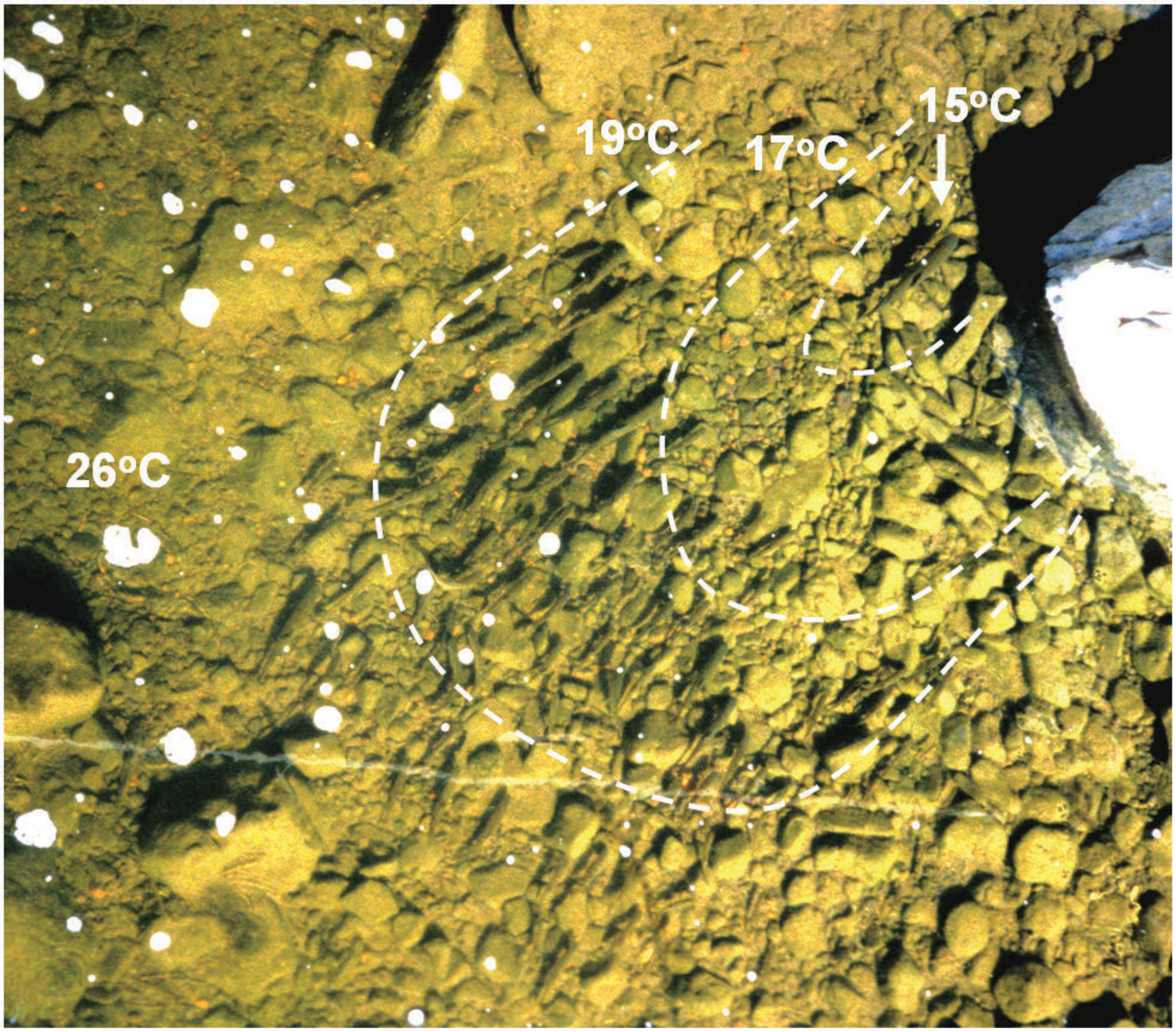

Figure 2.4.1.2. Rainbow trout in Joseph Creek in northeastern Oregon exhibit size hierarchy in occupying a cold-water refuge, with the largest individual in the coldest thermal zone (see Ebersole and others, 2001). When the availability and size of cold-water areas is limited, fish may elect habitats that are less desirable for growth and disease resistance (i.e., through crowding) in order to minimize deleterious physiological effects of high water temperature. Photograph taken by J. Ebersole in 1994. [77]

Figure 2.4.1.3. Adult spring chinook salmon (right) in the Middle Fork John Day River, Oregon, have been observed behaviorally thermoregulating in mid-summer by locating cold alcoves (left). Such habitats may provide temporary thermal refuge but may be insufficient in size or frequency throughout a river to promote long-term persistence at elevated water temperatures. Cold alcoves typically are shallow and offer limited cover for adult salmon. Photographs taken in 1993 by T. Reeve (Bonneville Environmental Foundation).

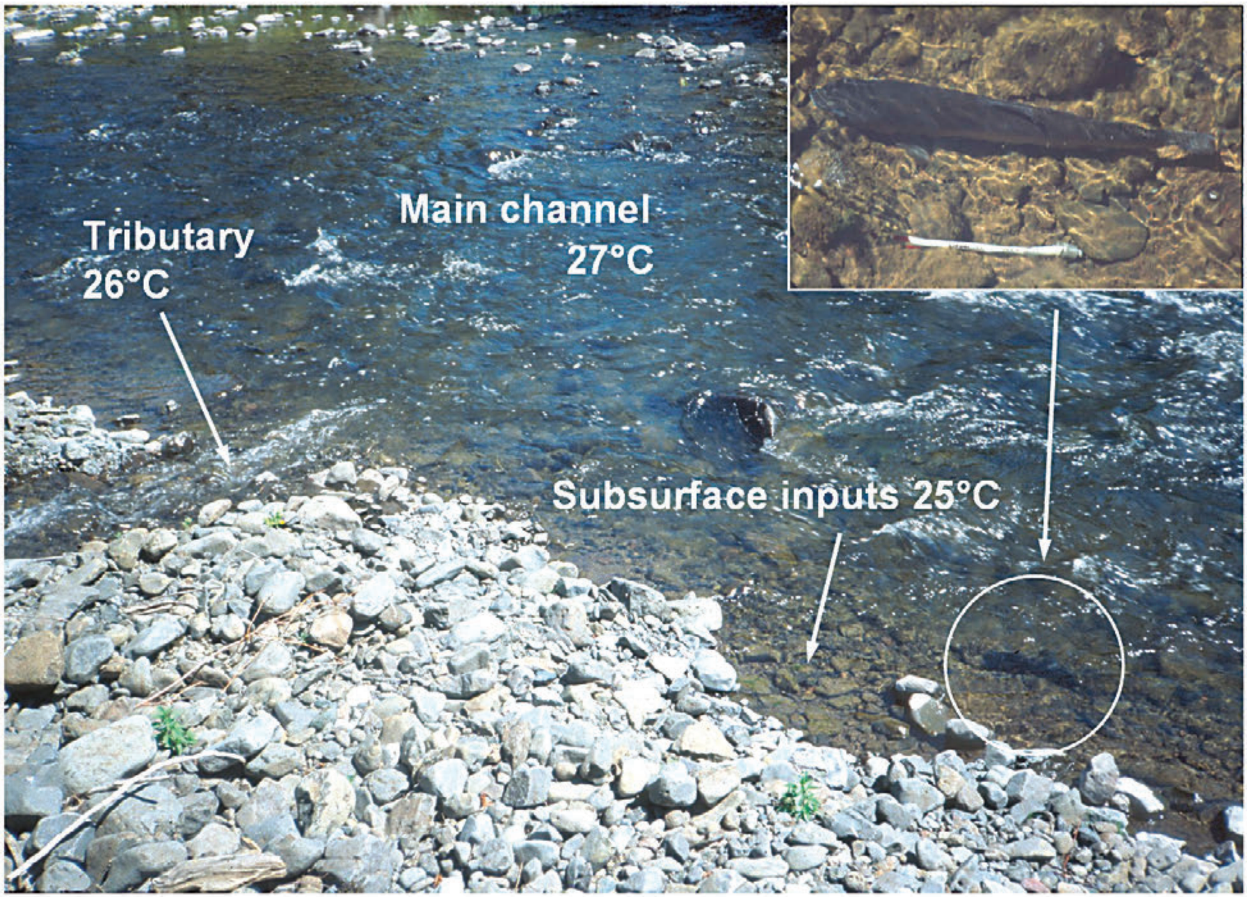

Figure 2.4.1.4. Small differences in water temperature over short distance are detected and used by coldwater fish, such as the rainbow trout depicted in the image of the Middle Fork John Day River, Oregon. Subsurface inputs originating in the tributary emerged from the cobble bar and constituted a cold-water refuge approximately 2°C cooler than the main channel, but the refuge lacked size and other characteristics (cover and food) necessary for survival and growth. The temperature was 2–3°C greater than the thermal tolerances for this species, and the fish elected thermal refuge over predator avoidance in allowing the photograph to be taken at close range. Photographs taken in 1994 by C. Torgersen.

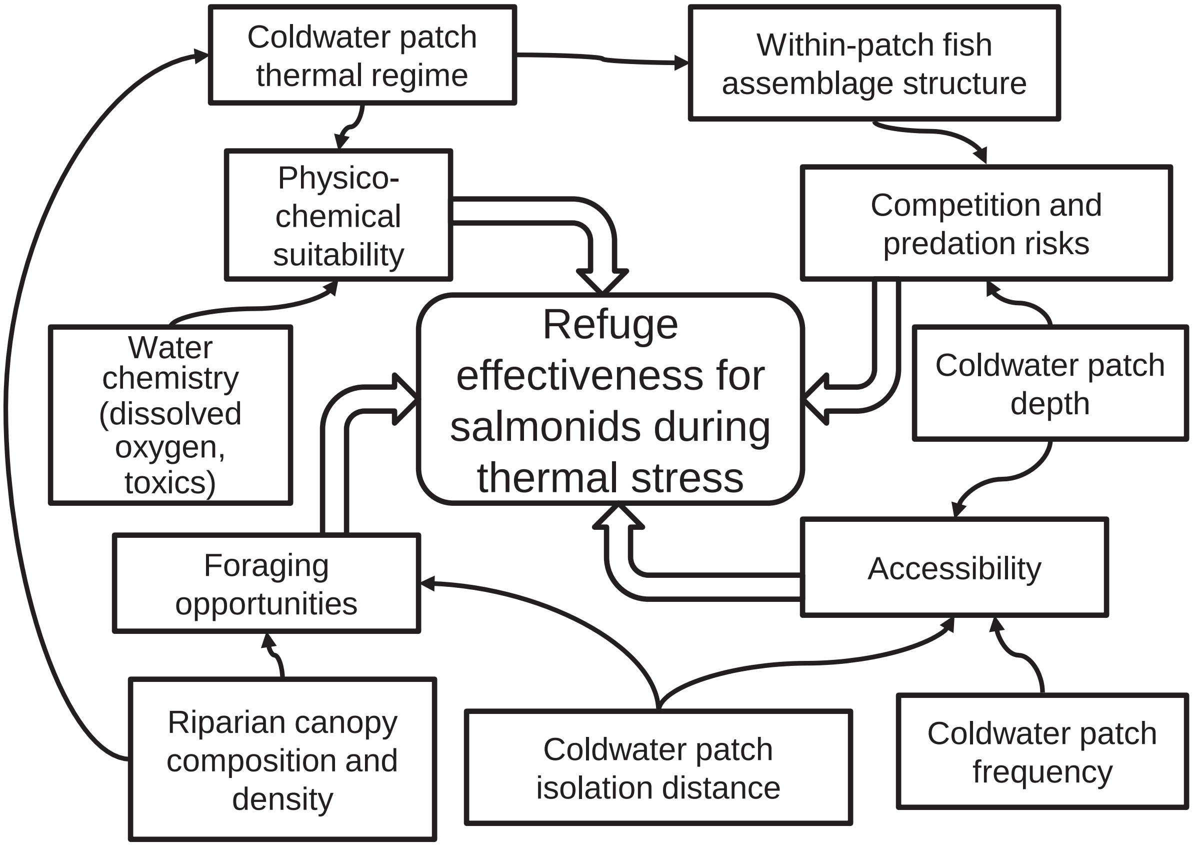

Figure 2.4.1.5. The effectiveness of a cold-water refuge depends on multiple biological and physical factors in addition to temperature. Direct physical impacts (wide arrows) on the fish are in turn affected by a suite of indirect factors (narrow arrows) that determine the capacity of a given refuge to provide protection during periods of thermal stress.

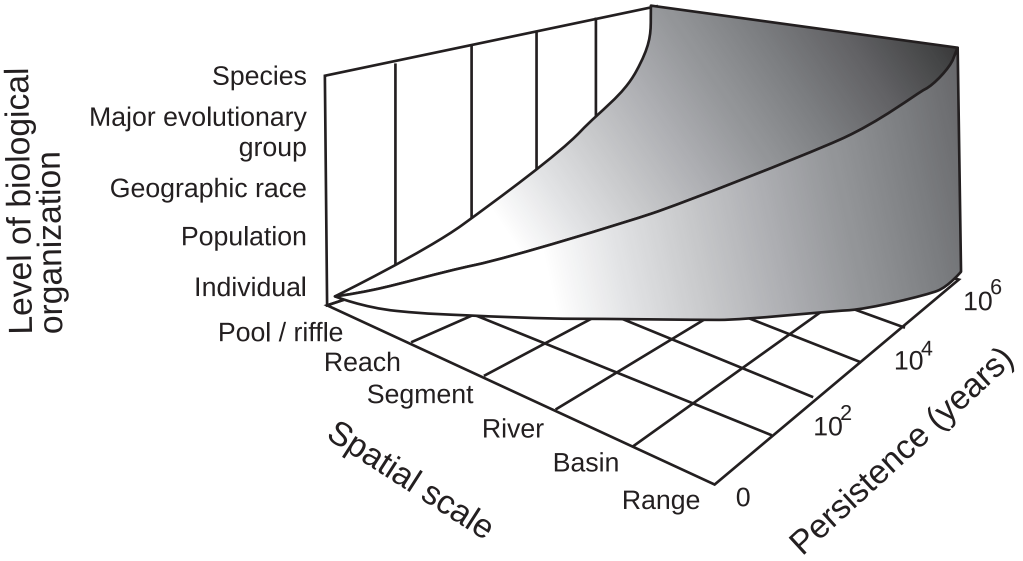

Figure 2.4.2.1. Hierarchical levels of biological organization for stream salmonids and their persistence at different spatial scales (adapted from Frissell and others, 1986, Currens 1997, and Gresswell 1999). Cold-water refuges occur at similar spatial and temporal scales and affect fish at corresponding levels of biological organization. For example, refuges at reach, pool/riffle, and smaller spatial scales influence individuals over short time scales, whereas populations respond to thermal heterogeneity at segment or larger spatial scales. Maintaining thermal diversity across multiple spatial scales—not just small-scale cold-water refuges in wadeable streams that are most easily detected—is essential for long-term viability of coldwater stream fish. [90, 66, 103]

