# Evaluation of Carrying Capacity and Limiting Factors for Production of Salmon and Steelhead in Stanshaw Creek, tributary to Klamath River

## Introduction

During October 2 and 3, 2017, I visited Marble Mountain Ranch to conduct a site orientation and stream survey of Stanshaw Creek. During the visit, I walked along about 0.25 mile of the diversion ditch from the point of diversion, and surveyed stream habitat features in Stanshaw Creek from the point of diversion down to the stream's entry onto the Klamath River floodplain. I also completed a similar survey on the lower 0.6 miles of Irving Creek out to the Klamath floodplain. My objective was to obtain the data needed to estimate the spawning and rearing capacity of Stanshaw Creek, including the floodplain pond it feeds, identify how flow and other factors may limit fish production, and evaluate the tradeoff in terms of fish production from delivering 3 cfs of outflow from the hydro plant to Irving Creek rather than Stanshaw Creek. During my habitat surveys, I measured habitat features that have a consistent and quantified relationship to a stream's capacity to support salmon and steelhead populations, and I identify the factors limiting production of those populations.

I chose the survey protocol to accomplish the following:

1. Identify and measure potential impediments to upstream passage of adult salmon and steelhead
2. Identify and measure potentially suitable patches of gravel for spawning;
3. Measure stream and floodplain features that determine rearing capacity for juvenile salmon and steelhead
4. Establish cross section where width, depth and velocity can be monitored at flows up to flood level.

## Methods

### Stream Survey

Working in the downstream direction with two assistants, we classified the type of all channel units from the point of diversion to the Klamath floodplain. We measured length, widths, and depths of all distinct pools, and for a subset of riffles, rapids, and cascades. Descriptions of the channel unit types we assigned are listed in Appendix 1. In order for an area of habitat to qualify as a channel unit, it must be at least as long as it is wide, and the unit's upper and lower limits must be distinguishable by distinct changes in channel gradient and velocity. We used an extendable stadia rod to measure widths and depths, and a 150 ft tape measure to measure lengths. We measured widths at approximately the points of 1/3 and 2/3 of the unit length, and we measured depth at deepest point along that width. The deepest point was generally close to midway across the width.

The average stream gradient, as estimated by Taylor (2015), was 9% to 11%, so most of the stream length was fast water morphologies that rapidly alternated between riffles, rapids, cascades and step pools, although in ever changing order. In most of these fast water sequences, it was not possible to classify distinct channel units, because boulders, woody debris, and uneven gradient were causing constant changes in velocity depth, including laterally in the channel. Only when there was a distinct channel unit did we measure widths and depths. Most of the fast water sequence that had varied morphologies continued out of the line-of-site, or through woody clusters that we could not penetrate. In these cases, we measured channel length over the line-of-sight with a Nikon laser range finder, and then moved to the end of that line, to measure distance on the next line of sight. We continued adding these lengths until we encountered a distinct channel unit or distinct change in gradient. Fast water sequences were categorized as riffle/rapids, cascade/rapids, or step pool/rapids depending which feature combined most with the rapids in the sequence.

In distinct channel units, substrate was classified visually as the percentage of the unit total that was composed by six categories:

| Category | Diameter | |
|---|---|---|
| Fines | organic mud up to pea gravel (< 2 mm) | |
| small gravel | pea gravel to walnut (0.1-0.8 inches mm) | |
| medium gravel | golf ball | (0.8 – 1.5 inches) |
| large gravel | baseball | (1.5-2.5 inches) |
| cobbles, | softball + | (2.5 – 10 inches) |
| boulders. | Basketball + | (>10 inches) |

At each location that appeared to be a possible impediment to upstream migration for adult trout or salmon, we used the stadia rod to measure both the height and lateral distance a fish would have to jump in order to pass over the obstruction. We also measured the maximum water depth at the closest point a fish could attempt a jump over the obstruction. We refer to this location as the jump pool. In the case of step or plunge pools below a falls, almost no lateral distance was required, and height was the primary obstacle. Below cascades and bedrock chutes, lateral distance of the required jump was a key component of passage difficulty.

## Channel Cross Section

We established and premeasured widths and heights of a channel cross section on the first riffle that could be easily accessed from the point of diversion. This was at channel unit 6 of the survey, and began 73 ft below the point of diversion (see Appendix 2). We first laid out the transect by anchoring 3ft steel stakes on each side of the channel, just above the active channel line. Distance between the stakes was 40.9 ft. Distance to the water's edge was 10.6 ft on river right (looking downstream) and was 20.1 ft on river left. Wetted channel width was 10.3 ft. Beginning at the wetted edges of the channel, we then measured the channel widths that corresponded with height increments of 0.4 ft, and, extending up to 3.2 ft above the wetted surface. All width measurements were referenced to the distance from the pin on river right.

We partitioned the channel width in 1 ft increments, the first ending at 11.6 ft from river right. We used a Swoofer model 2100 water velocity meter to measure water velocity at mid depth of the midpoint of each 1 ft width increment. To estimate streamflow, we calculated the trapezoidal area of depth and width in each width increment, and multiply by the velocity in that increment. We summed the volumes of flow across the 10 width increments to estimate total stream flow.

## Floodplain Pond

On October 3, 2017, I surveyed habitat in the pond that Stanshaw Creek feeds on the Klamath floodplain. I used the Nikon laser range finder to measure pond widths at two points. The full pond width is not visible from a single point, so I measured distances visible points along the side and summed them to estimate pond length. I measured height and length of the rock dam at the pond outflow, and distance from the base of the dam to the Klamath River.

One of my assistants in a wetsuit snorkeled the pond to observe fish. He twice made a full circuit around the pond, swimming slowly to minimize disturbing any fish. He delayed 10 minutes between circuits and kept separate counts of fish species and size classes for each circuit. He swam near and paused at all areas of underwater cover to look carefully for fish. Lighting and underwater visibility were good.

## Estimation of Steelhead Rearing Capacity

I used the Unit Characteristic Method (UCM) to estimate fish carrying capacity in the study reach. The method and its ability to predict carrying capacity have been vetted in peer-reviewed literature (Cramer and Ackerman 2009). Formulation of the UCM to predict carrying capacity is based first on consistent differences that are found in densities of parr between types of channel units (i.e., pool, riffle, rapid etc.). Further, parr densities within a specific type of channel unit are positively correlated to depth and cover complexity, and negatively correlated to fine sediment and temperature above their optimum range for fish performance. The UCM accumulates the sum of these effects in each channel unit, and multiplies by the area of the unit to predict the maximum number of parr the unit can hold under average environmental conditions.

The key principles underlying this method are:

1. Salmonids exercise strong and repeatable preferences for a suite of habitat features they will use, and these preferences determine the type of channel unit in which they choose to reside.
2. These preferences have repeatable patterns of change between life stages and in response to extremes in environmental variation.
3. The suite of habitat features available to a fish is related to the type of channel unit (e.g. pool, riffle, etc.), and differs between these channel unit types.
4. Therefore, densities of salmonid use follow consistent differences between types of channel units.
5. Habitat capacity for a particular life stage of salmonid can be predicted as the product of the expected density of fish supportable in a particular channel unit, multiplied by the surface area of the unit, and then summed with such products for all channel units in the stream.

As salmonids grow, territory size of salmonids increases exponentially with fish length, such that the demand for territory to support surviving members of a cohort increases at least through their first year of life. Changing habitat preferences and space demands, juxtaposed against shrinking habitat availability with the onset of summer low flows often results in a bottleneck to rearing capacity in wadable streams for salmonids greater than age 1 (Quinn 2005).

Given the lack of suitable habitat to support a self-sustaining population of Coho salmon, I estimated habitat carrying capacity exclusively for steelhead. Because steelhead typically rear in freshwater for two full summers before migrating to the ocean, they are larger in their second summer and their habitat demands are usually the most limiting to their production. I refer to this as the age 1+ parr life stage. Densities of age 1+ steelhead parr the have been found in coastal streams in years with sufficient spawner escapement to fully see available habitat are shown in Table 1. In the case of the Stanshaw Creek, riffles, rapids and cascades were often linked together and difficult to distinguish, so I used an intermediate value for parr densities of 0.043 parr/m$^2$ for all three unit types and their mixtures.

Densities within each channel unit type are strongly influenced by depth and cover. Combined observations from several experiments indicate that steelhead exercise habitat preferences in the priority order of depth first, velocity second, and cover third. Parr of all salmonid species strongly avoid areas with depths <0.5 ft and a variety of studies show that parr densities increase as unit depths increased up to at least 3 ft (Quinn 2005). Most unit depths in Stanshaw Creek fall within this range, so I applied the

**Table 1.** Expected parr densities (fish/100m$^2$) under average conditions, as used in the UCM for each channel unit type. Derivation of these values based on extensive sampling in coastal streams has been described for steelhead by Cramer and Ackerman (2009).

| ***Species*** | ***Pool*** | ***Riffle*** | ***Rapid*** | ***Cascade*** |
|---|---|---|---|---|
| Steelhead | 0.17 | 0.03 | 0.07 | 0.03 |

## Results

### Stanshaw Creek

Total length of the surveyed reach from the point of diversion to entry onto the Klamath floodplain was measured at 3,236 ft, excluding approximately 200 ft through the culverts under the. Distinct pools composed only 12% of the channel length, and distinct riffles composed only an additional 3% (Table 2). The remaining 85% of length was composed of complex sequences of cascade/rapids, riffle/rapids, and step-pool rapids.