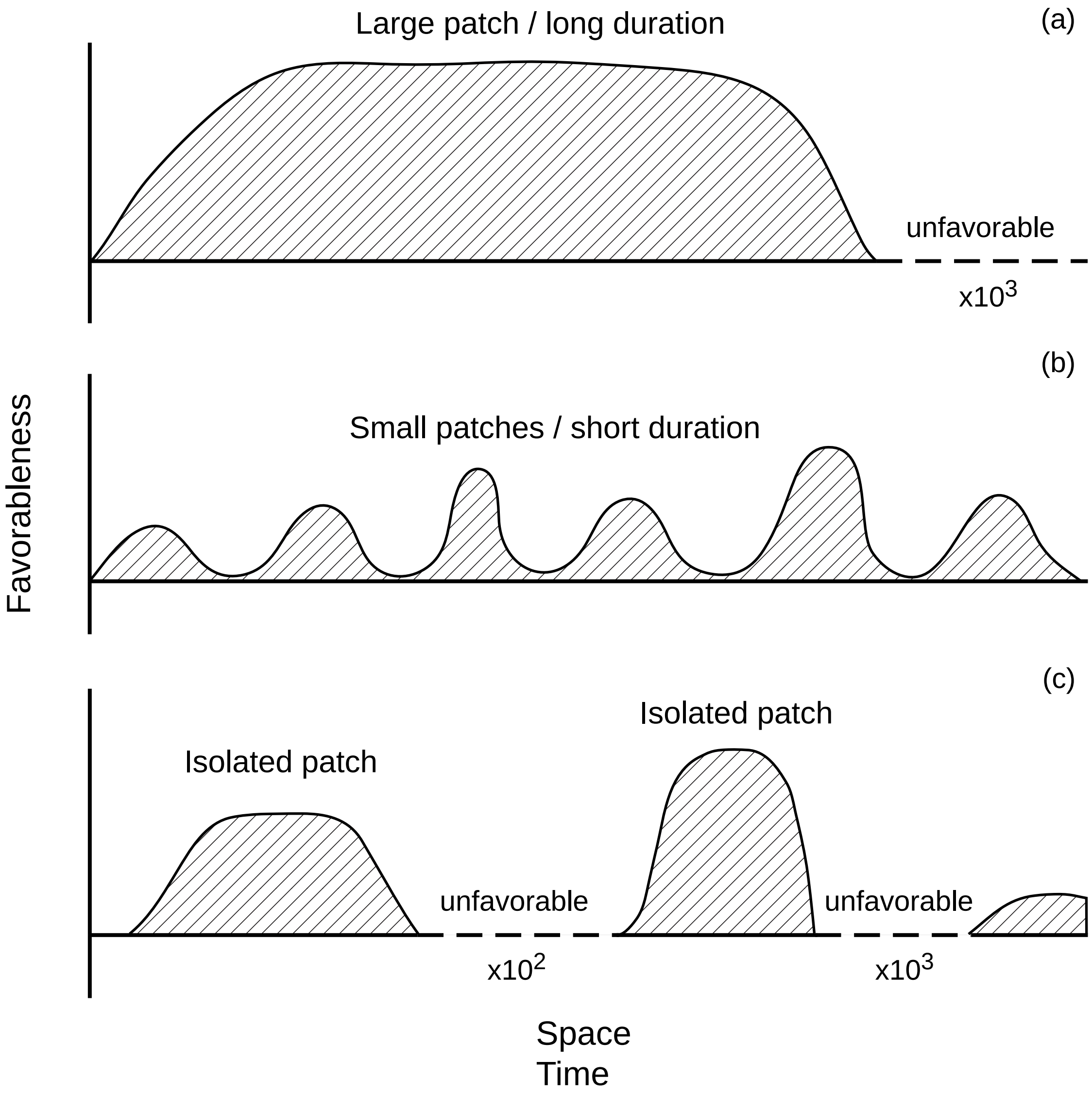

Figure 2.4.2.2. Variability in the favorableness of cold-water refuges in space and time (adapted from Southwood, 1977). For a given species, the favorableness of a cold-water refuge (cross-hatched area) varies spatially (length, area, or volume) from large (a) to small (b). In a fluctuating thermal environment, favorableness also varies temporally from long (a) to short (b) in duration. Cold-water refuges vary in degree of isolation (c) if movement between patches is impeded by unfavorable conditions or if an organism is only able to move between patches while conditions are favorable (i.e., at night when stream temperatures may be lower). [211]

Figure 2.4.2.3. Cool-water areas that are isolated from the main channel also may be shallow and lack overhead cover, channel complexity, and water depth due to altered riparian vegetation (left channel), thereby increasing the susceptibility of fish to predation while they are using these refuges (inset) (Grande Ronde River, Oregon). Photographs taken in 1998 by J. Ebersole.

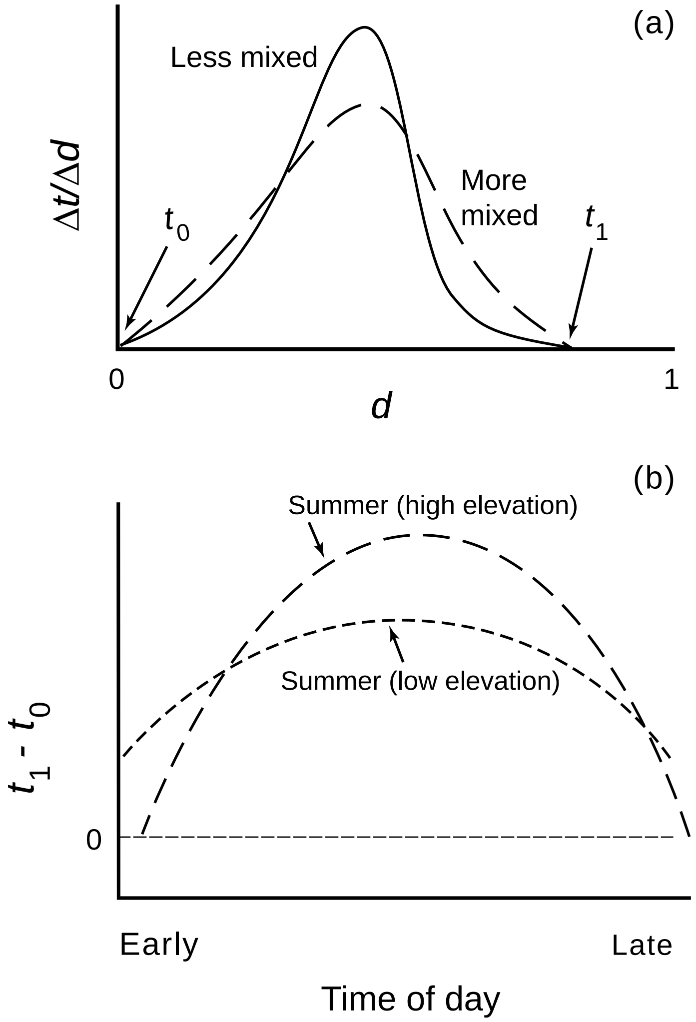

Figure 2.4.2.4. Defining cold-water refuges based on changes in temperature, time, and distance. Change in temperature (Δt) divided by change in distance (Δd) is plotted versus distance (d) along a transect from the coldest part of the refuge (t_0) to the point at which temperature (t_1) no longer changes with distance; this graphical approach provides a quantitative means for determining the spatial boundaries of a cold-water refuge (a). The two curves illustrate hypothetical differences between 'less mixed' (solid line) and 'more mixed' (dashed line) hydraulic environments (a). These temperature changes as a function of distance may be evaluated at a point in time, or by using standard temperature metrics (e.g., daily maximum, mean, or 7-day average daily maximum). For measurements at a given time, an appropriate time of day for delineating the spatial extent of cold-water refuges can be estimated by determining the time at which the difference between t_0 and t_1 is at a maximum (b). These times may vary among geographic locations and elevations (long- versus short-dashed lines) depending on the time of day of maximum ambient water temperature (b).

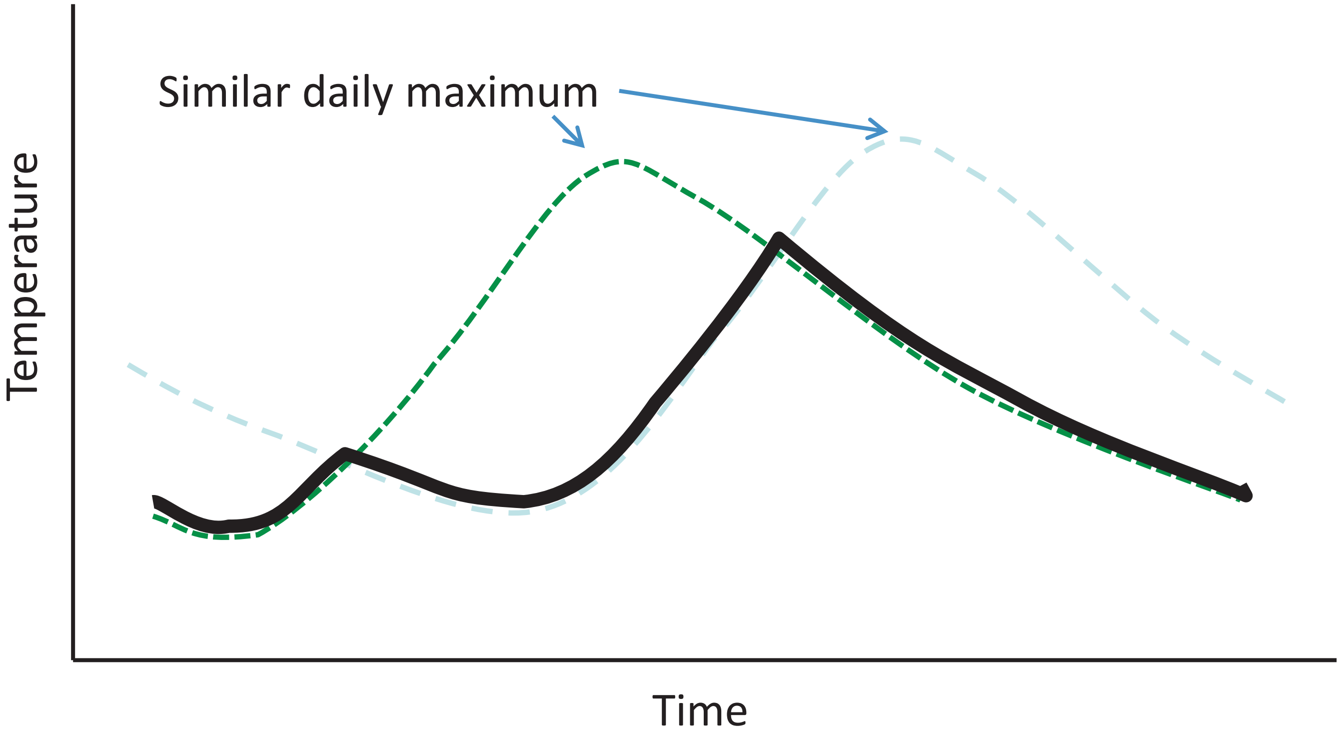

Figure 2.4.2.5. Example of a cold-water refuge created by asynchronous temporal variability among proximal patches in a river. In this example, locations A (green dashed line) and B (blue dashed line) are both accessible to fish and both have similar thermal daily maxima, but location B is temporally lagged relative to A. The thick solid line represents the minimum temperature available to a fish (i.e., the temporal refuge) that behaviorally thermoregulates by moving between locations.

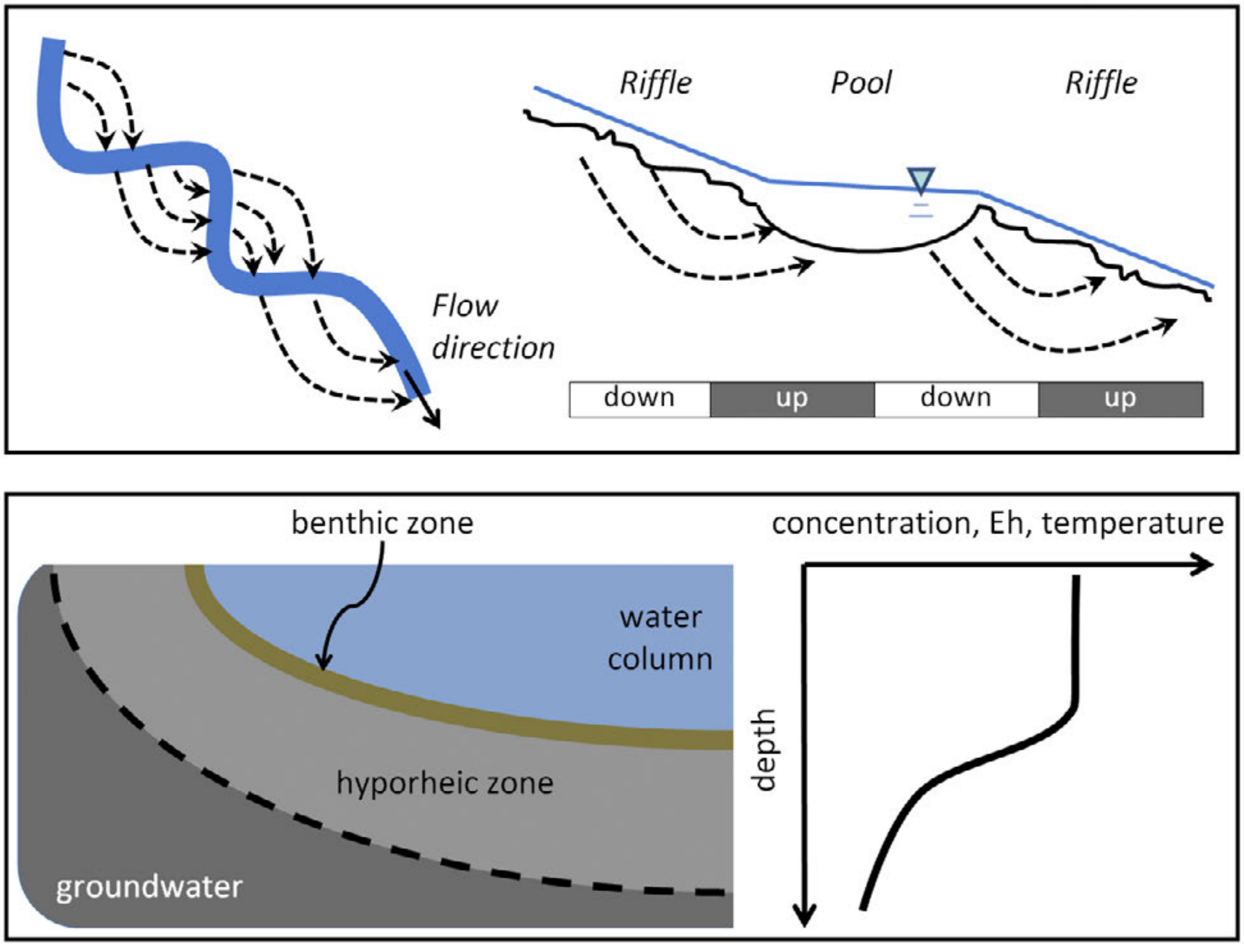

Figure 2.4.3.1. Hyporheic exchange in lateral (upper left) and vertical (upper right) dimensions in streams (adapted from Hester and Gooseff, 2010). Hyporheic exchange occurs laterally (upper left) through point bars and meander bends. The cross-sectional view in the upper right diagram illustrates down- and up-welling (white and grey bars, respectively) zones at the pool/riffle scale as water flows through topographic relief in the streambed. Vertical zones of stream surface flow, hyporheic flow, and groundwater flow (lower left) correspond with gradients in dissolved oxygen, redox state, and temperature associated with increasing depth (lower right). Hyporheic exchange occurs over a range of spatial scales from channel units and microhabitats (depicted above) to entire river segments (see Section 5.3). [111]

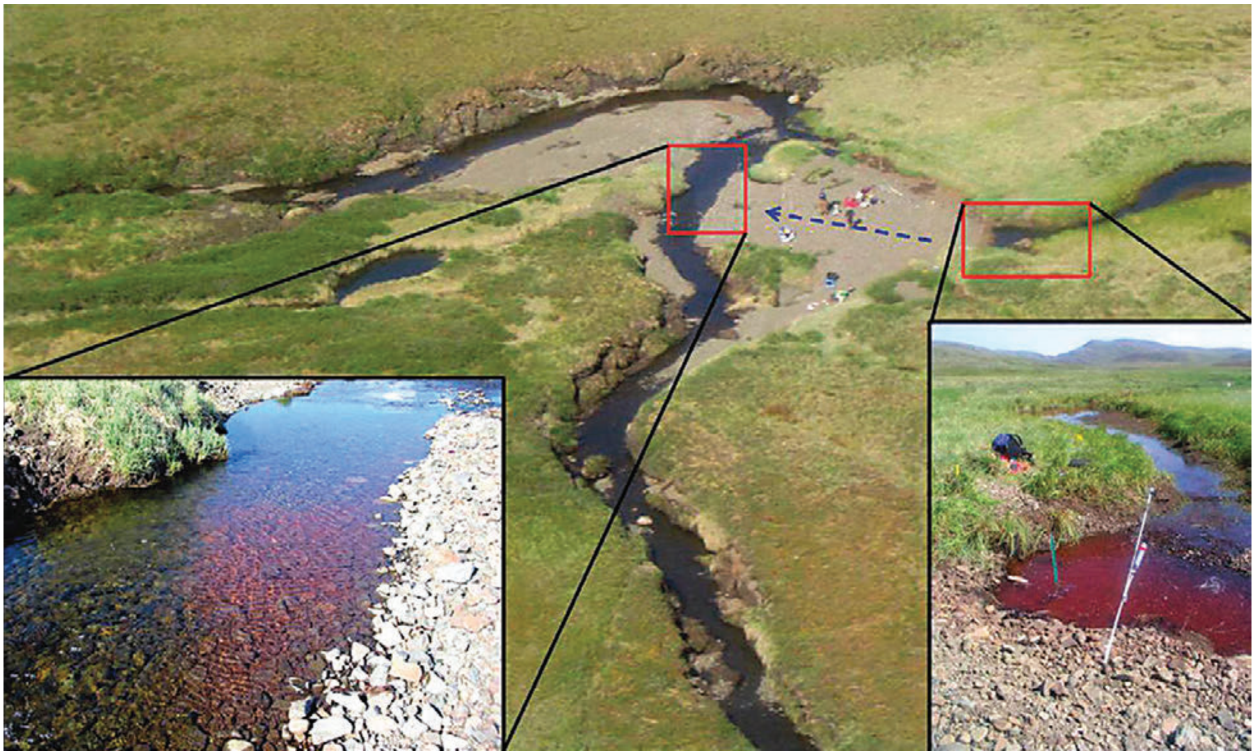

Figure 2.4.3.2. Hyporheic connectivity through alluvial deposits of gravel and cobble substrate is illustrated in a tracer experiment using red dye (rhodamine WT), which is shown emerging from the streambank (left inset) after being released at an upstream location in the floodplain (right inset). The blue dashed arrow in the central image indicates the direction of subsurface flow. The experiment was conducted in the northern foothills of the Brooks Range, Alaska. Cool water flows along hyporheic pathways, such as those shown above can emerge at varying temperatures depending on the depth and distance of subsurface connections. Photographs taken by Breck Bowden (University of Vermont) and Michael Gooseff (Pennsylvania State University) are from Hester and Gooseff (2010). [111]

Table 5.1.1. Hierarchical organization of cold-water refuges and associated geographical and physical drivers in the Pacific Northwest.