**Table 2.** Total length (feet) composed by different channel unit types in Stanshaw Creek. The reach above the Highway 96 extends from the point of diversion down to the Highway 96. The reach below the Highway 96 extends from the Highway 96 culvert outfalls to the creeks entry on to the Klamath floodplain where channel becomes unconfined.

| | Above Hwy | | Below Hwy | |
|---|---|---|---|---|
| Habitat Type | Total Length (ft) | Percent | Total Length (ft) | Percent |
| Pool | 312 | 10 | 123 | 12 |
| Step Pool | 40 | 1 | -- | -- |
| Riffle | 299 | 9 | 33 | 3 |
| Rapid | 112 | 3 | 20 | 2 |
| C-RA | 1023 | 32 | -- | -- |
| RI-RA | 1241 | 38 | 872 | 83 |
| SP-RA | 209 | 6 | -- | -- |
| **Total** | **3236** | **100** | **1048** | **100** |

The mean lengths and widths of each channel unit type were similar in the reaches above and below the Highway 96. Pools averaged 15.6 ft long and 8.4 ft wide above the Highway 96 compared with 15.4 ft long and 9.5 ft wide below the Highway 96 (Table 2). These are short pools averaging just under two channel widths long. Step pools averaged shorter at 13.3 ft, but similar in width at 8.2 ft. Channel units tended to be deeper in the lower portion of the stream, with pools averaging 1.4 ft above the Highway 96 and 2 ft below the Highway 96. Riffles averaged 0.6 ft deep above the Highway 96 and 1.3 ft below the Highway 96 (Table3).

**Table 3.** Mean dimensions (feet) for each channel unit type above and below the Highway 96 crossing. "N" represents the number of units measured.

| | Above Highway 96 | | | | | Below Highway 96 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Habitat Type | Mean Length | Mean Width | Mean Depth | Area ($ft^2$) | N | Mean Length | Mean Width | Mean Depth | Area ($ft^2$) | N |
| Pool | 15.6 | 8.4 | 1.4 | 130.6 | 20 | 15.4 | 9.5 | 2 | 151.6 | 8 |
| Rapid | 14.6 | 3.8 | 0.9 | 55.5 | 1 | -- | -- | -- | -- | -- |
| Riffle | 31.4 | 9.2 | 0.6 | 289.9 | 5 | 33 | 5 | 1.2 | 165 | 1 |
| Step Pool | 13.3 | 8.2 | 1.2 | 108.6 | 3 | -- | -- | -- | -- | -- |

Substrate composition differed between channel unit types, consistent with the differences in velocity and transport power typical of the unit types. Medium to large gravels best suited for invertebrate production and coho or steelhead spawning only composed a meaningful amount of substrate (23.3%) in riffles (Table 4). However, there was only one distinct riffle measuring 33 feet long, and 5 ft wide within the reach downstream of the Highway 96 that is accessible to salmon and steelhead. Consistent with the high stream gradient and transport capacity, even the pools had over 55% of substrate composed by cobbles and boulders. However, pools also had a high percentage of fines (25.6%) particularly in the lower reach, which likely is related to bank sloughing we observed throughout the surveyed reach following the effects of wildfire that burned the watershed this summer. Cobbles and boulders composed most of the substrate in all the rapid complexes, and there were no distinct gravel patches in such units.

**Table 4.** Mean percentage of substrate within each channel unit type that was composed by different grain sizes. The upper panel is for Stanshaw Creek and the lower panel is for Irving Creek.

| | | | Gravel | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Habitat Type** | **Stream** | **Fines** | **Small** | **Medium** | **Large** | **Cobble** | **Boulder** | **N** |
| Pool | Stanshaw | 25.6 | 1.2 | 5 | 3.1 | 35.6 | 29.4 | 16 |
| Step Pool | Stanshaw | 0 | 10 | 6.7 | 0 | 43.3 | 40 | 3 |
| Riffle | Stanshaw | 3.3 | 13.3 | 5 | 18.3 | 33.3 | 26.7 | 6 |
| Rapid | Stanshaw | 0 | 0 | 0 | 0 | 20 | 80 | 2 |
| | | | | | | | | |
| Pool | Irving | 40 | 0 | 22.5 | 0 | 25 | 12.5 | 2 |
| Riffle | Irving | 30 | 0 | 60 | 0 | 0 | 10 | 1 |
| RI-RA | Irving | 30 | 10 | 0 | 0 | 30 | 30 | 1 |

We measured nine potential barriers to upstream migration (Table 4). The lowermost barrier was only 66 ft upstream of the Klamath River floodplain and was composed of a man-made rock dam stacked up to 15 inches high at its center, and creating a jump height of 3ft plus 1 ft lateral. The outfall below the dam was a shallow riffle only 0.5 ft deep, thus making it impassable to either adults or juveniles at low season flows. The rock dam created a bathtub-like pool within sight of a private residence on left bank. This rock dam will certainly flush out at higher flows and thus represents only a seasonal block to fish passage.

The first permanent barrier to fish passage under most or all flow circumstances was located 40 ft upstream of the Highway 96 culverts (Photo 1). The barrier is a steep bedrock chute that would require a jump height of 4.6 ft in addition to a lateral jump distance of 7.5 ft (Table 5). Water at the base of the barrier is shallow (0.7 ft) and fast, providing insufficient space for a fish to accelerate to make the difficult jump. Another probable barrier to upstream passage follows only one channel unit upstream, and again has a shallow jump pool (0.5 ft) to make a jump 4 ft high and 4 ft laterally over a bedrock cascade. Two additional obvious barriers to fish passage were found further upstream with jump heights of 6 ft above jump pools with only 0. 5 ft and 2 ft of depth (Photos 2 and 3). None of these potential barriers had a nearby pinch point in the channel downstream that might create a backwater at high flow to improving jumping conditions.

**Table 5.** Location and dimensions of potential impediments to upstream fish passage in Stanshaw Creek. Channel unit numbers can be seen in sequence in Appendix 2.

| | | Jump Distance | | Jump Pool | |
|---|---|---|---|---|---|
| Unit # | Distance Down (ft) | Height (ft) | Lateral (ft) | Depth (ft) | Notes |
| 20 | 4,066 | 3.4 | 0 | 1.4 | |
| 32 | 3,543 | 4 | 1.5 | 2.2 | Falls over giant log |
| 35 | 3,419 | 6 | 2 | 2 | |
| 46 | 2,863 | 6 | 0 | 0.5 | Boulder falls. Rapids at base. No pool. |
| 53 | 2,547 | 4.6 | | 1.5 | Obstacles in jump path. |
| 67 | 1,416 | 4 | 4 | 0.5 | No jump pool - rapid across bedrock. |
| 69 | 1,308 | 3 | 6 | 2.3 | |
| 71 | 1,288 | 4.6 | 7.5 | 0.7 | 3 ft ht. Lead in 7 ft long bedrock chute |
| 89 | 66 | 3 | 1 | 0.5 | Man-made rock dam 15 inches high to enhance upstream pool. Riffle below |