System level	Spatial scale	Drivers	Type of cold-water refuge	Time scale (years)
Ecoregion	10^4–10^5 km^2	Geology and climate (e.g.,glaciation, volcanism, uplift), latitude	Relict habitats from Pleistocene glaciation	$\geq 10^4$
Basin and subbasin	10^2–10^3 km^2	Elevation, air temperature, precipitation, snowpack, hydrogeology	Summer streamflow derived from sustained, cold groundwater inputs or snowmelt	10^3
Segment	10^3 m	Valley segment type, groundwater/ surface-water interactions, hyporheic exchange, longitudinal position, land use (timber harvest, grazing, mining), land cover type (urban, forest, grassland)	Alluvial valley segment with high groundwater/surface-water exchange; topographic shading and vegetation (e.g., canyons and riparian gallery forests)	10^2
Reach	10^2 m	Surface and groundwater inflow, sediment type, grain size and sorting, floodplain connectivity	Springbrooks, side channels, and tributary junctions	10^1
Channel unit	10^1 m	Channel morphology, horizontal and vertical mixing (thermal stratification)	Alcoves and stratified pools	10^0
Microhabitat	10^{-1}–10^0 m	Hydraulic head differential caused by structural features (wood and boulders) and bedrock fractures	Springs and groundwater seeps	$\leq 10^{-1}$

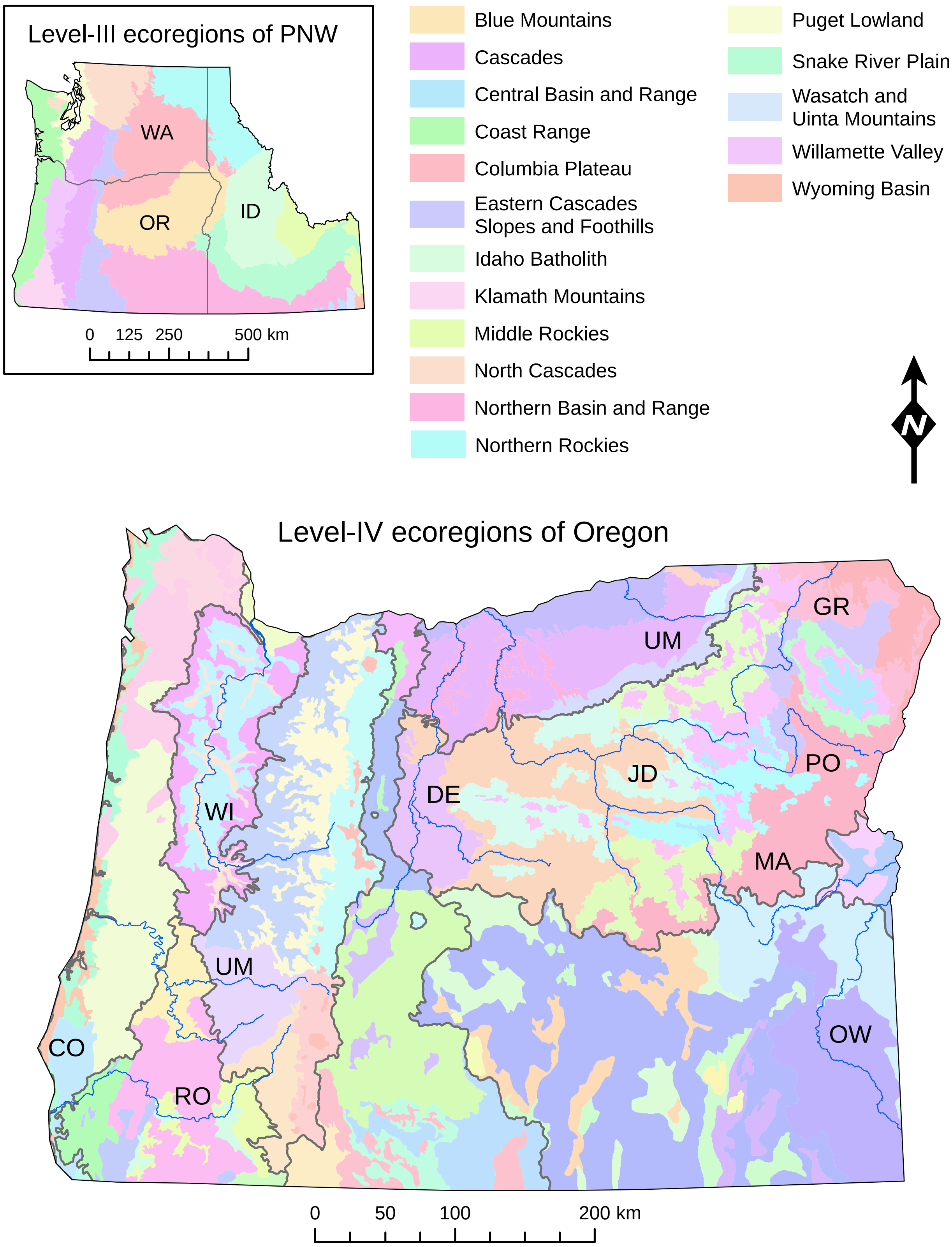

Figure 5.1.1. Ecoregions are based on geology, physiography, vegetation, climate, soils, land use, and hydrology and provide a landscape context for investigating potential broad-scale influences on thermal heterogeneity in rivers and streams. The diversity of landscapes in EPA level-III and level-IV ecoregions in the Pacific Northwest includes a corresponding varied array of riverscapes.

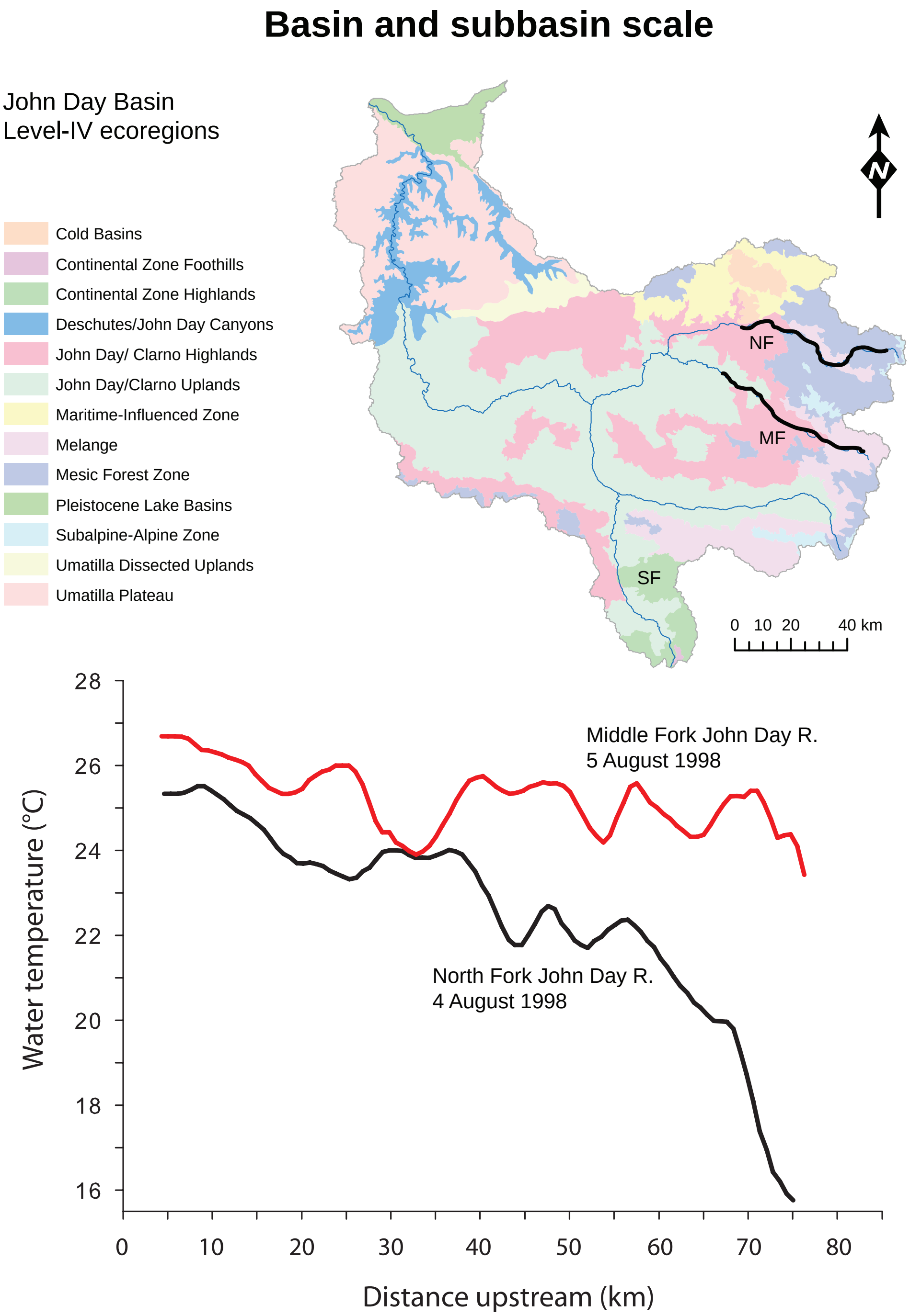
Basin and subbasin scale

Figure 5.2.1. EPA level-IV ecoregions and variation in longitudinal patterns of summer water temperature derived from airborne TIR remote sensing in the North and Middle Forks of the John Day River, Oregon. The more pronounced rate of increase in temperature in a downstream direction in the North Fork is associated with the rapid succession in a downstream direction of landscape transitions through which the river flows (i.e., subalpine, mesic forest, melange, cold basins, and John Day/Clarno highlands). The Middle Fork in comparison has a flatter longitudinal profile and originates at lower elevation and in more xeric conditions. Overall longitudinal change in temperature in the Middle Fork is less than in the North Fork over the same distance, but the Middle Fork still exhibits spatial variability at a 5–10 km scale due to local effects, such as thermal loading and hydrologic connectivity with hillslope and floodplain processes.

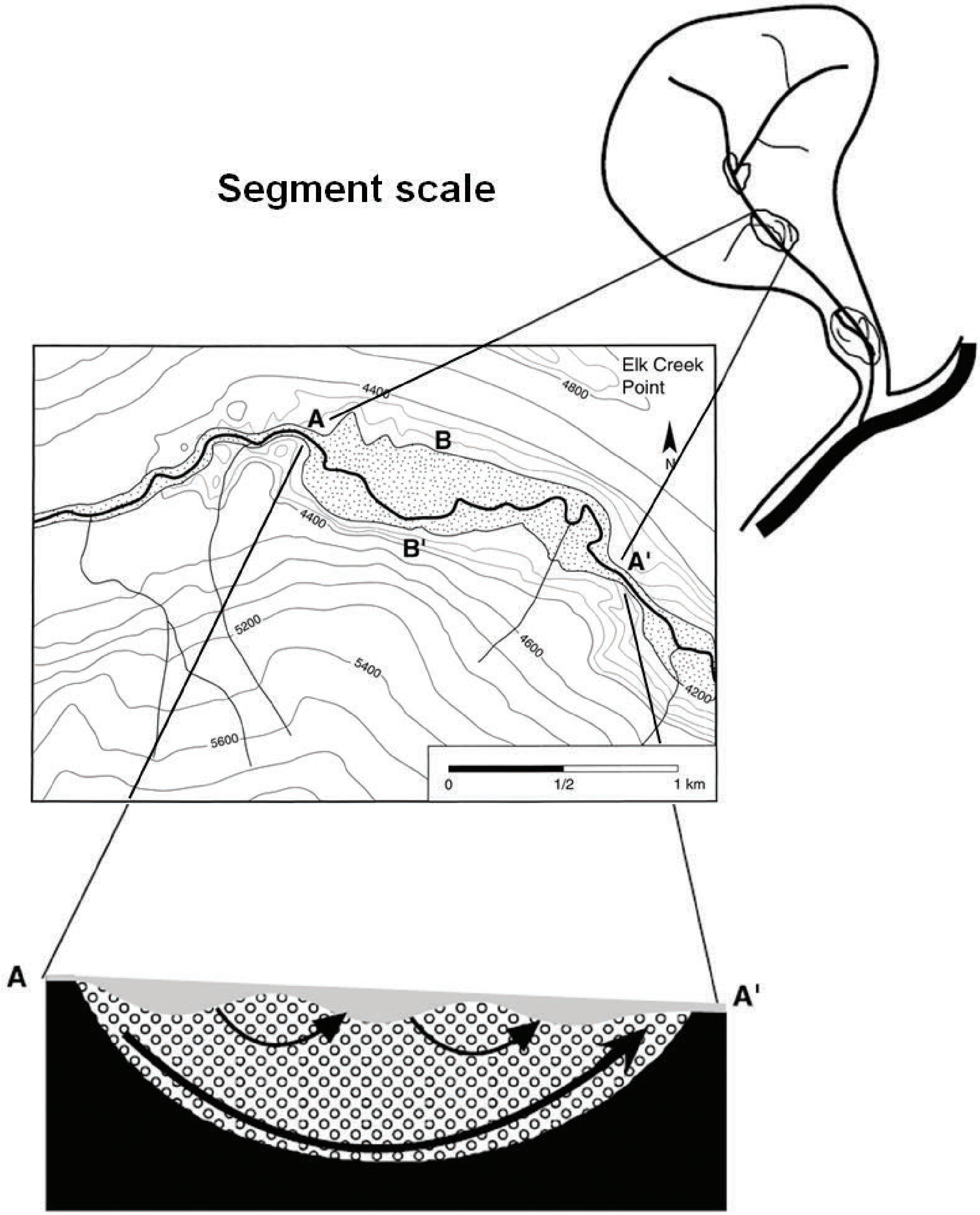

Figure 5.3.1. A bounded alluvial valley segment (BAVS) in the Elk Creek drainage, Montana. The dimensions of the BAVS were measured directly from USGS topographic 7.5 quadrangle maps (1: 24,000 scale) (*A–A'* = length, *B–B'* = maximum valley bottom width). The cross-sectional diagram (*A–A'*) illustrates how reach-scale (large arrow) and bedform-scale (small arrows) hyporheic exchange typically occurs within a BAVS. The stippling denotes the alluvial valley fill (adapted from Baxter and Hauer, 2000). Cold-water areas are most likely to occur at the downstream terminus (*A'*) of the BAVS. [16]

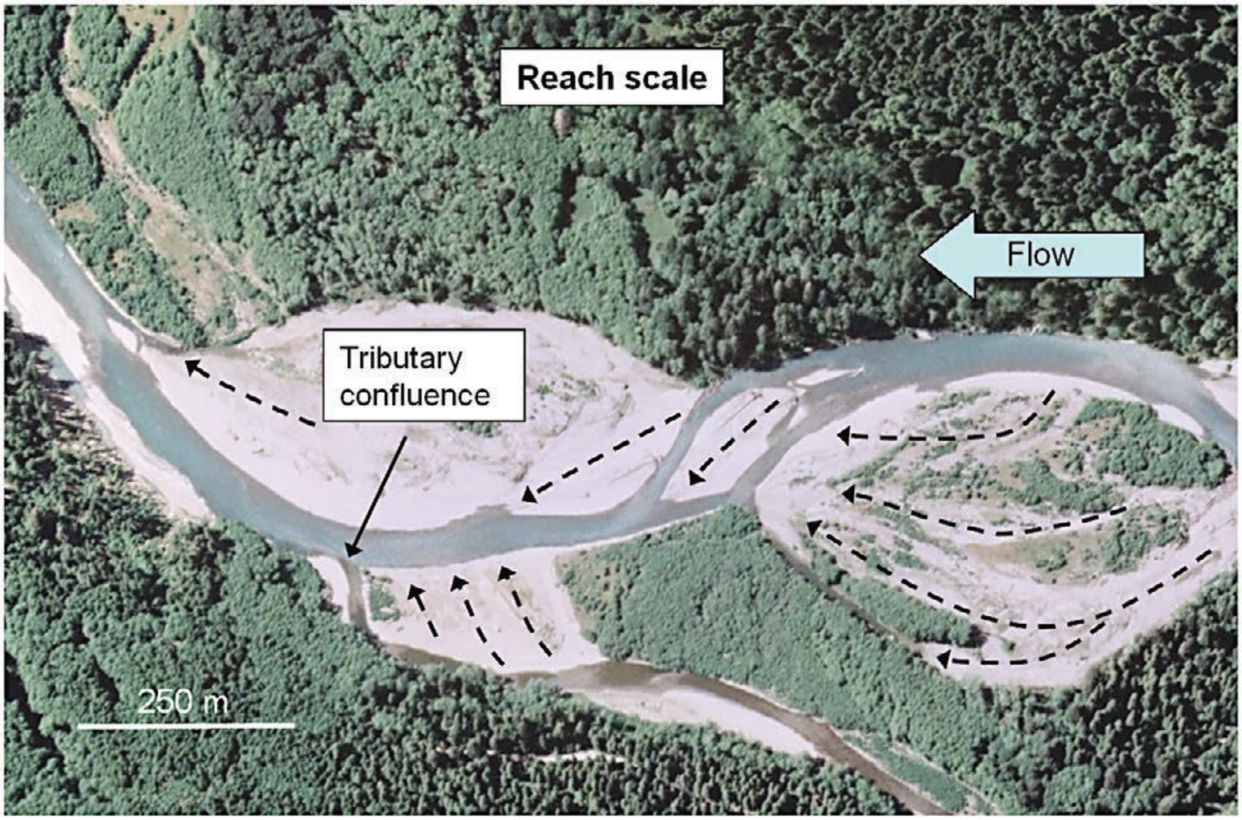

Figure 5.4.1. Reach-level cold-water refuges at the scale of hundreds of meters in an alluvial floodplain reach (depicted above) may be associated with the combined and interactive effects of tributary confluences, sinuosity, and floodplain connectivity via multiple surface and subsurface flow pathways (dashed arrows). The illustration above depicts potential locations of cold-water refuges where field-based measurements could be collected. Source: Queets River, Olympic Peninsula, Washington (Google© Earth).