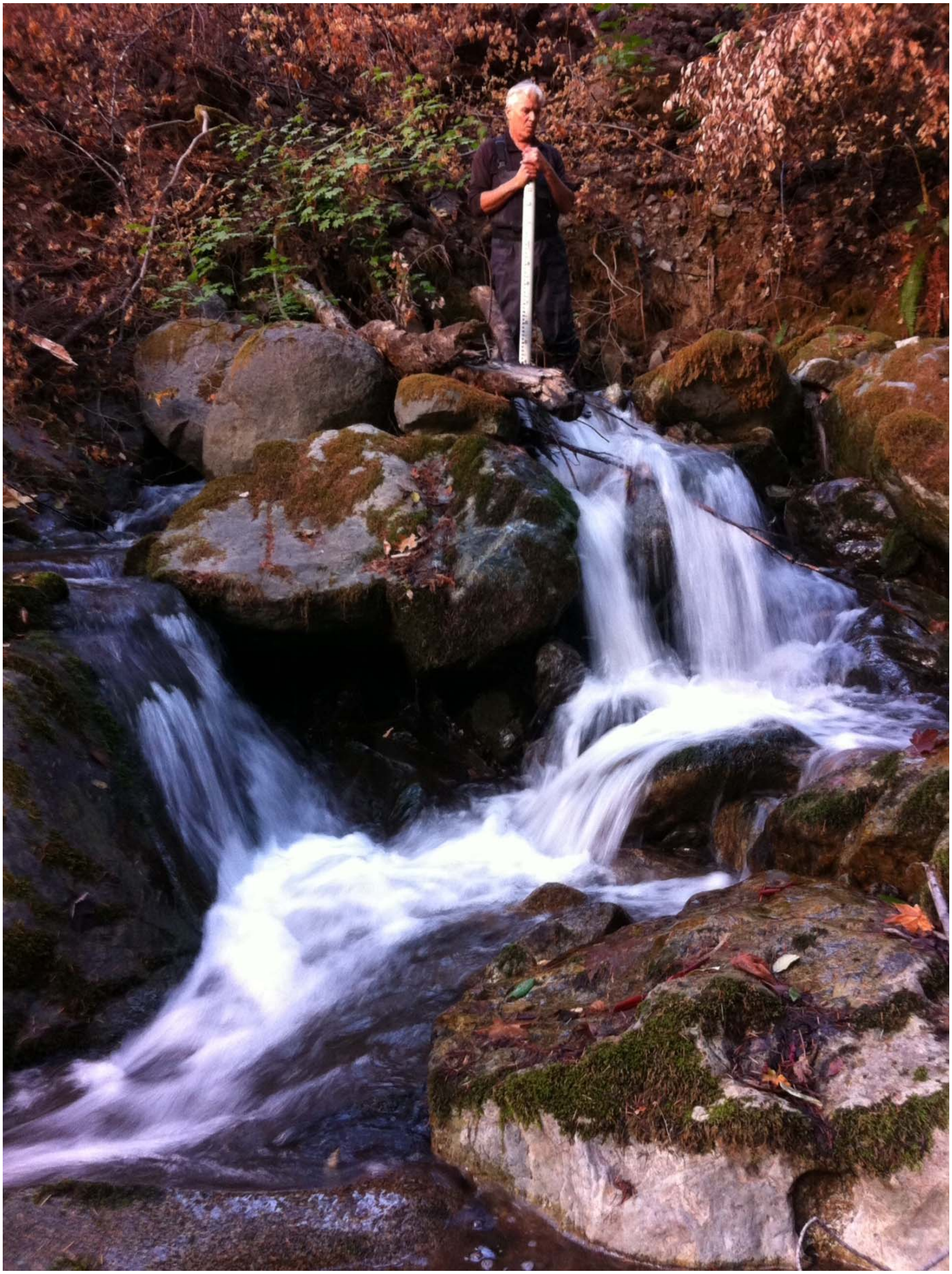

**Photo 1. Portion of falls and bedrock chute immediately upstream of the Highway 96 culverts on Stanshaw Creek.**

**Photo 2. Falls with 4 ft jump height and a 2 ft deep pool at the base.**

**Photo 3. Falls with 6 ft height and >2 ft lateral with not jump pool at base.**

The estimated carrying capacity of Stanshaw Creek below Highway 96 for age 1+ steelhead parr is only 36 fish (Table 6). Age 1+ parr must still survive through the winter before smolting, and typical winter survival is about 50%. That would leave 18 smolts at capacity. If we very generously assume smolt-to-return survival of 10%, then the18 smolts could produce 2 returning adults. A population with that low of production is not sustainable, because a few years of below average survival will lead to zero returns.

**Table 6**. Estimated rearing capacity for age 1+ steelhead parr in each channel unit of Stanshaw Creek below the Highway 96 crossing. Unit type, depth, and surface area were the input variables used to calculate rearing capacity. Assigned parr densities and habitat scalars are those described by Cramer and Ackerman (2009) (Appendix 3). Note that all dimensions are converted here to meters rather than feet.

| Habitat Type | Length (m) | Mean Width (m) | Mean Max Depth (m) | Area ($m^2$) | Parr density per $m^2$ | Depth Scalar | Parr Capacity |
|---|---|---|---|---|---|---|---|
| Pool | 7.3 | 4.0 | 0.4 | 29.0 | 0.170 | 0.54 | 3 |
| RI-RA | 46.3 | 1.5 | 0.4 | 70.6 | 0.043 | 1.00 | 3 |
| Pool | 4.3 | 3.0 | 0.6 | 13.0 | 0.170 | 0.92 | 2 |
| RI-RA | 48.8 | 1.5 | 0.4 | 74.3 | 0.043 | 1.00 | 3 |
| Pool | 4.3 | 2.4 | 0.6 | 10.4 | 0.170 | 0.86 | 2 |
| RI-RA | 28.3 | 1.5 | 0.4 | 43.2 | 0.043 | 1.00 | 2 |
| Pool | 5.5 | 2.4 | 0.5 | 13.4 | 0.170 | 0.81 | 2 |
| RI-RA | 18.3 | 1.5 | 0.4 | 27.9 | 0.043 | 1.00 | 1 |
| Pool | 5.5 | 3.4 | 0.7 | 18.4 | 0.170 | 1.13 | 4 |
| Riffle | 10.1 | 1.5 | 0.4 | 15.3 | 0.043 | 2.95 | 2 |
| Pool | 3.7 | 2.1 | 0.5 | 7.8 | 0.170 | 0.81 | 1 |
| Rapid | 6.1 | 1.5 | 0.4 | 9.3 | 0.043 | 1.00 | 0 |
| Pool | 3.0 | 2.4 | 0.7 | 7.4 | 0.170 | 1.08 | 1 |
| RI-RA | 103.9 | 1.5 | 0.4 | 158.4 | 0.043 | 1.00 | 7 |
| Pool | 4.0 | 3.4 | 0.8 | 13.3 | 0.170 | 1.19 | 3 |
| RI-RA | 20.1 | 1.5 | 0.4 | 30.7 | 0.043 | 1.00 | 1 |
|  |  |  |  |  | **TOTAL** |  | **36** |

## Stanshaw Pond

The floodplain pond was oval in shape, measuring 159 ft long and 91 ft wide. It had an island in the middle that was roughly 30 ft x 20ft. Water depth ranged from a maximum of 4 ft to about 1.5 ft in portions farthest from the creek entry point.

One of my assistants in a wetsuit snorkeled the pond to observe fish on October 3, 2017. He made two slow circuits around the pond, with a 10-minute rest before the second circuit repeating the same path.

He observed 9 juvenile steelhead (age 0+) and 2 Coho (age 0+) on the first circuit. After waiting about 10 minutes, he made a second circuit and counted 15 juvenile steelhead (14 age 0+ and 1 age 1+). Most fish ere in groups and it appeared he saw mostly the same fish on the two circuits. Given the slight variance in counts, it is likely that he observed at least half of the fish present. Thus, the pond likely contained less than 5 Coho and 30 steelhead juveniles.

The morphology of Stanshaw Creek changes dramatically as it enters onto the Klamath floodplain before reaching the floodplain pond. Right up to the edge of the floodplain, the channel is incised between confining hillslopes on both sides, and well shaded by dense riparian foliage and trees. Entering onto the Klamath floodplain is like stepping out of an enclosed rough hallway onto a wide open rocky beach that slopes moderately to the Klamath River. The channel immediately becomes braided and spreads out on the floodplain. There are not trees and only occasional bushes.

Of the streamflow arriving from Stanshaw Creek at the Klamath floodplain, about two thirds of the flow on October 3, 2017 was **not** entering the pond, but was flowing straight across the cobbles and sand bar to the Klamath River. All flow that was entering the pond was artificially directed there by hand built rock berms that formed miniature levees leading water to the pond (Photos 1-3). This berm was no more than a few cobbles high, and would be completely washed away by high flows from Stanshaw Creek during fall through spring. The confined channel of Stanshaw Creek is not directed at the pond, but is directed about 45° to the left looking downstream (to right in Photo 1 looking upstream). Thus, flow entering the Klamath floodplain must make a sharp right turn to reach the pond, which is located about 45 feet to the sharp right of the floodplain entry point.

Thus, it appears that flow from Stanshaw Creek to the off-channel floodplain pool requires constant work by humans to redirect some of the low-season flow to the pool. Without the rock berms and the rock dam across the pond outlet, most or all of flow from Stanshaw Creek would not have flowed to the pond. More flow will not cure this situation, but rather will tend to wash out or expand gaps in the man-made rock berms.

The extensive berms of hand-stacked rocks, while directing flow to the pool, were also blocking any fish passage between the pool and the Klamath River. Absent the berms, fish access to the creek and pond would likely have been possible, although it is hard to determine what the pond and multi creek channels would look like without the extensive berms. I carefully inspected all flow paths out of the pond, and they all passed through pores in the stacks of rocks, such that the artificially place rocks blocked fish passage to the pond. An especially tall berm of rocks was stacked at the pond outflow (perhaps as part of the restoration), and flow emerged through the rocks rather than over it (Photo 4). Thus, there was more than sufficient flow from Stanshaw Creek to enable juvenile salmonids to access the stream and pond, but the constructed rock berms that allow seepage back to the river were blocking any fish access to or from the Klamath River. Clearly, removal of the rock berms, rather than providing more flow from Stanshaw Creek, was the answer for providing fish access between the pond, the creek, and the Klamath River.