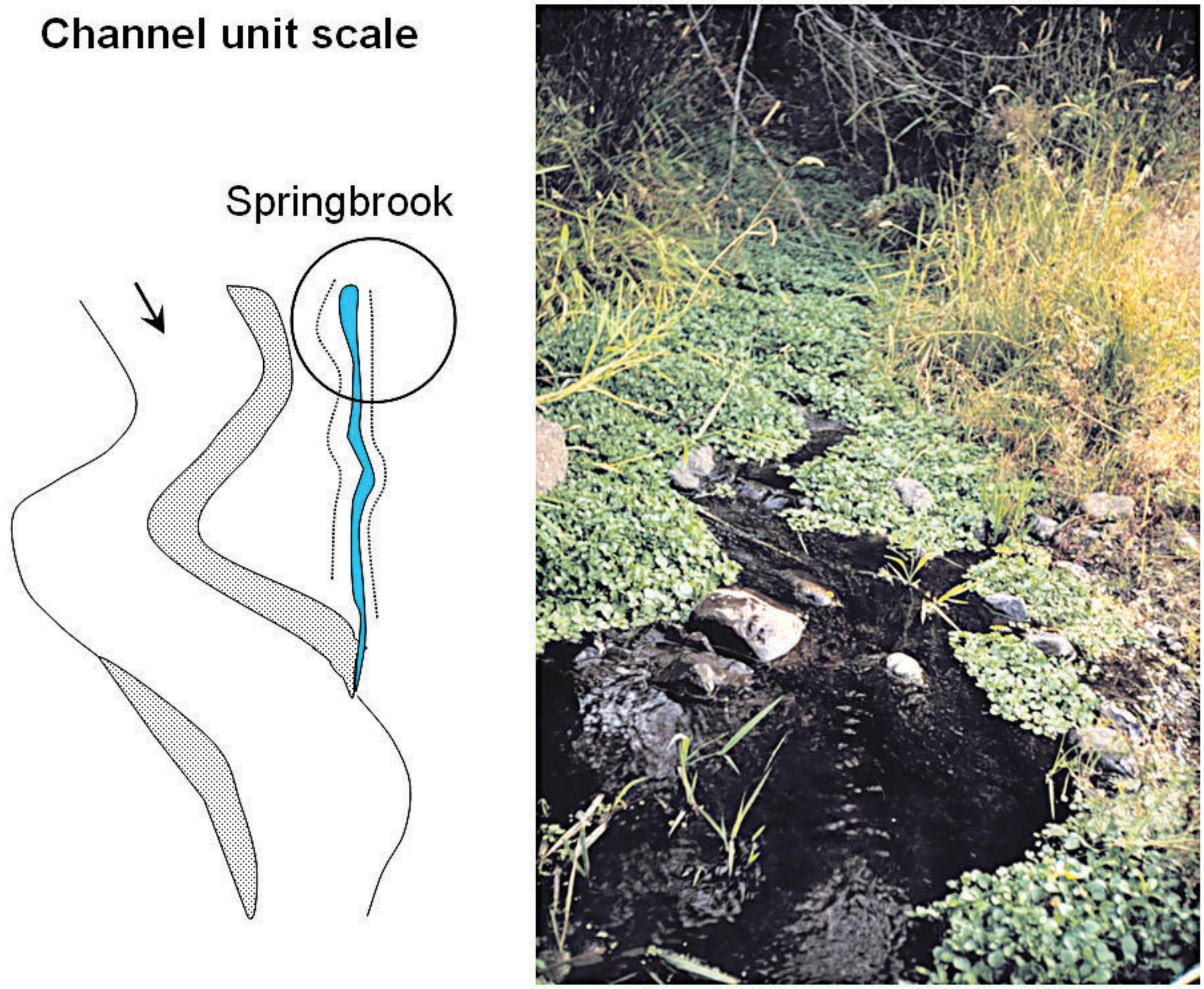

Figure 5.5.1. Floodplain springbrooks have steady, shallow, spring-like flow (blue fill in the diagram at left) emerging downstream from bars (stippling) near floodplain depressions and abandoned channels. The black circle (left inset) shows the area depicted in the photograph (right). Springbrooks are most common in river systems with active transport of coarse sediment and high hydraulic transmissivity associated with recent glaciation (e.g., the Flathead basin in Montana and the Olympic Peninsula in Washington) but may occur at a smaller scale in lower-energy rivers and streams (see Figure 3b in Torgersen and others, 2001) (adapted from Ebersole and others, 2003a). Photograph taken in 1993 by J. Ebersole. [78, 228]

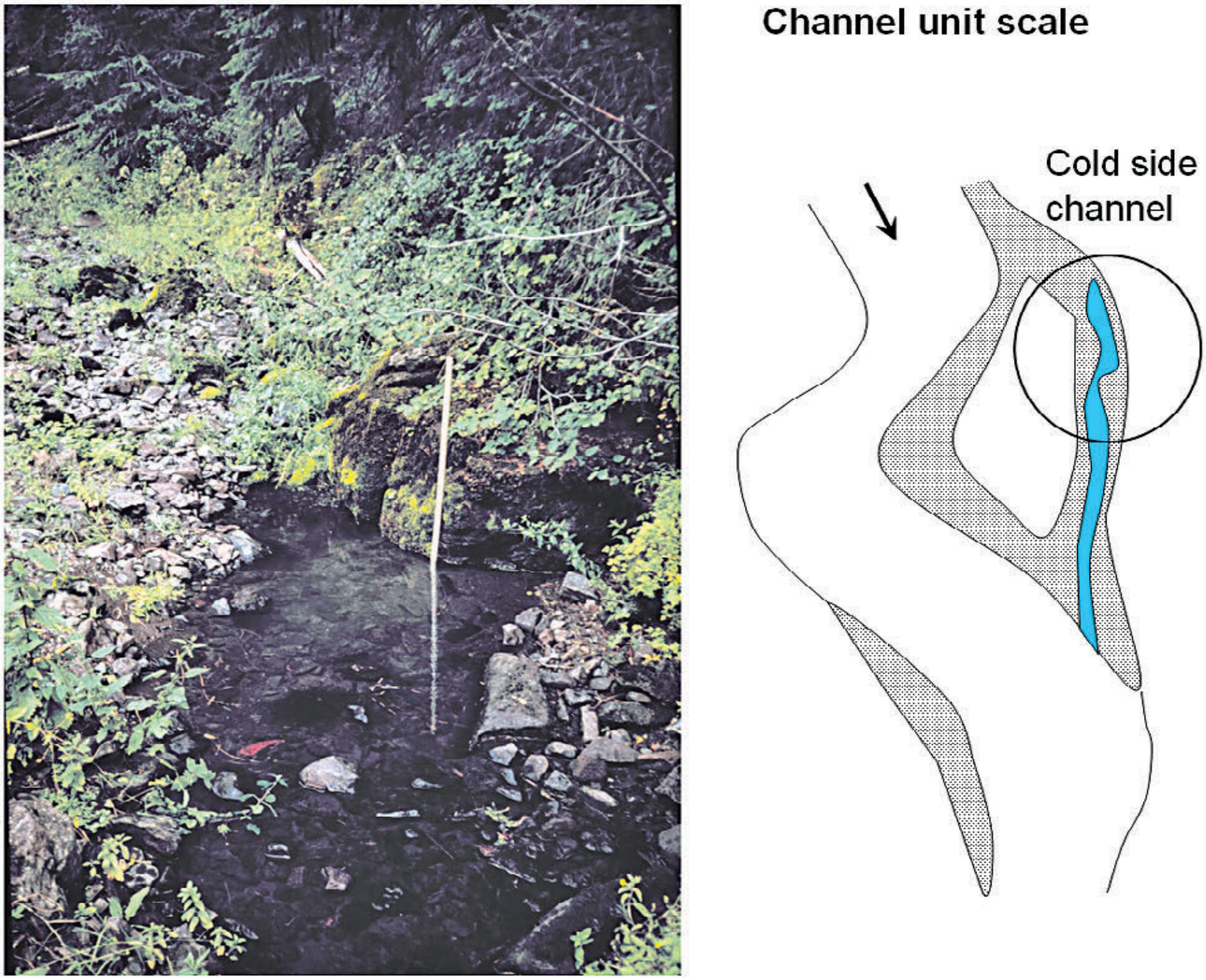

Figure 5.5.2. Cold side channels (blue fill in the diagram at right) often emerge from seasonal overflow channels. The black circle (right inset) shows the area depicted in the photograph (left). Flow may become intermittent or remain continuous at the downstream end of the channel, depending on the bar surface morphology (stippling in diagram on right) and cold-water source (e.g., hillslope groundwater) (adapted from Ebersole and others, 2003a). Photograph taken in 1993 by J. Ebersole. [78]

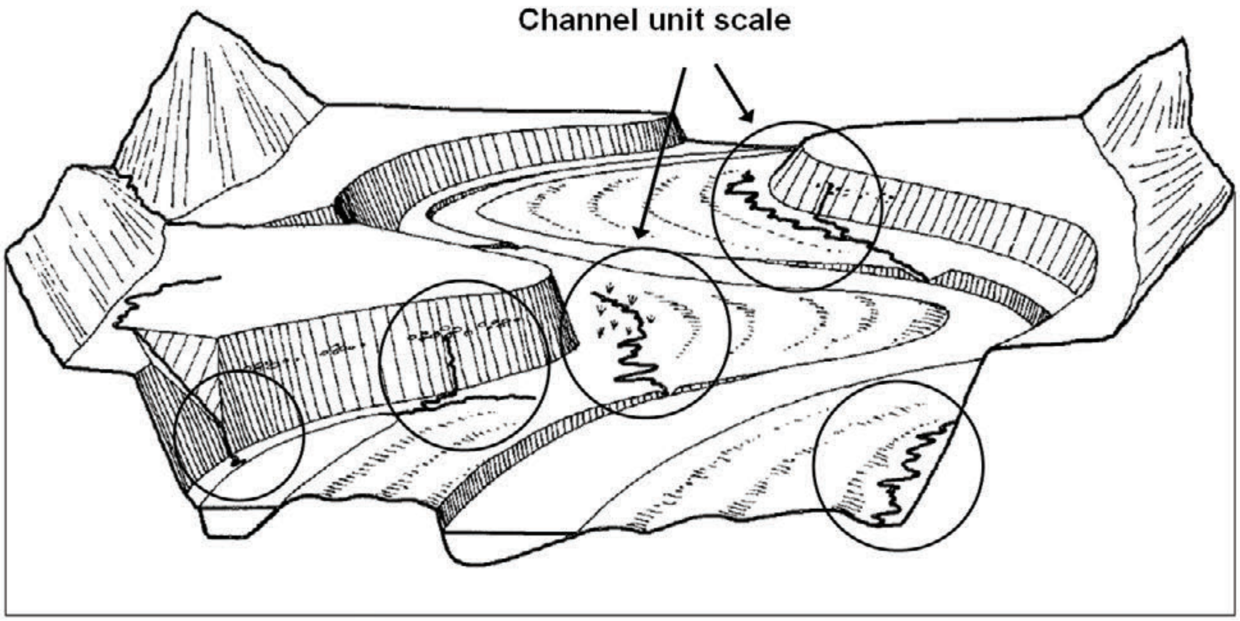

Figure 5.5.3. Up-valley oblique view of a meandering river and wall-base channels (circled) in the Clearwater River on the Olympic Peninsula, Washington, showing examples of associated cold-water habitat types (adapted from Peterson and Reid, 1984).[178]

Figure 5.6.1. Cold alcoves (blue in diagram at left) are a common cold-water patch type and are typically observed emerging from relict channels/swales where stream channels converge with valley walls downstream from floodplains or large gravel point bars (stippling on diagram at left) (adapted from Ebersole and others, 2003a). The black circle (left inset) shows the area depicted in the photograph (right). Photograph taken in 1998 by J. Ebersole. [78]

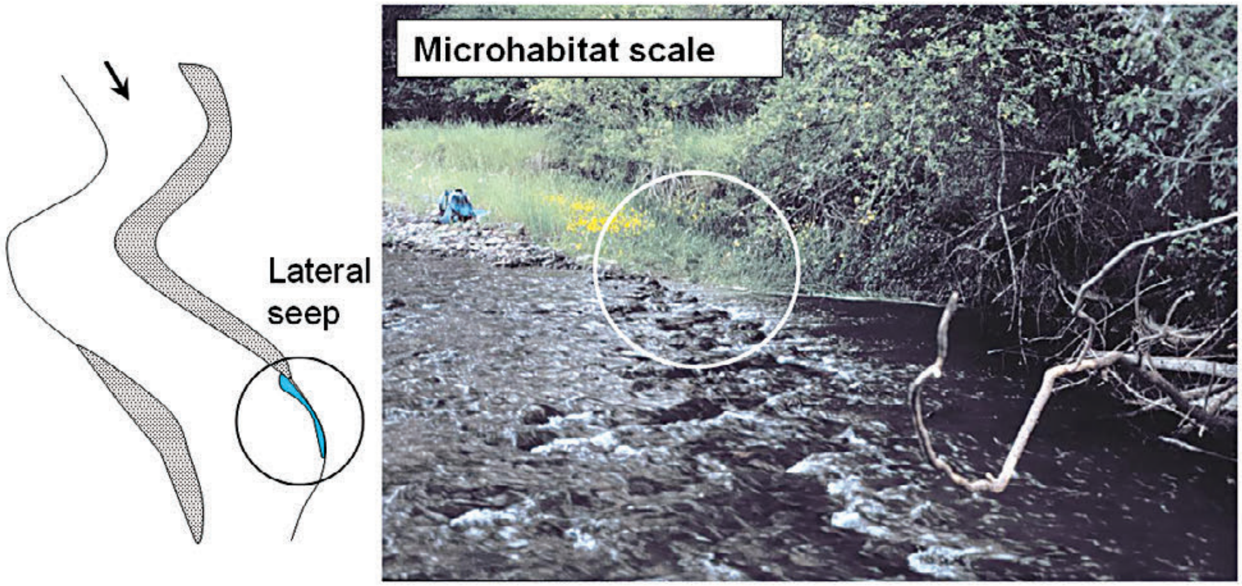

Figure 5.6.2. Lateral seeps (blue) are low-volume but relatively common cold-water areas that occur where the active channel directly intercepts groundwater flow through a terrace, alluvial fan, or hillslope. The black circle (left inset) shows the area depicted in the photograph (right). When these areas are located near the main flow downstream of point bars (stippling), they may be difficult to detect, except during low-flow conditions when the surrounding water is warm (adapted from Ebersole and others, 2003a). Photograph taken in 1998 by J. Ebersole. [78]