Photo 1. View looking upstream at the location where Stanshaw Creek emerges from its confined channel and enters the active floodplain of the Klamath River. The velocity energy of the channel is toward the right in this picture, but rocks were hand-placed at the head of that channel to block its flow, and a continuing berm of rocks was placed along flow directed toward the left in this picture. The floodplain pond is about 45 feet to the left and 5 to 8 feet downslope from this picture. The next photo shows the view down one of two channels directed to the pond.

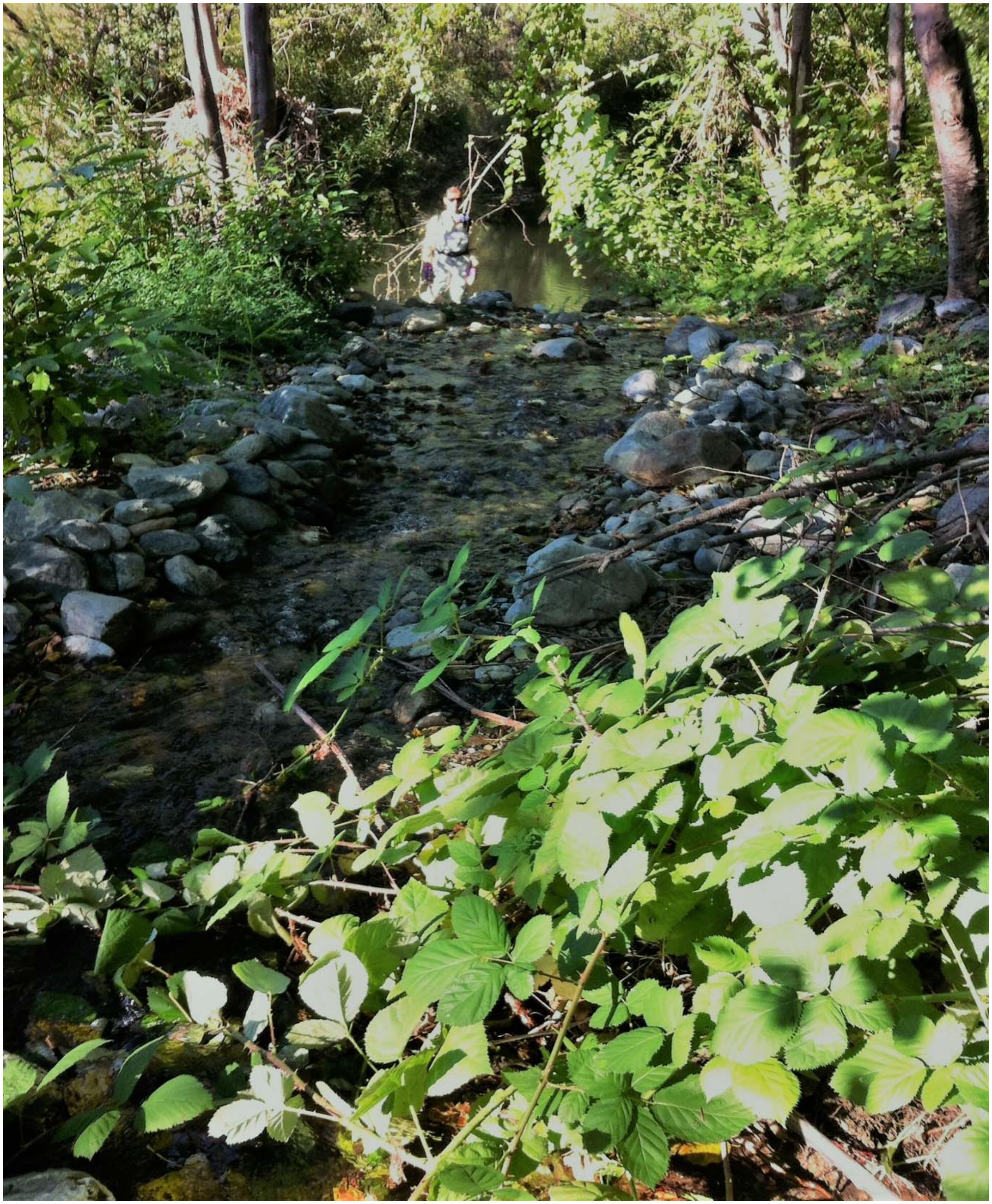

Photo 2. Berm-lined channel leading some of Stanshaw Creek flow to the floodplain pond. This is one of two channels directed by hand-built berms to the pond. The person in this picture is standing at the edge of the pond.

Photo 3. Downstream view of second berm-lined channel directing portion of Stanshaw Creek flow to the floodplain pond. The pond outflow, obscured by bushes, is to the left. Note the flow going under the rock berm to the left. That flow passes directly to the Klamath River

Photo 4. Rock berm at the floodplain pond outflow. I am standing in Klamath River backwater where some of Stanshaw Creek flows emerge through the rock berm to enter the Klamath. None of the flow exiting from the pond flowed out over the surface where fish could pass.

### Stanshaw Flow

As expected, velocities and depths increased at our cross section (Figure 1) with the first modest increase in flow. On October 20 at an estimated flow of 14.2 cfs, most of the riffle is less than 6 inches deep and velocities already reach 4 ft/sec or more across almost half the channel (Tables 7 and 8). These are shallower depths and faster velocities than preferred by juvenile salmonids. We chose this location because it was one of the few distinct riffles in stream, and riffle has slower velocity that either rapid or a cascade. So, riffles are the next best opportunity for juvenile rearing, a distant second to pools. But what these measurements indicate is that conditions for rearing juvenile salmonids are declining, rather than improving, as flows increase. Due to the effects of high gradient, velocities will increase quickly with further increases in flow, and Stanshaw Creek will become a very difficult environment for juvenile salmonids to survive in through the winter.

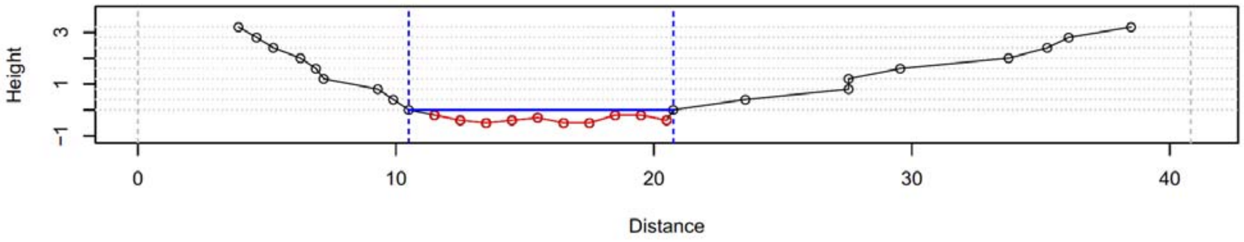

Figure 1. Upstream view of Stanshaw Creek cross section measured October 4, 2017 on channel unit 6, a riffle 73 ft downstream from the point of diversion. Drawn to scale. Red line and dots show submerged portion of channel. Dashed blue vertical lines are edges of the wetted channel. Distance is measured from pin on river right bank (left side of this graph).

**Table 7.** Flows in Stanshaw Creek estimated on three dates at the channel cross section established October 4, 2017.

| Date | Flow (cfs) |
|---|---|
| 10/4/2017 | 5.3 |
| 10/13/2017 | 7.2 |
| 10/20/2017 | 14.2 |

**Table 8.** Measured depths and velocities on three dates at the cross section established October 4, 2017. There was a rain event associated with increases flows on October 20. Note that depths and velocities both increased but wetted width increased only a few tenths of a foot.

| | | |
|---|---|---|
| **DATE: 10/4/17** | | |
| **Width Increment (ft)** | **Depth (tenths of ft)** | **Velocity (ft/sec)** |
| **1** | 0.2 | 0.0 |
| **2** | 0.4 | 1.6 |
| **3** | 0.5 | 0.5 |
| **4** | 0.4 | 3.0 |
| **5** | 0.3 | 0.5 |
| **6** | 0.5 | 0.0 |
| **7** | 0.5 | 4.6 |
| **8** | 0.2 | 0.4 |
| **9** | 0.2 | 1.3 |
| **10** | 0.4 | 1.0 |
| **Average** | **0.4** | **1.3** |

| | | |
|---|---|---|
| **DATE: 10/13/17** | | |
| **Width Increment (ft)** | **Depth (tenths of ft)** | **Velocity (ft/sec)** |
| **1** | 0.2 | 0.0 |
| **2** | 0.6 | 2.6 |
| **3** | 0.5 | 5.2 |
| **4** | 0.3 | 0.0 |
| **5** | 0.2 | 0.3 |
| **6** | 0.4 | 3.3 |
| **7** | 0.4 | 2.5 |
| **8** | 0.0 | 0.0 |
| **9** | 0.2 | 0.3 |
| **10** | 0.4 | 1.6 |
| **Average** | **0.3** | **1.7** |
| | | |
| **DATE: 10/20/17** | | |
| **Width Increment (ft)** | Depth (tenths of ft) | Velocity (ft/sec) |
| **1** | 0.4 | 1.0 |
| **2** | 0.7 | 3.4 |
| **3** | 0.5 | 5.9 |
| **4** | 0.4 | 0.3 |
| **5** | 0.2 | 0.0 |
| **6** | 0.3 | 4.4 |
| **7** | 0.6 | 3.5 |
| **8** | 0.4 | 4.9 |
| **9** | 0.5 | 4.2 |
| **10** | 0.4 | 2.3 |
| **Average** | **0.4** | **3.0** |

### Irving Creek

Our measurements revealed there was similar composition of channel units in Irving Creek to that in Stanshaw Creek (Table 9), but Irving Creek wider and deeper on average. The temperature in Irving Creek during our survey was 9C.