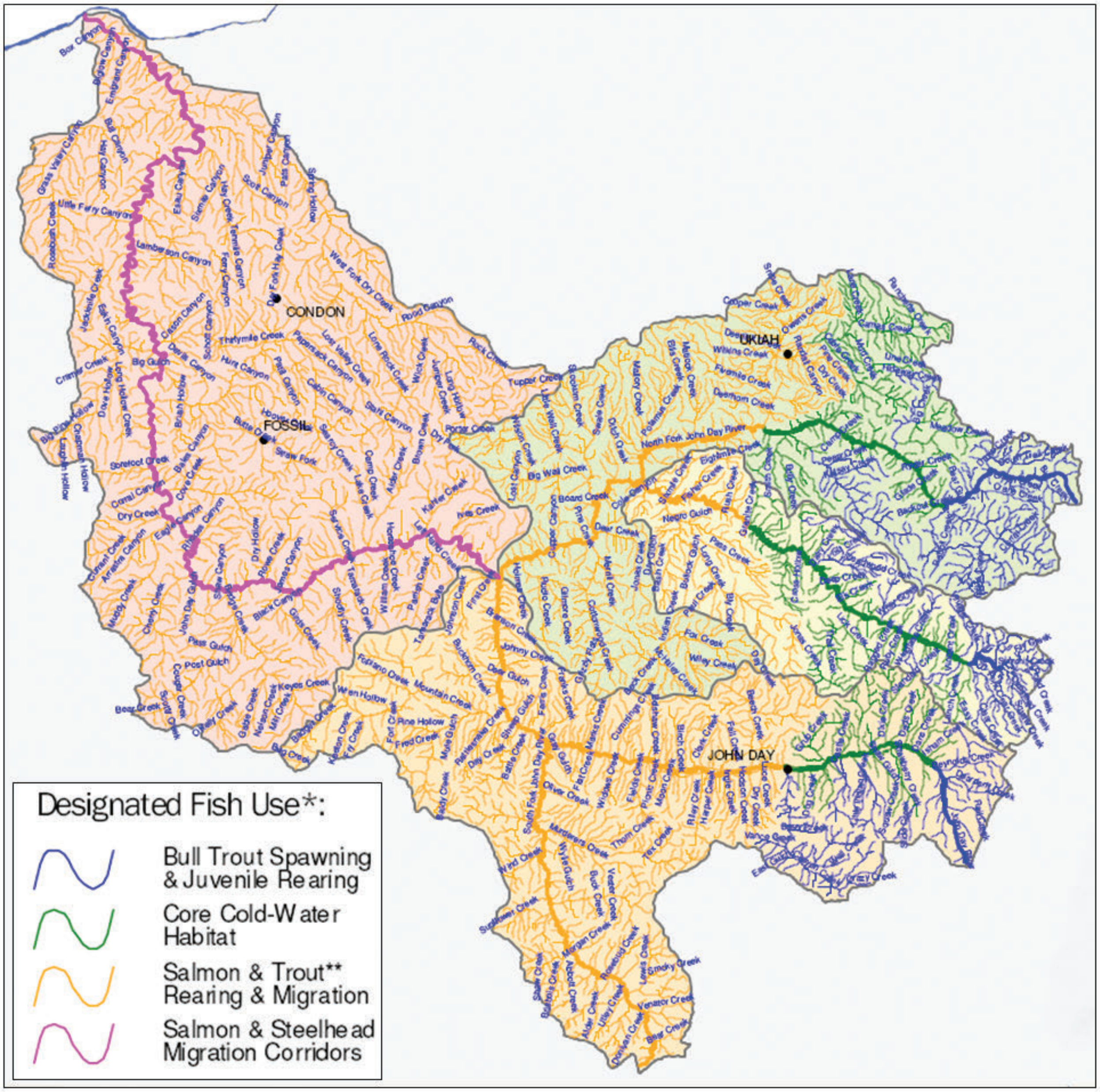

Figure 6.1.1. Designated fish use maps include qualitative, broad-scale assessments of thermal requirements for salmonids in 15 major hydrologic basins in Oregon and provide spatial context for evaluating thermal potential in riverine landscapes at a state-wide level. In the John Day River Basin (depicted above), the coldest sections of stream are represented by the year-round distribution of bull trout (≤12°C) (blue), followed by “core cold-water habitat” (≤16°C) (green), salmon and trout rearing and migration (≤18°C) (orange), and salmon and steelhead migration corridors (≤20°C) (magenta), which generally are too warm during the summer to support coldwater salmonids (see Figure 5.2.1 for additional information on map orientation, scale, and the names of the main forks). Water temperatures associated with the designated fish use categories refer to the 7-day average daily maximum as outlined in the Oregon water quality standards. Source: Oregon Department of Environmental Quality, Water Quality Program. http://www.deq.state.or.us/wq/rules/div041tblsfigs.htm#t2

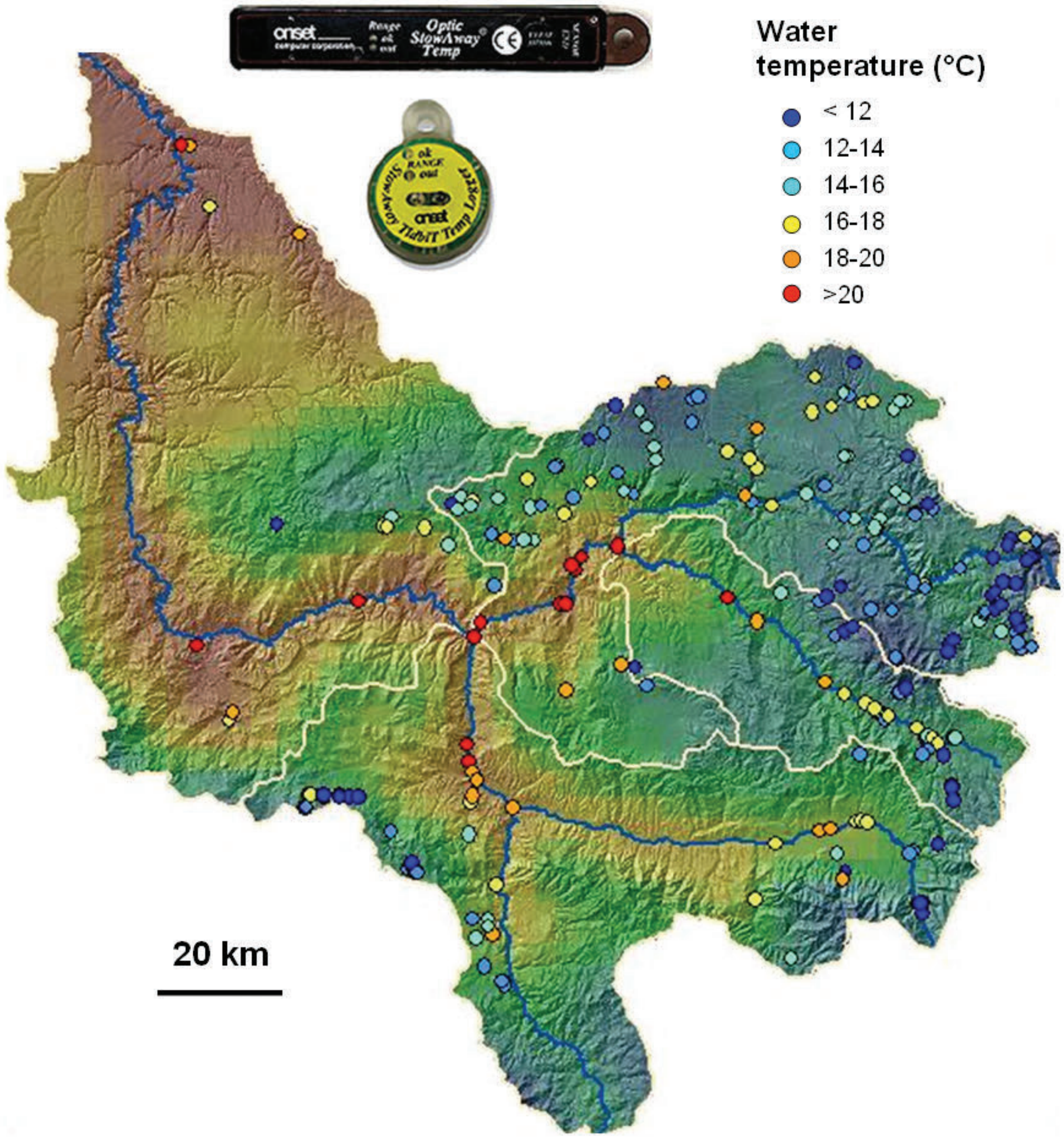

Figure 6.1.2. Basin-scale variation in mean water temperature for August (1992–2003) in the John Day River basin, Oregon. Multi-agency coordination in digital temperature data logger deployment and data analysis facilitates spatially explicit modeling and the identification of cold-water refuges at a subbasin scale from a stream network perspective. Broad-scale databases provide the spatial context necessary for identifying cold-water refuges at multiple spatial scales (see Table 5.1.1). Sources: Carol Volk and Chris Jordan (NOAA Fisheries, Seattle, Washington and Corvallis, Oregon; Ruesch and others, in review).[198]

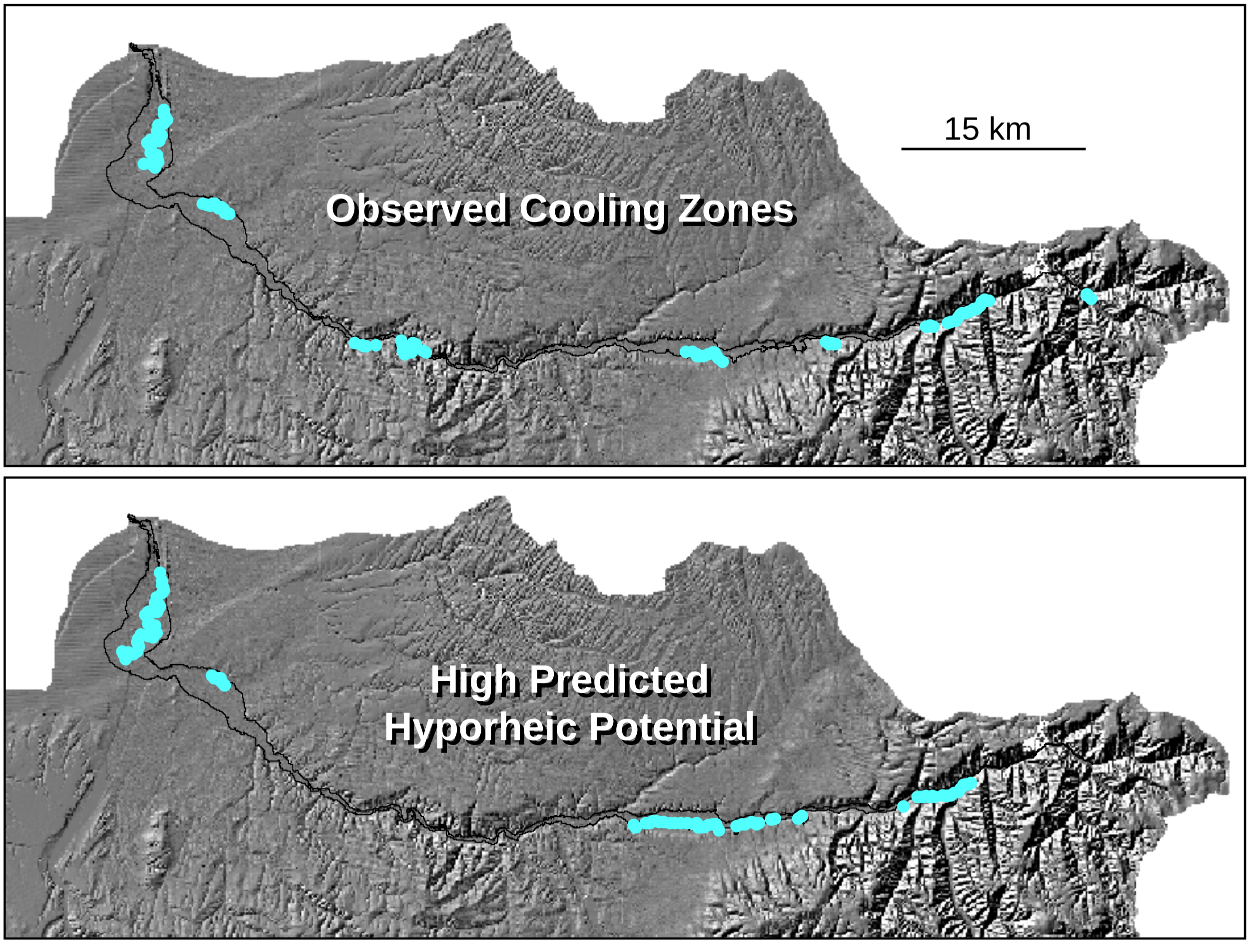

Figure 6.1.3. Observed and predicted zones of cooling and hyporheic potential based on 10-m digital elevation models (DEMs) of floodplain and channel geomorphology in the Umatilla River, Oregon. Geomorphic parameters were derived from DEMs and included in the model predicting hyporheic potential based on sinuosity, stream gradient, floodplain width, and valley width (O'Daniel, 2005). Source: Scott O'Daniel, GIS Program, Confederated Tribes of the Umatilla Indian Reservation, Pendleton, Oregon). [169]

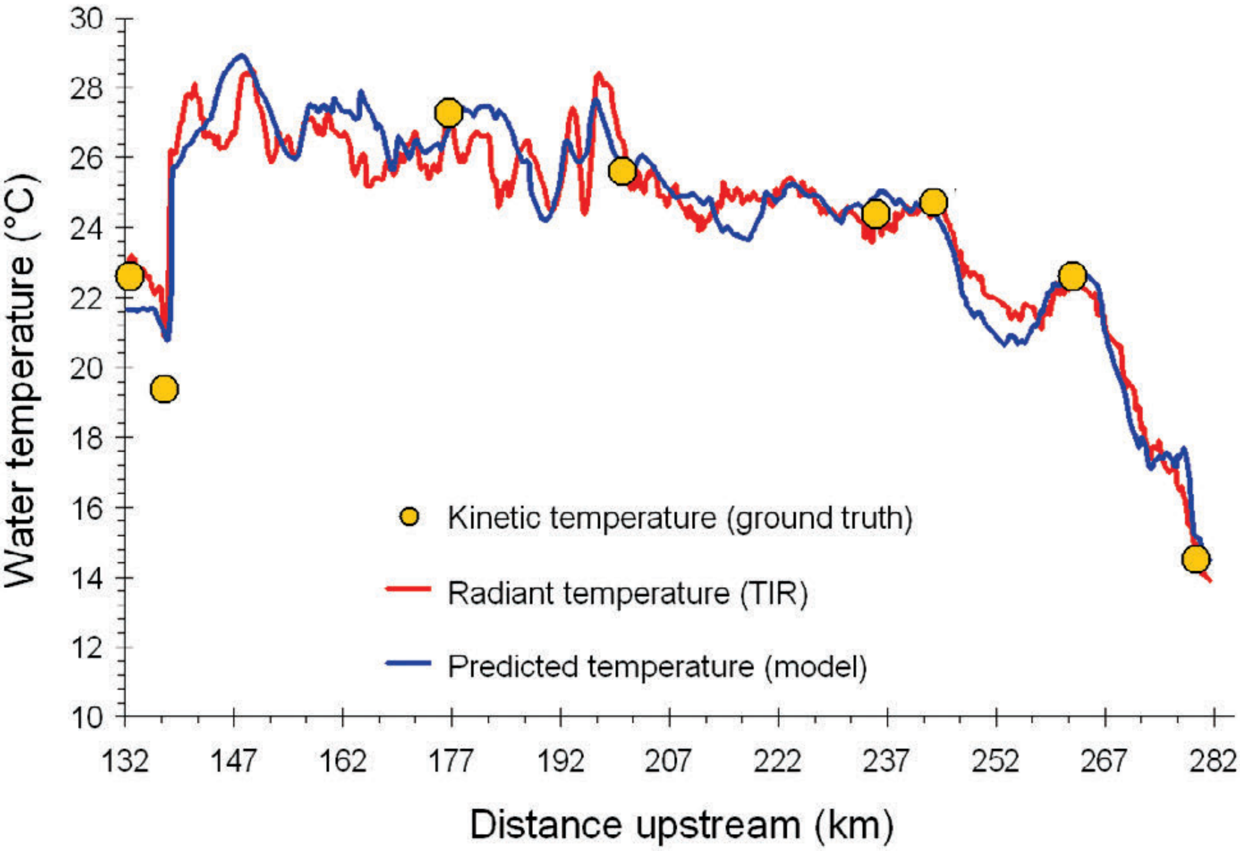

Figure 6.2.1. Predicting cold-water refuges at the kilometer scale with spatially explicit, process-based modeling. The above longitudinal profile of water temperature in the upper Grande Ronde River (Oregon) depicts radiant temperature acquired during an airborne thermal IR overflight (August 20, 1999), in-stream measurements of kinetic temperature, and calibrated model predictions. Distance upstream (x-axis) was determined from the river mouth (Oregon Department of Environmental Quality Upper Grande Ronde Subbasin Total Maximum Daily Load [TMDL], April 2000, Appendix A: Temperature Analysis, p. A-86) (adapted from Handcock and others, in press). [105]