**Table 9.** Total length (feet) composed by different channel unit types in Irving Creek extending downstream to the point of entry onto the Klamath River floodplain.

| Habitat Type | Stream | Total Length | Percent |
|---|---|---|---|
| Pool | Irving | 146 | 5 |
| SP | Irving | 15 | 0 |
| RUN | Irving | 48 | 2 |
| RI | Irving | 83 | 3 |
| RA | Irving | 36 | 1 |

| | | | |
|---|---|---|---|
| C | Irving | 50 | 2 |
| RI-RA | Irving | 2645 | 87 |
| **Total** | | **3023** | **100** |

**Table 10.** Mean dimensions (feet) for each channel unit type measured in Irving Creek. "N" represents the number of units measured.

| Habitat Type | Stream | Mean Length | Mean Width | Mean Depth | Area ($ft^2$) | N |
|---|---|---|---|---|---|---|
| Pool | Irving | 30.5 | 13.1 | 2.5 | 399.5 | 4 |
| Riffle | Irving | 41.5 | 13.1 | 1.5 | 598.5 | 2 |
| Run | Irving | 48 | 11.5 | 1.7 | 552 | 1 |
| Step Pool | Irving | 15 | 13 | 3.8 | 195 | 1 |

### Irving Creek Floodplain

Irving Creek enters onto the Klamath River floodplain about one mile downstream from the mouth of Stanshaw Creek. Although the stream braided into numerous channels upon entry to the floodplain, at least one of the small channels formed a small pond within a clump of rooted vegetation on the floodplain (Photo 5). We observed fish darting for cover in the pond as we approached.

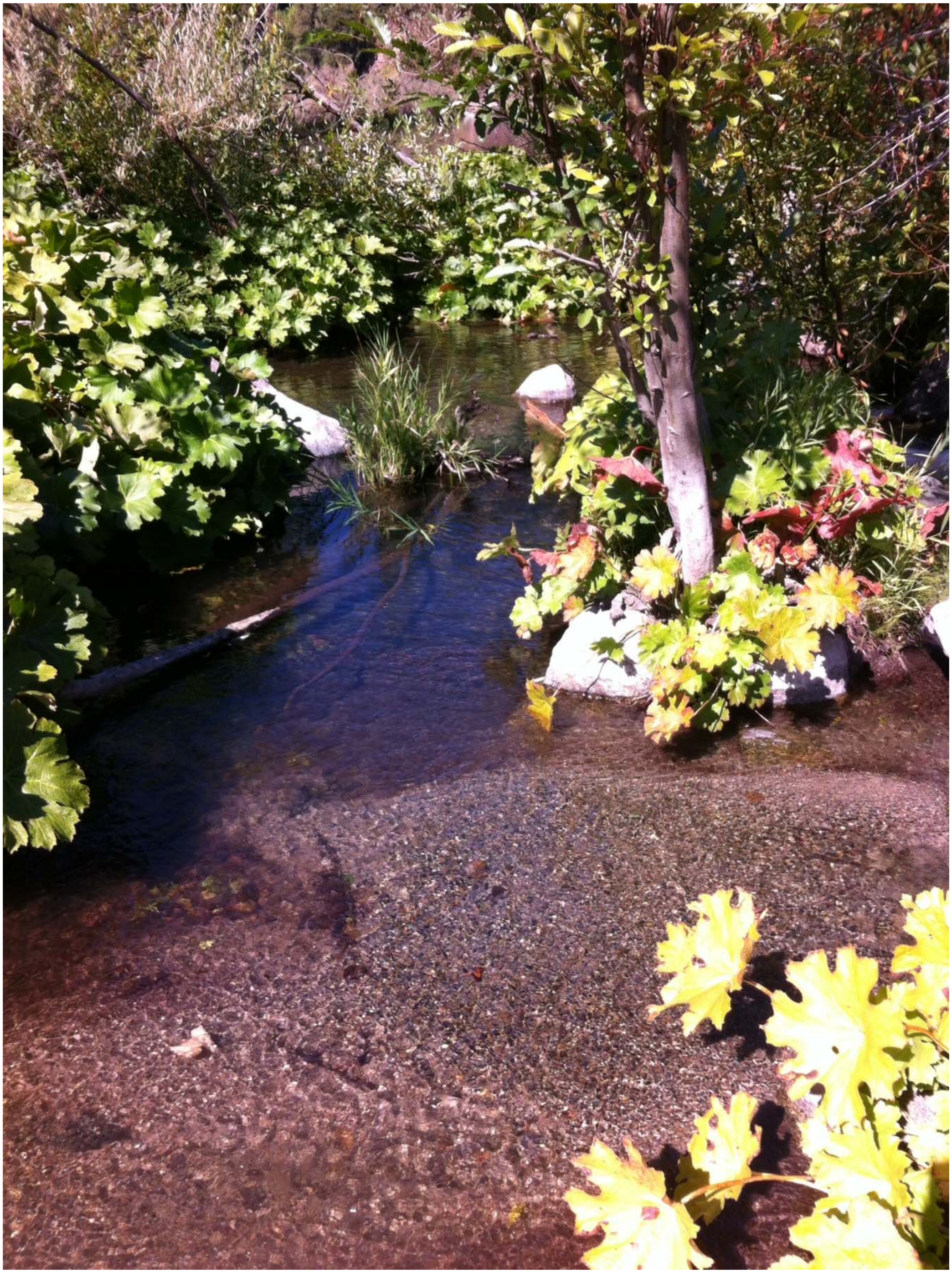

Photo 5. Floodplain pond at mouth of Irving Creek. This pond was about 30 ft from the Klamath River and was fed by one of many braided channels proceeding from the creek across the Klamath River floodplain. Fish were observed darting in pool

# Discussion

## Value of Creek for rearing

While the pool that Stanshaw Creek feeds on the Klamath River floodplain provides desirable habitat for a small number of juvenile salmonids, the results of my habitat survey and that of Taylor (2015) confirm that the remainder of Stanshaw Creek provides minimal habitat for salmonids.

## Off-channel Pond

We observed only 2 Coho in the Stanshaw pond. Substantially higher numbers have been observed during years that Marble Mountain Ranch operated its hydro plant in typical manner than in any years since the habitat restoration project and the absence of hydro diversion by Marble Mountain Ranch. I note that the Karuk tribe observed 156 juvenile Coho in the creek in 2005, 130 in 2008, and 55 in 2010. Whitmore estimate 120 were present in the floodplain pond in 2012. All of those observations were made before hydro plant operations were diminished.

The Yurok Tribe has been researching fish use of cold-water tributaries entering the Klamath River for a number of hears. Strange (2011) summarizes the findings of their work as follows:

> "*Salmonid use of thermal refuges during 2010 at the index sites was dominated by young-of-the-year Chinook salmon and 1+ steelhead as typical." "Depth, velocities, velocity cover, escape cover, and levels of human visitation are all notable features of thermal refuges that have been observed to strongly influence the use of a given thermal refuge by salmonids. The water temperature and flow rate of the thermal refuge forming tributary are also important, but in the collective experience of YTFP researchers, the features listed above tend to override the influence of the tributary inflow. For example, the Red Cap Creek thermal refuge had very low observed counts of salmonids in 2010 and featured shallow depth, relatively high velocities, and poor cover quality. In contrast, during previous study years the mouth of Red Cap Creek was configured differently resulting in great depth and low velocities with consistently high abundances of salmonids (Benson and Holt 2006). As another example, Elk Creek has a large volume of cool water inflow but very low observed abundances of salmonid use (Belchik 2003), which corresponds with its consistent extreme lack of cover, relatively high velocities, and shallow depth. YTFP researchers have also observed reduced fish counts and fish leaving thermal refuges with high quality features that also had heavy human visitation and use (typically for swimming and fishing), such as at Horse Linto Creek on the Trinity River and Indian Creek on the Klamath River."*

The index thermal refuges that we surveyed by Strange (2011) during the summer of 2010 were Red Cap (rkm 85), Bluff (rkm 80), Tully (rkm 61.5), and Cappel (rkm 53) creeks. Strange (2011) also notes, "No coho were observed using the index thermal refuges during the 2010 study, consistent with previous study years' results."

## Conclusions

1. I agree that the floodplain pool fed by Stanshaw Creek near its confluence with the Klamath River provides refuge habitat during summer and winter for juvenile salmonids that enter from the Klamath River. As identified by NMFS, the key months during which juvenile salmonids will seek access to this refuge are in the spring during May and June, and again in the fall and winter when streamflows rise in response to rainfall.
2. Access to the floodplain pool should be possible at flows between 2 and 3 cfs and greater, if people are prevented from building rock berms that passage of fish in and out of the pond and creek. Natural variation in flow will provide substantially more flow than this minimum during multiple episodes in most spring and fall seasons.
3. Access to the floodplain pool in summer provides little added benefit to salmonid populations, because few fish move at that time.
4. Stanshaw Creek is not suitable for spawning of Coho salmon;
5. Stanshaw Creek is unlikely to support a self-sustaining population of steelhead, although small numbers could be supported in some water years;
6. Stanshaw Creek appears to support a small population of small-sized resident trout, although these may be fish that came down from sources in the upper watershed.

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**Appendix 1. Description of channel unit types.**

| Habitat type | Characteristics |
|---|---|
| | |
| Cascade | A series of small steps of alternating small waterfalls and small pools. |
| Rapid | A shallow fast-water unit with high turbulence and whitewater surface |
| Riffle | A unit with discernable gradient and surface turbulence. |
| Glide | A fast-water unit with no pronounced turbulence and relatively homogenous depth. |
| Run | A fast-water unit with no pronounced turbulence and distinctly greater depth down the thalweg. |
| Pool | A slow water unit a unit with no surface turbulence, except at the inflow, and has depth extending below the plane of the streambed |
| Step pool | A basin scoured by a vertical drop over a channel obstruction. |
| Alcove | A slack water unit extending laterally from the channel margin separated from the main current. |
| Beaver Pond | A pool impounded by a beaver dam |
| Backwater pool | An eddy or slack water along the channel margin separated from the main current by a gravel bar or small channel obstruction. |

Appendix 2. Channel unit measurements for Stanshaw Creek on October 2, 2107, starting with unit 1 at the point of diversion.

| Unit # | Habitat Type | Length | Width 1 | Width 2 | Width 3 | Depth 1 | Depth 2 | Depth 3 | Falls Height + jump pool depth | Jump Pool Depth | Jump Height | Jump Lateral Length | Fines | Gravel sm | Gravel md | Gravel lg | Cobble | Boulder | Bedrock | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | RA | 14.6 | 1.6 | 6 |  | 0.8 | 1 |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.3 | 0.7 | 0 |  |
| 2 | P | 19 | 7 | 7.5 |  | 1.20 | 0.50 |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | Step pool |
| 3 | SP | 13.9 | 10 | 6.5 |  | 1.20 | 1.05 |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | Step pool |
| 4 | RA | 10.6 | 6.5 |  |  |  |  |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.1 | 0.9 | 0 |  |
| 5 | P | 14.6 | 6.8 | 6 |  | 0.65 | 1.10 |  |  |  | 0 |  | 0 | 0 | 0.1 | 0 | 0.3 | 0.6 | 0 |  |
| 6 | RI | 12 | 6 |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |
| 7 | SP | 13 | 8 | 9 |  | 1.00 | 1.60 |  |  |  | 0 |  | 0 | 0.3 | 0 | 0 | 0.5 | 0.2 | 0 |  |
| 8 | SP | 13 | 6.5 | 9 |  | 0.40 | 1.90 |  |  |  | 0 |  | 0 | 0 | 0.2 | 0 | 0.3 | 0.5 | 0 | Return flow enter |
| 9 | RI | 14 | 8 | 8 |  | 0.40 | 1.00 |  |  |  | 0 |  | 0 | 0 | 0 | 0.2 | 0.4 | 0.4 | 0 |  |
| 10 | RI | 26 | 9 | 8 |  | 0.50 | 0.80 |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.8 | 0.2 | 0 |  |
| 11 | C | 40 |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |
| 12 | C | 40 |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |
| 13 | P | 7.5 | 6 |  |  | 1.30 |  |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.4 | 0.6 | 0 |  |
| 14 | RI | 45 | 4.4 | 8.1 |  | 0.80 | 0.10 |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 |  |
| 15 | RI | 21 |  |  |  |  |  |  |  |  | 0 |  | 0 | 0 | 0.1 | 0.2 | 0.2 | 0.5 | 0 |  |
| 16 | P | 21 | 6.5 | 6 |  | 0.80 | 1.50 |  |  |  | 0 |  | 0 | 0.2 | 0 | 0 | 0.6 | 0.2 | 0 |  |
| 17 | RA | 54 |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |
| 18 | P | 12 | 7 | 7.50 |  | 1.30 | 1.60 |  |  |  | 0 |  | 0.2 | 0 | 0 | 0 | 0.3 | 0.5 | 0 |  |
| 19 | RI | 33 | 14 | 11.00 |  | 0.50 |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |
| 20 | JUMP |  |  |  |  |  |  |  | 4.8 | 1.4 | 3.4 | 0 |  |  |  |  |  |  |  |  |
| 21 | C | 17 |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  |  |
| 22 | P | 20 | 10 | 7.00 |  | 0.60 | 1.40 |  |  |  | 0 |  | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 |  |
| 23 | C | 120 |  |  |  |  |  |  |  |  | 0 |  |  |  |  |  |  |  |  | Buried under burnt, fallen wood. Lots fo fines in substrate. |

| Unit # | Habitat Type | Length | Width 1 | Width 2 | Width 3 | Depth 1 | Depth 2 | Depth 3 | Falls Height + jump pool depth | Jump Pool Depth | Jump Height | Jump Lateral Length | Fines | Gravel sm | Gravel md | Gravel lg | Cobble | Boulder | Bedrock | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | RI-RA | 55 | | | | | | | | | 0 | | | | | | | | | |
| 25 | RI-RA | 69 | | | | | | | | | 0 | | | | | | | | | |
| 26 | P | 17.5 | 5.5 | 10.00 | | 1.10 | 2.10 | | | | 0 | | 0 | 0 | 0.2 | 0 | 0.5 | 0.3 | 0 | No patches |
| 27 | C | 36 | | | | | | | | | 0 | | | | | | | | | |
| 28 | P | 33 | 7.3 | 9.00 | | 1.00 | 1.40 | | | | 0 | | 0.4 | 0 | 0.3 | 0 | 0.1 | 0.2 | 0 | Gravel 2 by 20'. 3-6" high. Embedded. Unconsolidated. |
| 29 | SP-RA | 100 | | | | | | | | | 0 | | | | | | | | | |
| 30 | RI | 42 | | | | | | | | | 0 | | | | | | | | | |
| 31 | RI | 13 | | | | | | | | | 0 | | | | | | | | | |
| 32 | JUMP | | | | | | | | 6.2 | 2.2 | 4 | 1.5 | | | | | | | | Giant log. See photo |
| 33 | C | 33 | | | | | | | | | 0 | | | | | | | | | |
| 34 | RI-RA | 91 | | | | | | | | | 0 | | | | | | | | | |
| 35 | JUMP | | | | | | | | 8 | 2 | 6 | 2 | | | | | | | | |
| 36 | RI-RA | 74 | | | | | | | | | 0 | | | | | | | | | |
| 37 | C-RA | 44 | | | | | | | | | 0 | | | | | | | | | |
| 38 | RI | 33 | | | | | | | | | 0 | | | | | | | | | |
| 39 | SP-RA | 75 | | | | | | | | | 0 | | | | | | | | | |
| 40 | P | 12 | 13 | | | 2.20 | | | | | 0 | | | | | | | | | |
| 41 | C-RA | 108 | | | | | | | | | 0 | | | | | | | | | |
| 42 | P | 12 | 13 | | | 2 | 1.5 | | | | 0 | | | | | | | | | |
| 43 | C-RA | 149 | | | | | | | | | 0 | | | | | | | | | |
| 44 | P | 16 | 10 | 6.5 | | 0.95 | 1.5 | | | | 0 | | | | | | | | | |
| 45 | RA | 33 | | | | | | | | | 0 | | | | | | | | | |
| 46 | JUMP | | | | | 0.5 | | | 6.5 | 0.5 | 6 | 0 | | | | | | | | Boulder falls. Rapids at base. No pool. |