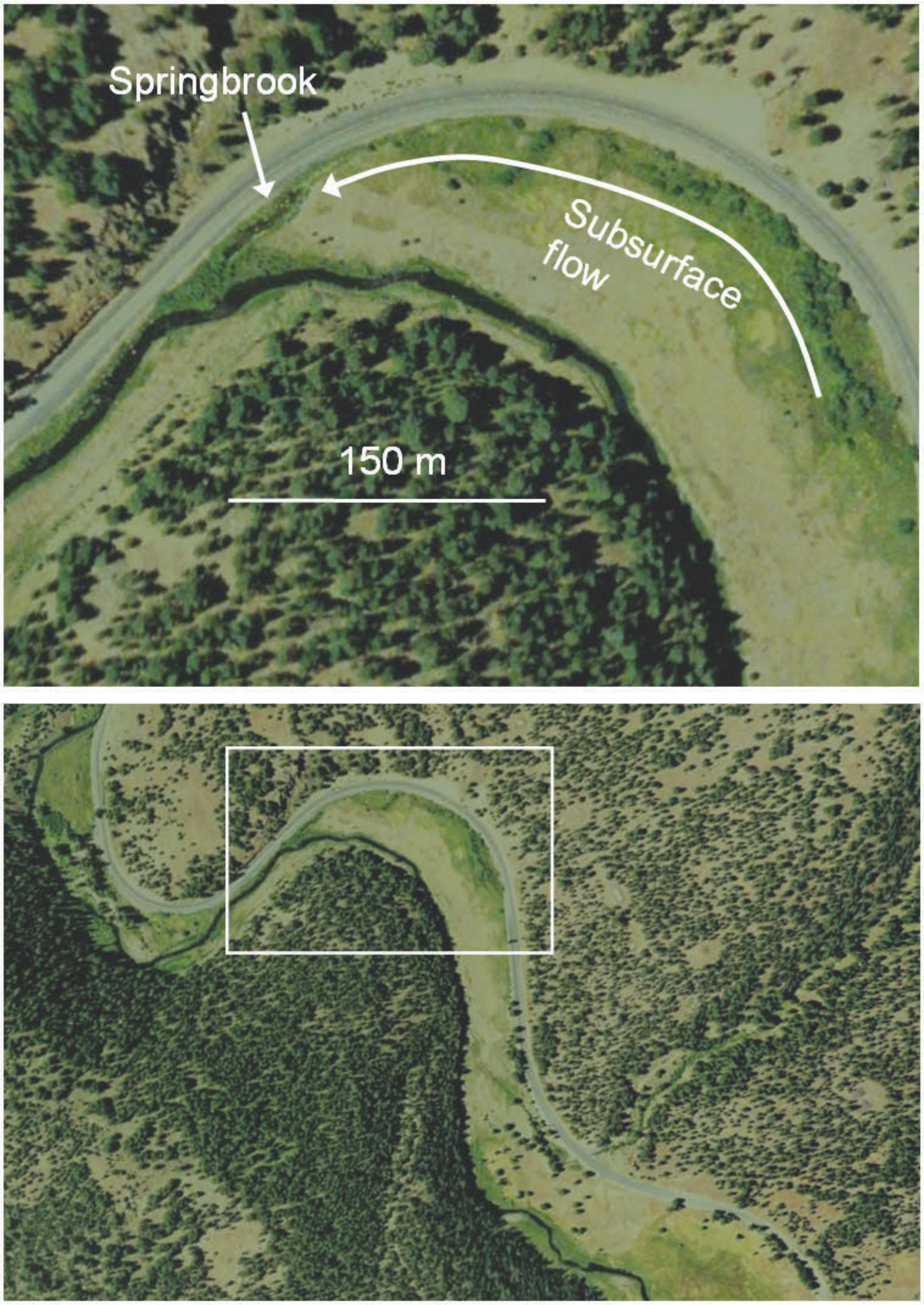

Figure 6.3.1. High-resolution Google© Earth imagery of a springbrook in the upper Middle Fork John Day River, Oregon, illustrates the accessibility and utility of readily available Internet imagery for identifying potential locations of cold-water refuges in small to large rivers. Riparian canopy may obscure precise locations of cold-water areas but also can provide an indication of subsurface flow pathways leading to cool-water areas as indicated above by different levels of greens in floodplain vegetation.

Figure 6.3.3.1. Helicopter and gimbal mount (inset) for airborne TIR remote sensing of stream temperature. The thermal imager (8–14 µm wavelength) and paired daylight video camera (lower left inset) are controlled from inside the aircraft and are georeferenced with a global positioning system (GPS) (for more detail see Torgersen and others, 2001228 and Handcock and others, in press). Photographs taken in 1995 by C. Torgersen. [105]

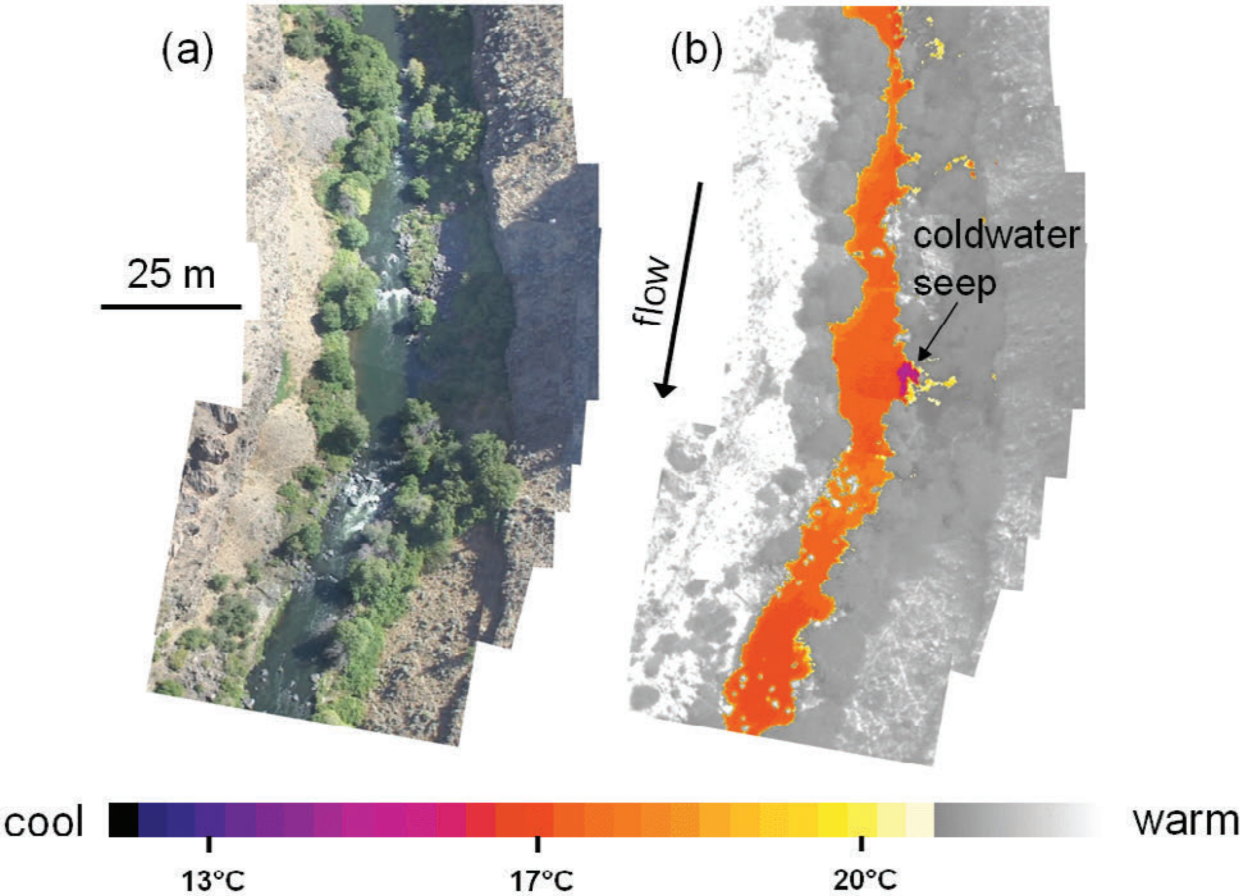

Figure 6.3.3.2. Aerial images in (a) natural color and (b) airborne TIR of a cold-water seepage area in the Crooked River, Oregon, in a high-desert basalt canyon (August 27, 2002). The colored portion of the TIR temperature scale spans the approximate range in water-surface temperature in the image; land and vegetation surface temperature are depicted in shades of gray. Lateral cold-water seeps, such as the one depicted above, are relatively small in area but provide important cold-water refuges for salmonids (Bureau of Land Management; Watershed Sciences, Inc., Corvallis, Oregon) (adapted from Handcock and others, in press). [105]

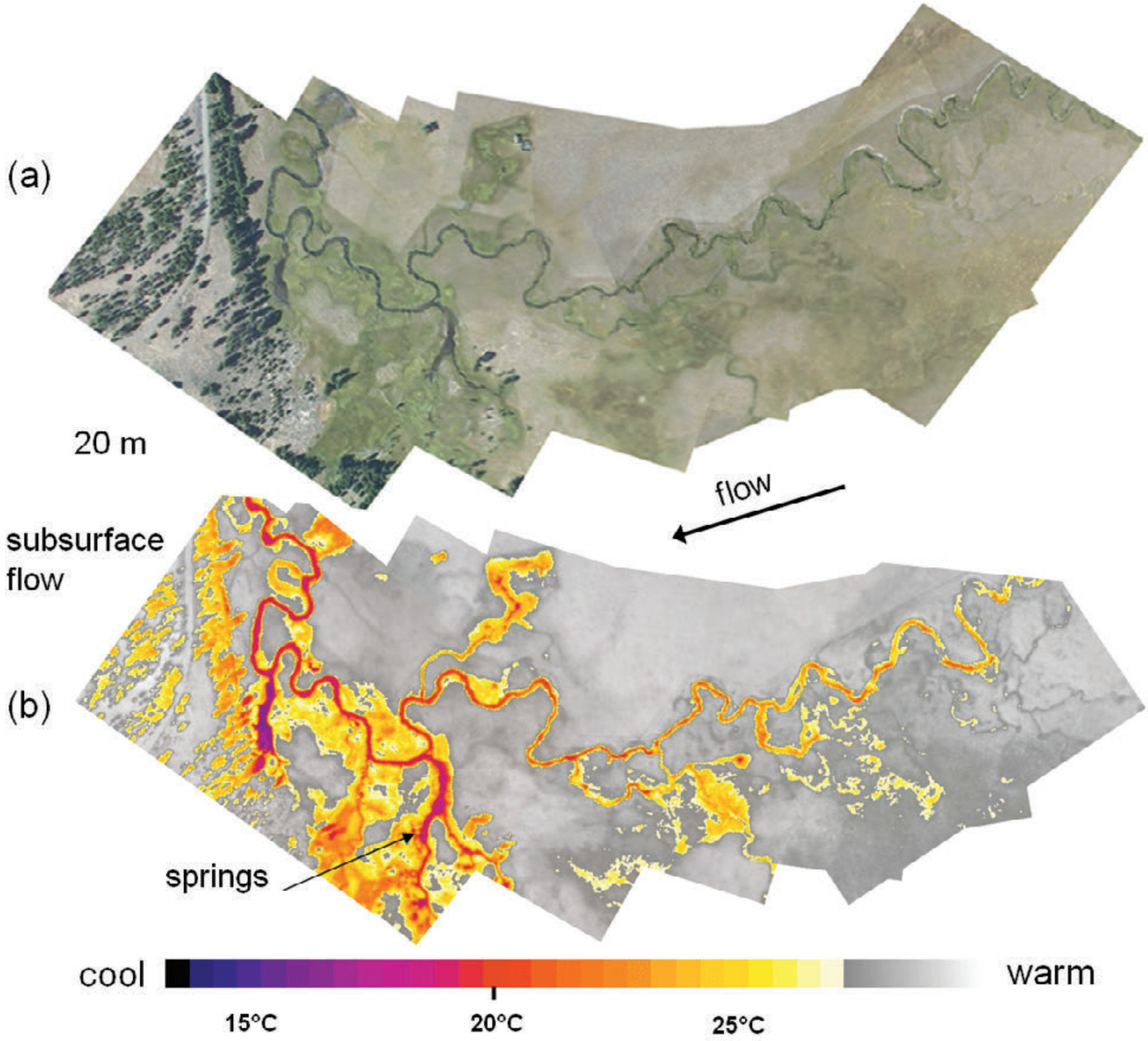

Figure 6.3.3.3. Aerial images in (a) natural color and (b) airborne TIR of groundwater springs flowing into the upper Middle Fork John Day River, Oregon, in a montane meadow (August 16, 2003). See Figure 6.3.3.2 for an explanation of the color and grayscale thermal classification. Complex subsurface hydrologic flow paths and areas of increased soil moisture adjacent to the wetted channel are revealed by lower temperatures compared to the surrounding landscape (Bureau of Reclamation; Watershed Sciences, Inc., Corvallis, Oregon) (adapted from Handcock and others, in press). [105]

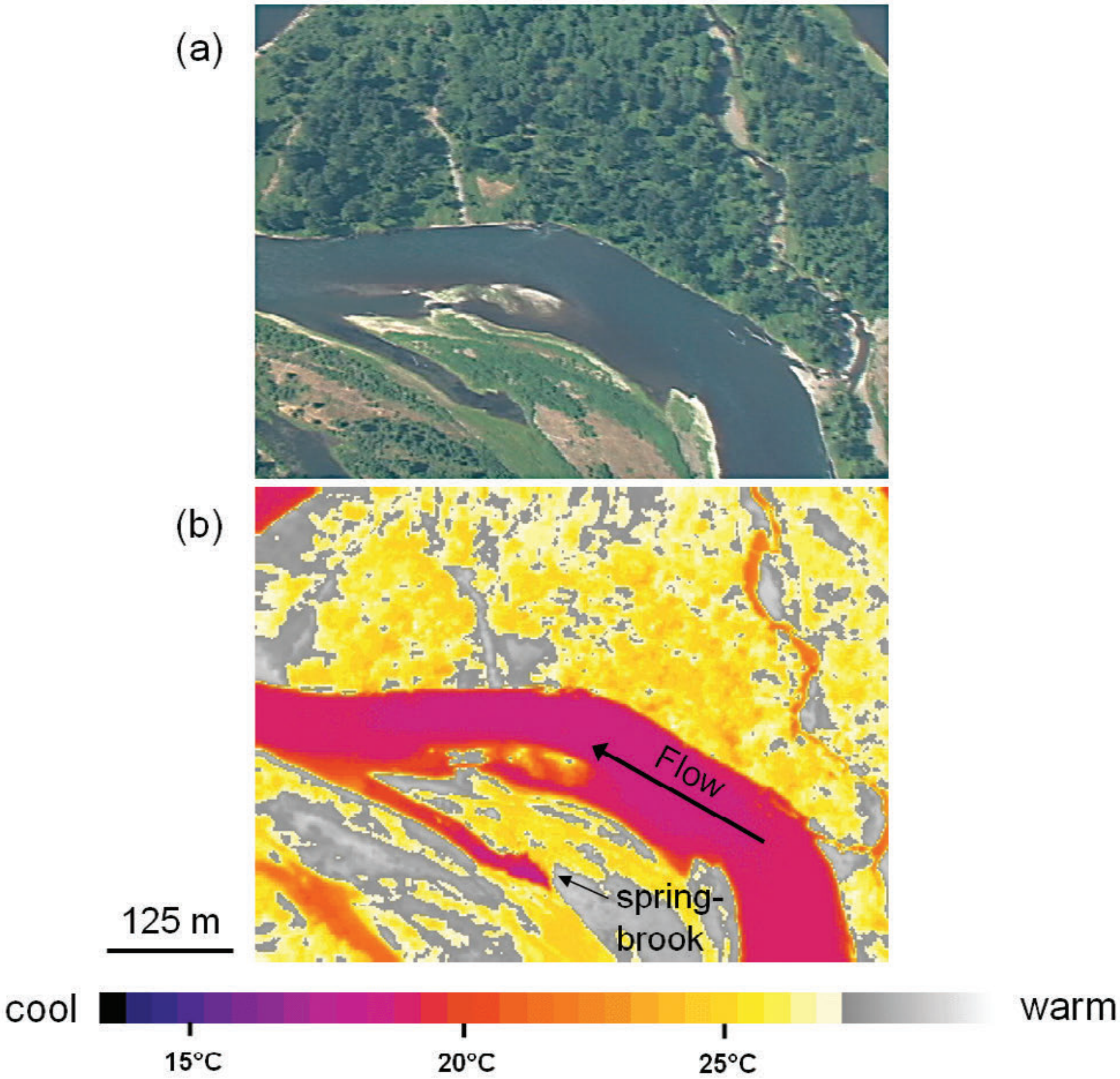

Figure 6.3.3.4. Aerial images in (a) natural color and (b) airborne TIR showing thermal heterogeneity in a complex floodplain of the Willamette River, Oregon, which flows through a large, low-elevation agricultural valley (July 22, 2002). See Figure 6.3.3.2 for an explanation of the color and grayscale thermal classification. Radiant water temperature varies laterally from the cooler and relatively homogeneous thalweg and main channel to warmer backwaters and disconnected channels. A springbrook is indicated with a black arrow where relatively cooler hyporheic flow emerges from the unconsolidated substratum of a large riverine island (Oregon Department of Environmental Quality; Watershed Sciences, Inc., Corvallis, Oregon) (adapted from Handcock and others, in press).[105]