| Unit # | Habitat Type | Length | Width 1 | Width 2 | Width 3 | Depth 1 | Depth 2 | Depth 3 | Falls Height + jump pool depth | Jump Pool Depth | Jump Height | Jump Lateral Length | Fines | Gravel sm | Gravel md | Gravel lg | Cobble | Boulder | Bedrock | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 47 | SP-RA | 34 | | | | | | | | | 0 | | | | | | | | | |
| 48 | P | 12 | 9.5 | 7.5 | | 1.4 | 1.4 | | | | 0 | | 0 | 0 | 0 | 0 | 0.5 | 0.5 | 0 | |
| 49 | C-RA | 84 | | | | | | | | | 0 | | | | | | | | | |
| 50 | C | 90 | | | | | | | | | 0 | | | | | | | | | |
| 51 | P | 10 | 7 | | | 1.3 | | | | | 0 | | | | | | | | | |
| 52 | RI-RA | 86 | | | | | | | | | 0 | | | | | | | | | |
| 53 | JUMP | | | | | | | | 6.1 | 1.5 | 4.6 | | | | | | | | | Obstacles in jump path. |
| 54 | P | 15 | 8 | | | 1.8 | | | | | 0 | | | | | | | | | Pool beneath above jump |
| 55 | C | 160 | | | | | | | | | 0 | | | | | | | | | |
| 56 | P | 12 | 8 | 10 | | 1.6 | 0.8 | | | | 0 | | | | | | | | | |
| 57 | RI-RA | 140 | | | | | | | | | 0 | | | | | | | | | 10x20 gravel patch 0-1 feet out of water at end of sequence. Mix of angular and |
| 58 | RI | 39 | 8.5 | 9 | 15 | 0.8 | 0.7 | 0.5 | | | 0 | | 0.2 | 0.3 | 0.2 | 0.2 | 0.1 | 0 | 0 | Lateral wall collide |
| 59 | RI-RA | 130 | | | | | | | | | 0 | | | | | | | | | Gravel patch 10x15 1-8 inches above water. Uneven. Undualting |
| 60 | RI-RA | 276 | | | | | | | | | 0 | | | | | | | | | |
| 61 | P | 10 | 8.5 | | | 1.6 | | | | | 0 | | | | | | | | | |
| 62 | RI-RA | 167 | | | | | | | | | 0 | | | | | | | | | |
| 63 | P | 15 | 7 | 10.5 | | 0.9 | 1.2 | | | | 0 | | 0.8 | 0 | 0.2 | 0 | 0 | 0 | 0 | Dry gravel bar 0-2 feet above lateral slope. |
| 64 | RI-RA | 108 | | | | | | | | | 0 | | | | | | | | | |
| 65 | P | 14 | 8.5 | 11 | | 1.5 | 1.7 | | | | 0 | | 0.8 | 0 | 0 | 0 | 0 | 0.2 | 0 | WCD covered |
| 66 | RI-RA | 45 | | | | | | | | | 0 | | | | | | | | | |
| 67 | JUMP | | | | | | | | 4.5 | 0.5 | 4 | 4 | | | | | | | | No jump pool - rapid across bedrock.. |
| 68 | C | 102 | | | | | | | | | 0 | | | | | | | | | |

| Unit # | Habitat Type | Length | Width 1 | Width 2 | Width 3 | Depth 1 | Depth 2 | Depth 3 | Falls Height + jump pool depth | Jump Pool Depth | Jump Height | Jump Lateral Length | Fines | Gravel sm | Gravel md | Gravel lg | Cobble | Boulder | Bedrock | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 69 | JUMP | 6 | | | | | | | 5.3 | 2.3 | 3 | 6 | | | | | | | | 3 ft up, 6 long. 2.3 deep. |
| 70 | P | 20 | 14 | 8 | 7 | 1.6 | 1.2 | 2 | | | 0 | | 0.5 | 0 | 0 | 0 | 0.4 | 0.1 | 0 | Pool at base of jump listed above |
| 71 | JUMP | | | | | | | | 5.3 | 0.7 | 4.6 | 7.5 | | | | | | | | Lead in 3 ft ht 7 ft long bedrock chute |
| 72 | P | 19 | 8 | 8 | | 0.9 | 2.4 | | | | 0 | | 0.5 | 0 | 0 | 0 | 0.4 | 0.1 | 0 | |
| 73 | RI | 21 | 10 | | | | | | | | 0 | | | | | | | | | |
| 74 | CULVE | 200 | | | | | | | | | 0 | | | | | | | | 0 | ESTIMATE. Not measured |
| 75 | P | 24 | 13 | | | 1.3 | | | | | 0 | | 0.3 | 0 | 0 | 0 | 0.5 | 0.2 | 0 | Colvert outfall |
| 76 | RI-RA | 152 | | | | | | | | | 0 | | | | | | | | | |
| 77 | P | 14 | 10 | | | 2 | | | | | 0 | | | | | | | | | |
| 78 | RI-RA | 160 | | | | | | | | | 0 | | | | | | | | | |
| 79 | P | 14 | 8 | | | 1.9 | | | | | 0 | | | | | | | | | |
| 80 | RI-RA | 93 | | | | | | | | | 0 | | | | | | | | | |
| 81 | P | 18 | 8 | | | 1.8 | | | | | 0 | | 0.3 | 0 | 0 | 0.3 | 0.2 | 0.2 | 0 | |
| 82 | RI-RA | 60 | | | | | | | | | 0 | | | | | | | | 0 | |
| 83 | P | 18 | 11 | | | 2.4 | | | | | 0 | | 0.3 | 0 | 0 | 0.2 | 0.5 | 0 | 0 | |
| 84 | RI | 33 | 5 | | | 1.2 | | | | | 0 | | 0 | 0.5 | 0 | 0.5 | 0 | 0 | 0 | Embedded .5 |
| 85 | P | 12 | 7 | | | 1.8 | | | | | 0 | | | | | | | | | |
| 86 | RA | 20 | | | | | | | | | 0 | | | | | | | | | |
| 87 | P | 10 | 8 | | | 2.3 | | | | | 0 | | | | | | | | | |
| 88 | RI-RA | 341 | | | | | | | | | 0 | | | | | | | | | |
| 89 | P | 13 | 11 | | | 2.5 | | | | | 0 | | | | | | | | | inches hi at center |
| | JUMP | | | | | | | | 3.5 | 0.5 | 3 | 1 | | | | | | | | Man-made rock dam 15 inches high to enhance upstream pool. Riffle below |
| 90 | RI-RA | 66 | | | | | | | | | 0 | | | | | | | | | |

**EXHIBIT A**

American Fisheries Society Symposium 71:255–288, 2009

# Prediction of Stream Carrying Capacity for Steelhead: the Unit Characteristic Method

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*Abstract.*—We describe and demonstrate the Unit Characteristic Method (UCM) as a means by which measurements of habitat from typical stream surveys can be used to estimate the capacity of a stream to rear juvenile steelhead *Oncorhynchus mykiss*. Channel unit features of importance include surface area by unit type, depth, substrate, and cover. The influence of a stream's primary productivity is represented in the method through measures of alkalinity and turbidity. We tested the fit of model predictions to juvenile steelhead production observed in seven watersheds ranging in size from 26 to 1,420 km$^2$. Model predictions of capacity were significantly correlated to observed maximum production of juvenile steelhead ($P < 0.005$, $R^2 = 0.88$), as was watershed area ($P < 0.005$, $R^2 = 0.88$). The UCM predictions revealed that parr capacity was unevenly distributed in the watersheds, and that habitat quality (smolt capacity/m$^2$) differed between reaches among all watersheds by up to 15-fold across seven basins surveyed, and ranged more than 10-fold between reaches within four of seven test watersheds. Thus, the UCM can be used to discriminate stream reaches and features that either warrant habitat restoration or conservation. Key factors driving high or low habitat quality differed between reaches, and included pool area, riffle depth, boulder substrate, alkalinity, fine sediment, and turbidity. The UCM provides a framework for understanding the habitat features that determine the production potential of a basin, for identifying factors that limit production, and for predicting potential fish benefits from differing habitat management strategies.

## Introduction

### *Problem and Need*

The need to accurately estimate carrying capacity of streams for salmonids has been accentuated by the recent focus on assessing population viability and planning for recovery of salmon and steelhead populations listed under the Endangered Species Act (ESA). This focus on restoring healthy fish populations has placed a burden on resource managers to choose among competing proposals designed to restore stream habitats, restore fish passage, reduce harvest, or alter the use of hatchery fish. More than ever, resource managers need a reliable basis for determining which combination of projects will provide the greatest benefits to targeted fish

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populations. Estimation of fish benefits from each strategy relies on accurate knowledge of the suite of factors, and the magnitude of influence from each, that determine a stream's capacity to produce the species of interest. Further, this same knowledge is needed to determine how a population is performing relative to its potential in a given basin.