Figure 6.4.1.1. Rapid temperature assessment in wadeable streams with fast-response thermocouple probes. Locations of cold-water areas can be identified by walking through or along the stream and sweeping the extendable probe along the stream bottom. The near instantaneous response of the thermocouple and digital readout of the instrument (Atkins, Inc., Models 35200 and 39658) are essential for identifying thermal anomalies with the pole-mounted probe. Photographs taken by J. Ebersole in 1997, Mark Coleman in 2009 (Coleman Ecological, Inc., personal commun.), and Nancy Raskauskas in 2004 (Oregon State University). http://www.techinstrument.com/acatalog/Digital_Thermometers_Thermocouple.html

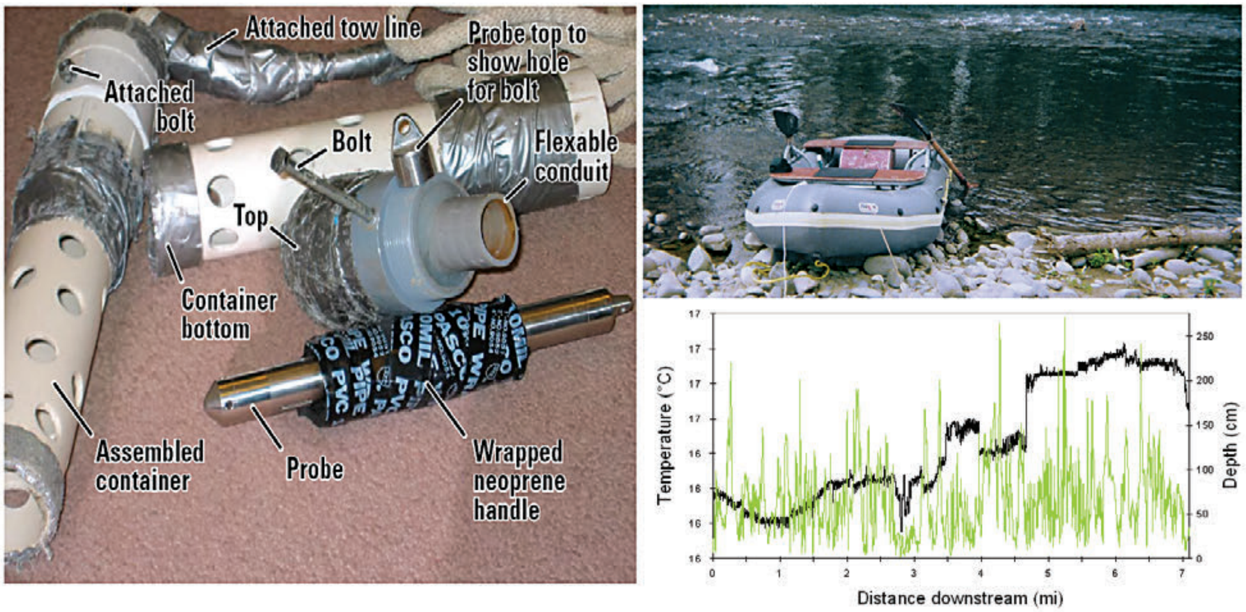

Figure 6.4.1.2. Towable temperature/pressure transducer probe for mapping thermal anomalies and water depth in large, deep rivers that are navigable by raft or inflatable kayak. The user tows the probe downstream and maps spatial variation in temperature (lower right: temperature in black and depth in green) at 1–2 second intervals by synchronizing the data logger time stamps with geographic coordinates collected simultaneously using an on-board global positioning system (GPS). Spatial variation in water temperature depicted in the lower right panel was measured in the upper Yakima River, Washington, in September 2001. Source: John Vaccaro, U.S. Geological Survey, personal commun. (see Vaccaro and Maloy, 2006). [231]

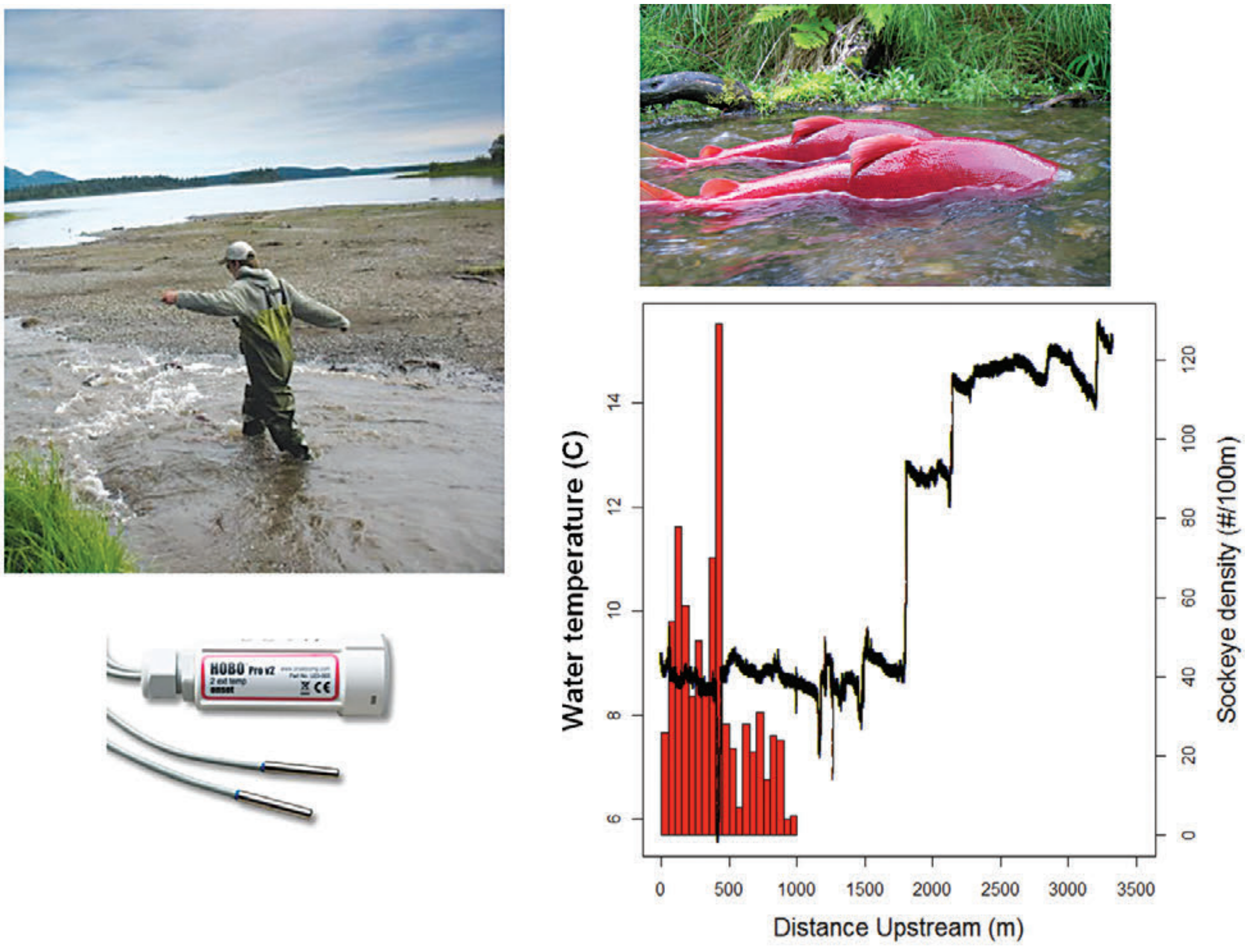

Figure 6.4.1.3. Miniature temperature mapping system designed for evaluating fish response to thermal heterogeneity in wadeable streams. The user pulls the external-probe digital temperature data logger (lower left) downstream and maps the longitudinal temperature profile (lower right) at 1-second intervals by synchronizing the temperature data with geographic coordinates collected simultaneously using the track-log function of a hand-held global positioning system (GPS). Photographs taken and data collected in 2009 by Jonny Armstrong, University of Washington, unpublished data (see also Ruff and others, 2011). [199]

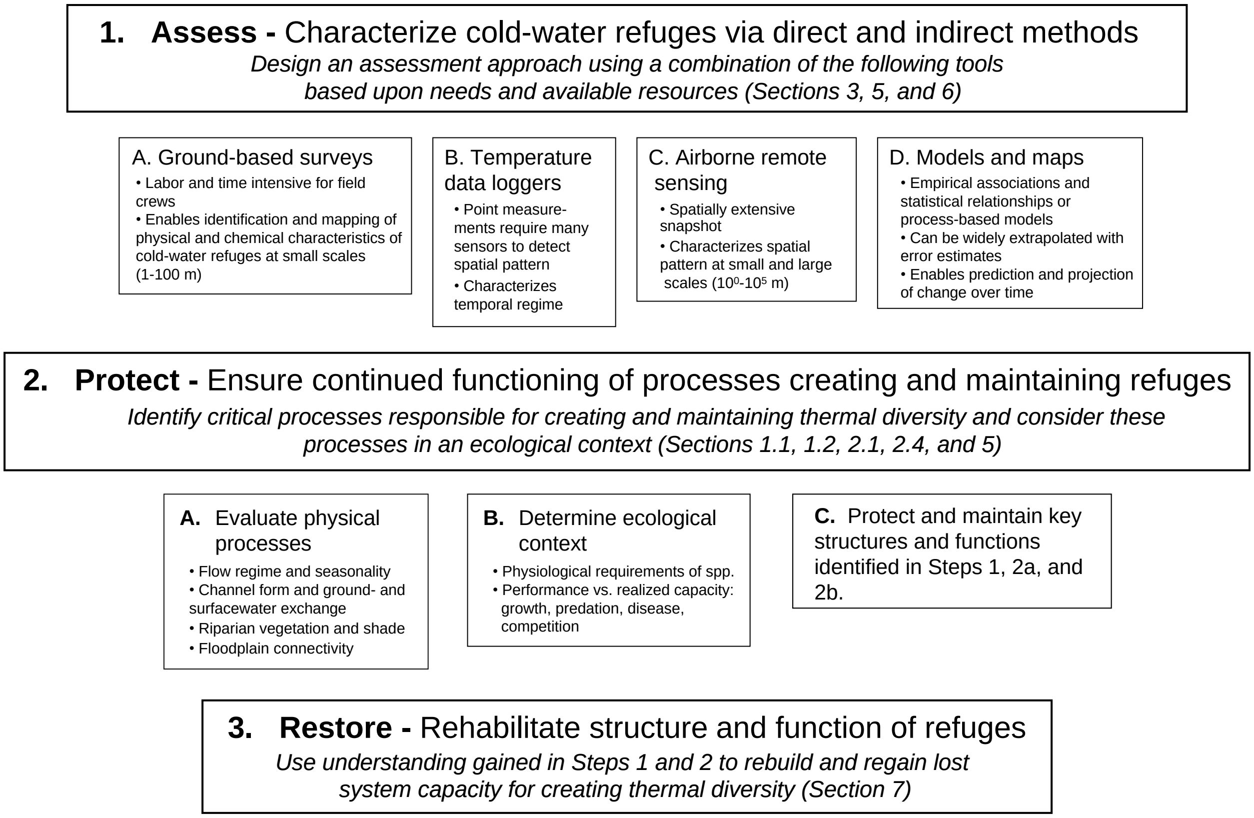

Figure 7.1.1. Conceptual model outlining steps for assessing, protecting, and restoring cold-water refuges and thermal diversity in riverine landscapes. Sections are specified at each step and indicate locations in this document where relevant information, illustrations, and citations can be found.

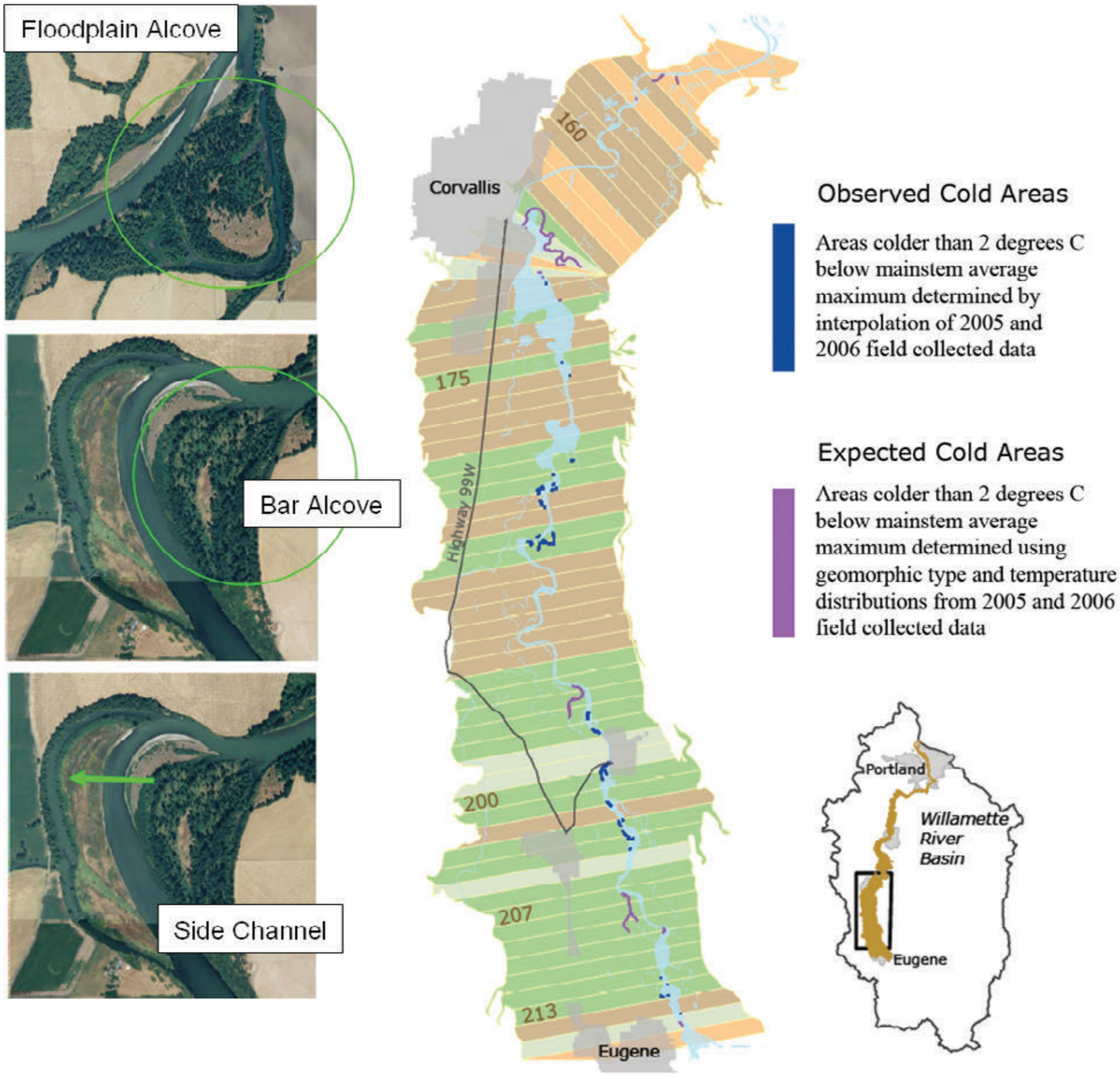

Figure 7.4.1. Observed and expected cold-water areas in the middle Willamette River, Oregon, based on qualitative evaluation of historical and current aerial photographs and field measurements of stream temperature obtained from digital data loggers. Thermal reach types (e.g., floodplain alcoves, bar alcoves, and side channels depicted above) were determined from channel morphology, riparian vegetation, and floodplain structure. Slices at 1-km intervals spanning the floodplain indicate areas with high ecological potential and social constraints (gray), low ecological potential and high social constraints (tan), high ecological potential and low social constraints (green), and low ecological potential and low social constraints (brown) (adapted from Hulse and others, 2007).[117]

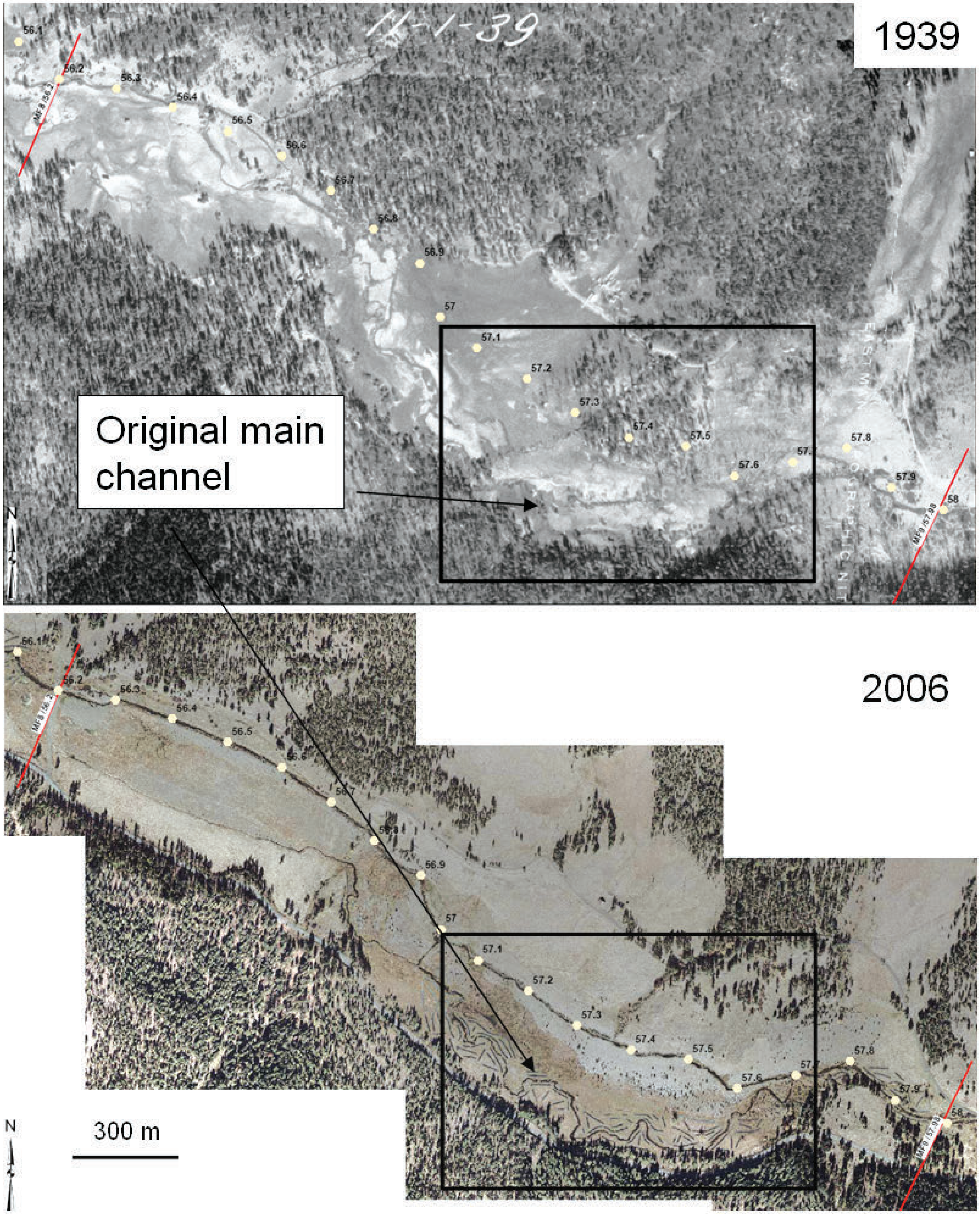

Figure 7.5.1. Historical and current aerial photographs of the Oxbow Conservation Area of the Middle Fork John Day River, Oregon, in 1939 and 2006. Tan dots provide a spatial reference in the 1939 photograph for the approximate location of the current main channel, which is located north of the original main channel. Source: Brian Cochran, Restoration Ecologist, Confederated Tribes of the Warm Springs Indian Reservation of Oregon; Oxbow Conservation Area, Middle Fork John Day River Dredge Mining Restoration Project. http://www.usbr.gov/pn/programs/fcrps/thp/lcao/index.html

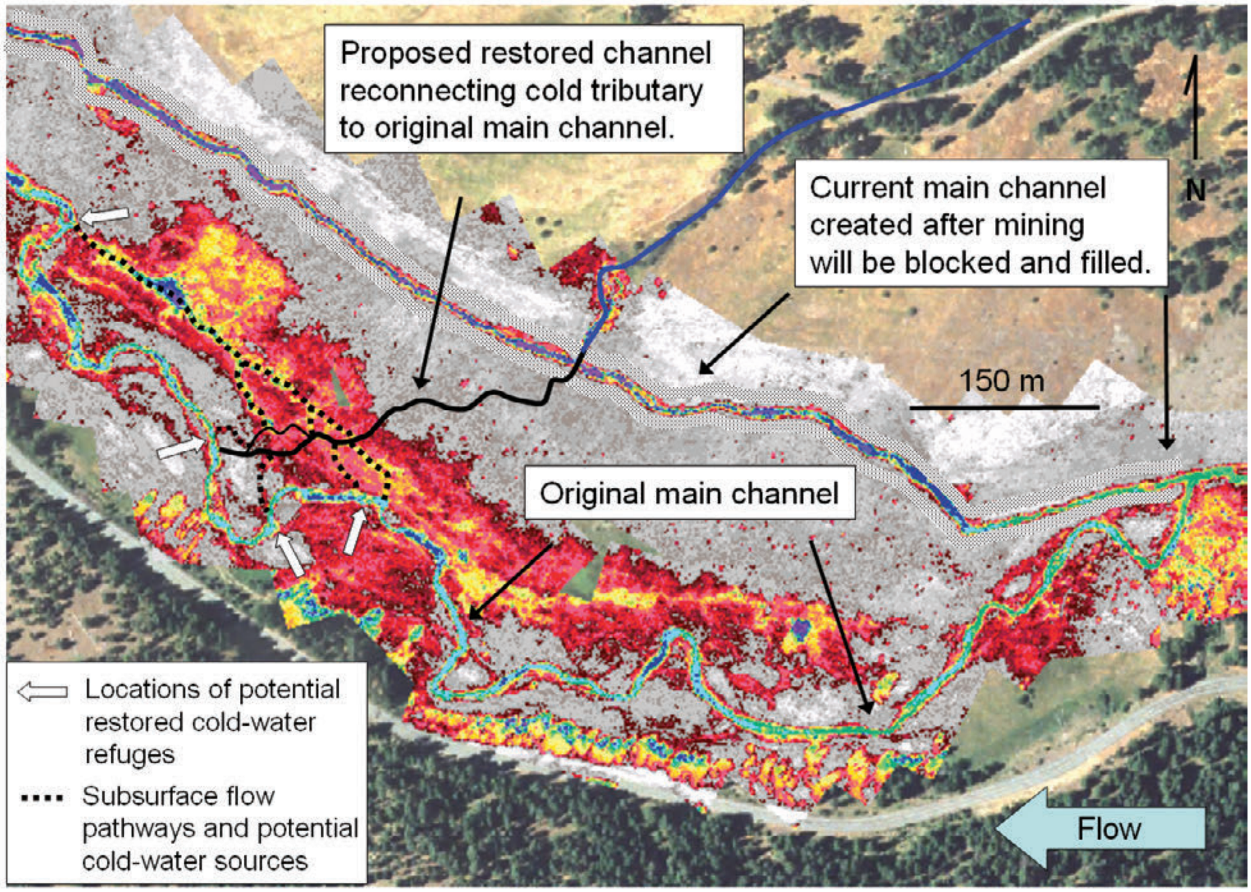

Figure 7.5.2. Floodplain restoration in the Oxbow Conservation Area of the Middle Fork John Day River, Oregon, incorporated aerial TIR imagery (above) and digital elevation models derived from LiDAR to guide channel placement (solid black line) in relation to subsurface-flow patterns (red and yellow tones in thermal image). The cold tributary (solid blue line) will be reconnected with the floodplain of the original main channel (blue and green tones) located in the lower portion of the image. An objective of restoration is to create cold-water refuges (small white arrows) where relatively cool subsurface flow (dotted lines) from the reconnected tributary enters the main channel. Cold water from the tributary currently flows into the isolated north channel created after the floodplain was dredge mined in the 1940s and 1950s. Source: Brian Cochran, Restoration Ecologist, Confederated Tribes of the Warm Springs Indian Reservation of Oregon; Oxbow Conservation Area, Middle Fork John Day River Dredge Mining Restoration Project. http://www.usbr.gov/pn/programs/fcrps/thp/lcao/index.html

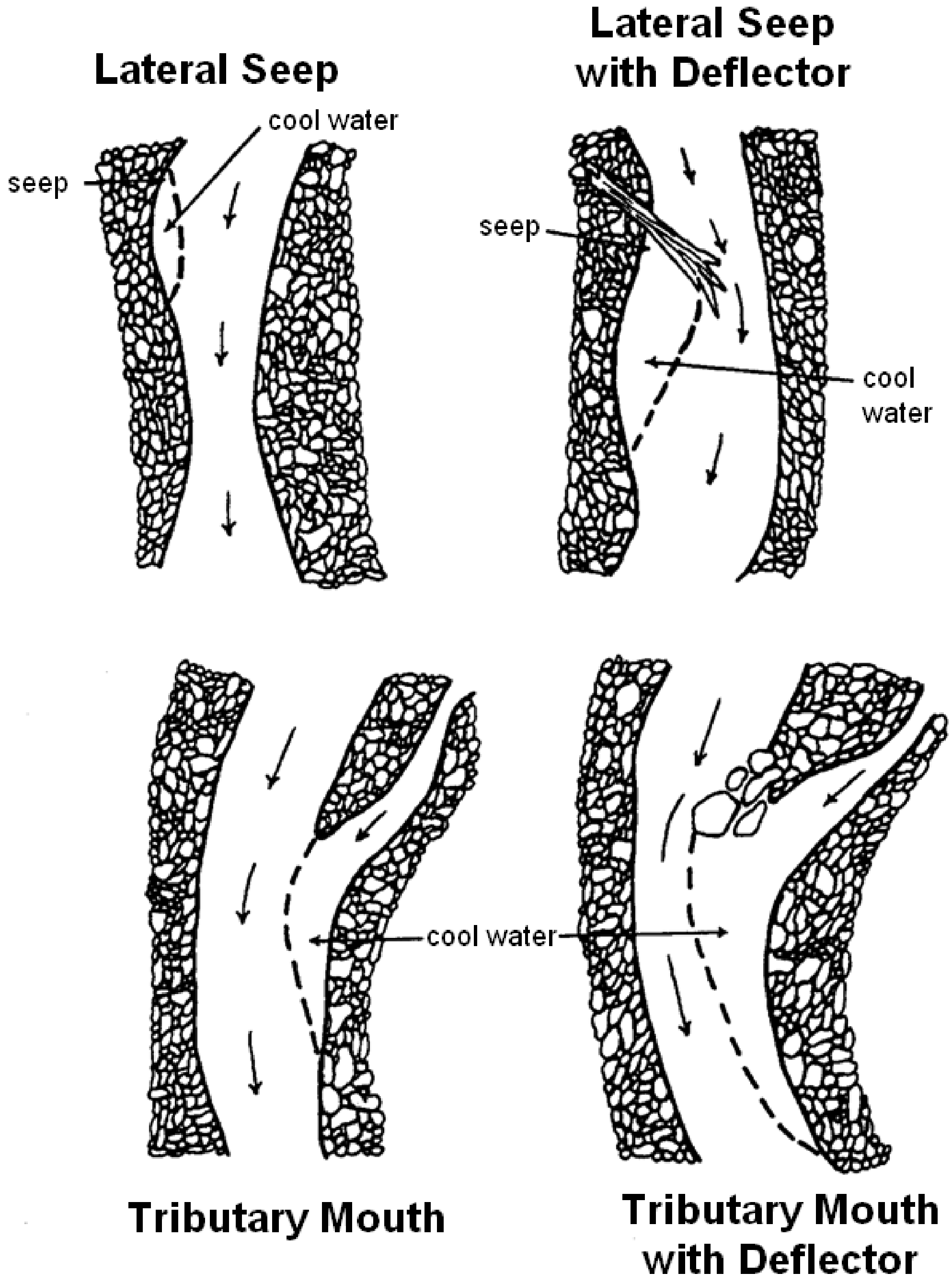

Figure 7.5.3. Channel unit and microhabitat-scale restoration of cool-water areas, such as seeps (top) and cold tributaries (bottom), may include placements of wood (top right) and bar (bottom right) deflectors upstream of cool-water inputs to increase channel complexity and reduce mixing and effectively increase the size of cold-water refuges (adapted from Bilby, 1984).[28]

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9. References

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10. Appendix A. Streaming video of a symposium on cold-water refuges

Special Symposium: "Identifying, protecting, and restoring thermal refuges for coldwater fishes" at the Joint Annual Meeting of the Western Division and Oregon Chapter American Fisheries Society, Portland, Oregon, May 4–8, 2008.
Conveners: Christian E. Torgersen and Joseph L. Ebersole
Streaming video available online http://www.ruraltech.org/video/2008/WDAFS/index.asp
Videographer: Matthew McLaughlin, School of Forest Resources, University of Washington, Seattle.

Presentation and Speaker Information	Time
Policy and regulatory context for cold-water refugia Dru Keenan - EPA Region 10; Office of Water and Watersheds	18:07
Cold-water refuges in the Willamette River: Implications for conservation and restoration Stan Gregory - Oregon State University	18:15
Combining spatial and temporal stream temperature measurements to investigate surface/groundwater exchange across a semi-arid alluvial floodplain Scott O'Daniel – Confederated Tribes of the Umatilla Indian Reservation; UC Santa Barbara	16:43
Influence of hyporheic flow and geomorphology on temperature of a large, gravel-bed river, Clackamas River, Oregon, USA Barbara Burkholder - GeoEngineers, Inc.	21:54
Assessing thermal suitability of streams for establishment of native trout conservation populations in high-elevation streams Mark Coleman - Principal Scientist for Coleman Ecological, Inc.	20:29
A thermal profile method for long river reaches to identify potential areas of ground-water discharge and preferred salmonid habitat and to document the longitudinal temperature regime John Vaccaro - USGS Washington Water Science Center	19:03
Remote sensing techniques for mapping aquatic habitat river channel morphology and thermal heterogeneity Russ Faux - Watershed Sciences, Inc.	17:30
The effect of landscape topography and in-stream habitat on the distribution, growth, and survival of Lahontan cutthroat trout (*Oncorhynchus clarki henshawi*) in a high desert watershed George Boxall - Oregon State University	12:27
Behavioral thermoregulation by adult Chinook: Beneficial thermoregulation or ecological trap? Chris Peery - University of Idaho	18:03
Assessing thermal rearing restrictions of juvenile coho, Redwood Creek, CA Mary Ann Madej - USGS Western Ecological Research Center	16:12
Klamath River thermal refugia: physical and biological characterization Ron Sutton - Bureau of Reclamation; Mike Deas - Watercourse Engineering, Inc.	23:36
Coldwater fishes and thermal refuges in hot water: Synthesis and future directions Christian Torgersen - USGS Forest and Rangeland Ecosystem Science Center	18:11
Panel Discussion: • **Jim Sedell** - National Fish and Wildlife Foundation • **Debra Sturdevant** - Oregon Dept. of Environmental Quality • **Jeff Lockwood** - NOAA, National Marine Fisheries Service, NW Region • **Gordie Reeves** - U.S. Forest Service, Pacific Northwest Research Station • **Stan Gregory** - Oregon State University	29:58
General Discussion Questions and answers discussed among the panel and symposium attendees.	14:14

11. Appendix B. Airborne thermal infrared surveys of stream temperature (DVD)

Contractors

Surveys were conducted from 1994 to 2007 by Environmental Research Institute of Michigan (ERIM), and Russ Faux, Watershed Sciences, Inc., http://www.watershedsciences.com/

Locations: Oregon, Washington, Idaho, Nevada, California, Utah, and Wyoming

Database

Metadata on surveyed sections include: date of survey, river/stream name, description of longitudinal extent (start and end points), length (miles), location (state), permission to distribute (yes, no, or with permission), client and point of contact (address). This database is intended to be publically available.

Maps

ESRI GIS shapefiles if available are included on DVD. These data include the actual surface-water temperatures sampled from thermal imagery and their associated geographic locations and times of acquisition, with notes on tributary junctions, landmarks, and thermal anomalies. Raw thermal imagery in raster format is not included. Shapefiles may be available to the public on request from the authors.

Reports

In some cases, reports describing the methodology, results, and preliminary interpretation of thermal surveys are available. These reports are associated with their respective map and survey data in the compact disk. Reports may be available to the public on request from the authors.

Additional resources

Extensive airborne thermal infrared surveys of rivers and streams in Idaho were conducted by the Idaho Department of Environmental Quality from 1999 to 2001. More information on these surveys is available online from the Idaho Department of Environmental Quality: http://www.deq.idaho.gov/water-quality/surface-water/temperature.aspx

The Washington Department of Ecology provides (1) lists of rivers and streams surveyed with airborne thermal infrared remote sensing by Watershed Sciences, Inc., and (2) links to online reports with preliminary analyses of the data. More information on these surveys is available online from the Washington Department of Ecology:
http://www.ecy.wa.gov/apps/watersheds/temperature/

EPA 910-C-12-001 **Primer for Identifying Cold-Water Refuges to Protect and Restore Thermal Diversity in Riverine Landscapes**