Fisheries managers are often frustrated by the poor precision of carrying capacity estimates derived from stock-recruitment relationships, and the high cost of estimating all components of adult recruitment restricts data collection to a few streams. The estimation of stream carrying capacity has long been a foundation of assessments and strategies for managing salmon and trout populations, primarily as a parameter of stock-recruitment functions that predict harvestable surpluses (Beverton and Holt 1957: Ricker 1975). The traditional approach for estimating carrying capacity has been to fit a relationship between adult recruits and the number of parents that spawned them. This approach requires a long time series of data, but such data are lacking for the great majority of salmonid-producing basins. Even when the data are available, the statistical fit, and thus the confidence in capacity estimates, is often poor (Cramer 2000). Further, the statistical approach is not helpful for identifying the specific habitat factors that are limiting the population, nor in estimating the benefits from selected stream alterations in a small portion of the watershed.

The joint need to estimate (1) carrying capacity and (2) fish benefits from specific habitat changes, highlights the value of developing methods to estimate salmonid carrying capacity directly from measurements of stream habitat features. Cramer and Ackerman (2007) describe the Unit Characteristic Method (UCM) as an analytical framework intended to fill these needs. In this chapter, the UCM to predict carrying capacity of steelhead (anadromous rainbow trout) *Oncorhynchus mykiss* is described and tested in seven basins ranging in size from 26 to 1,420 km$^2$. Data from state and federal agencies on stream features and juvenile steelhead abundance are used to determine the fit of predicted to observed smolt production at carrying capacity. Results from these test basins are used to evaluate the sensitivity of UCM to the different habitat factors it includes, and to evaluate variation in habitat quality for producing steelhead within and between basins.

## *Approach*

The UCM quantifies stream carrying capacity for salmonids in terms of stream features that can be targeted by actions to conserve or restore habitat, and are measured during stream habitat surveys that follow protocols typical of most natural resource agencies. Hawkins et al. (1983) noted from their review of studies on channel unit classifications that, "variation in the structure and dynamics of the physical environment are primary factors affecting production and diversity of stream biota." Further, "differences in habitat quality among channel units are often associated with differences in morphology (e.g., depth, width, shape), water velocity (hydraulics) and bed roughness (substrate size)." The UCM is based on empirical evidence of relationships between fish production and driving factors such as those noted by Hawkins et al. (1983), and utilizes stream inventory data as model inputs. The UCM is similar to the method used by Nickelson (1998), who described methods for estimating stream capacity for rearing juvenile coho based on the area of channel unit types.

We define stream carrying capacity as the maximum number of juveniles that a stream can produce under average environmental conditions for the juvenile life stage most limited by availability of suitable space. This definition recognizes that realized maximum production will vary temporally with environmental conditions, and that the life stage most constrained by space may vary between streams. Capacity is generally most constrained for steelhead during summer for age >1 parr (Bjornn 1978; Everest et al. 1987; Reeves et al. 1997; Cramer and Ackerman 2007), thus this is the season and life stage targeted by the UCM for predicting capacity.

In some instances, availability of overwinter habitat may limit production (Solazzi et al. 2000; Solazzi et al. 2002). Accordingly, a winter capacity function is included in the UCM in case the number of parr entering the winter exceeds the capacity of winter habitat.

## Methods

### *Model development and structure*

A combination of literature search, researcher interviews, and findings from our own field studies was used to assemble data from which parameters could be estimated to relate maximum rearing densities to habitat features. Habitat features incorporated into the model included those features that can be, and typically are, measured during stream survey inventories conducted by government agencies (e.g., USFS 1999; Pleus et al. 1999; Moore et al. 2002). In addition, the water quality variables of turbidity and alkalinity are included within the model, and regional samples of these parameters are generally available through state and federal agencies.

The UCM assigns a standard density of age >1 parr to each unit type, and then increments or decrements that density according to the amount that habitat features of channel size, substrate, depth, and cover deviate from the model's expected value. The combined capacity of units within a reach is then scaled by factors affecting productivity. That is:

(1) $\text{Capacity}i = (\Sigma\, area_k \cdot den_j \cdot chnl_{jk} \cdot dep_{jk} \cdot cvr_{\text{jk}}) \cdot prod_i$;

Where

*Capacity* = maximum number of age >1 parr supported under average environmental conditions,

$i$ = stream reach. "Reach" is a sequence of channel units that compose a geomorphically homogenous segment of the stream network,

$j$ = channel unit type,

$k$ = individual channel unit,

*area* = area ($m^2$) of channel unit k,

*den* = standard fish density (fish/$m^2$) for species $i$ in unit type $j$,

*chnl* = discount scalar for unproductive portions of large channels with expected value of 1.0,

*dep* = depth scalar with expected value of 1.0,

*cvr* = cover scalar with expected value of 1.0, and

*prod* = productivity scalar for the reach, with expected value of 1.0. This scalar combines the separate effects from four additional factors defined in equation (2).

Variables that are represented as scalars having an expected value of 1.0 in this function are defined by a separate function that relates that variable to fish density. These scalars represent proportional changes to parr density compared to the standard fish densities (*den*). The value of the variable when the scalar is 1.0 represents the average value of that variable for the data set from which the standard fish density was determined. For example, the standard densities for steelhead parr (Table 1) are taken

Table 1. Formulas, definitions and values of variables and parameters used in the UCM.

| Parameter/Function | | Value/Equation | Source(s) |
|---|---|---|---|
| *den (fish/m$^2$)* | | | |
| | Backwaters | 0.05 | Johnson et al. 1993 |
| | Beaver Ponds | 0.07 | |
| | Cascades | 0.03 | |
| | Glides | 0.08 | |
| | Pools | 0.17 | |
| | Rapids | 0.07 | |
| | Riffles | 0.03 | |
| *chnl* | | | |
| | Glides | If $W > 24$: $(W - 24)*0.35/W + 24/W$ | Cramer et al. 1998; |
| | Pools | If $W > 24$: $(W - 24)*0.75/W + 24/W$; and | O'Neal and Cramer 1999; |
| | | If $L > 4*W$: $L = 4*W$ | Romey et al. 2001 |
| | Riffles | If $W > 24$: $(W - 24)*0.15/W + 24/W$ | |
| *dep* | | | |
| | Pools | If $D$ is $<0.10$: $0.0*D$ | Beecher et al. 1993; |
| | | If $D$ is $0.10 - 0.80$: $(0.30*D - 0.027)/0.17$ | Dambacher 1991; |
| | | If $D$ is $>0.80$: $0.22/0.17$ | Bisson et al. 1998; |
| | Riffles | If $D$ is $<0.1$: $0.0*D$ | et al. 1995; |
| | | If $D$ is $0.10 - 0.16$: $(0.5*D - 0.050)/0.03$ | Bovee 1978; |
| | | If $D$ is $0.16 - 0.30$: $(0.29*D - 0.017)/0.03$ | D. B. Lister and |
| | | If $D$ is $0.30 - 0.80$: $(0.25*D - 0.003)/0.03$ | Associates, unpublished |
| | | If $D$ is $0.80 - 0.90$: $0.20/0.03$ | data |
| | | If $D$ is $0.90 - 1.50$: $(-0.32*D + 0.485)/0.03$ | |
| | | If $D$ is $>1.50$: 0 | |
| *cvr* | | | |
| | Pools and Glides | If wood complexity = 1: 0.58 | Johnson et al. 1993; |
| | | If wood complexity = 2: 1.00 | Johnson 1985 |
| | | If wood complexity = 3: 1.42 | |
| | | If wood complexity = 4 or 5: 1.84 | |
| | Boulders | If $B_{Pr} < 0.25$: 1.0 | |
| | | If $B_{Pr}$ is $0.25 - 0.75$: $1 + 12*(B_{Pr} - 0.25)$ | |
| | | If $B_{Pr}$ is $>0.75$: 7.0 | |

TABLE 1. Continued.

| Parameter/Function | Value/Equation | Source(s) |
|---|---|---|
| *den (fish/m$^2$)* | | |
| *turb* | If $D_R$ is <0.3m: $10^{(2-(1+0.024*T)*0.1)}/10^{2-0.1}$<br>If $D_R$ is 0.3–0.5m: $10^{(2-(1+0.024*T)*0.3))}/10^{2-0.3}$<br>If $D_R$ is > 0.5m: $10^{(2-(1+0.024*T)*0.5))}/10^{2-0.5}$ | Lloyd et al. 1987 |
| *drift* | If $R_P$ >0.5: 1.0<br>If $R_P$ is $\geq$0.5: 0.1+1.8*$R_P$ | Waters 1962;<br>Waite and Carpenter 2000 |
| *fines* | If $F_P$ is <0.1: 1.0<br>If $F_P$ is $\geq$0.1: 1.11 – 1.1*$F_P$ | Bjornn et al. 1977 |
| *alk* | Alkalinity (mgCaCO$_3$/l)$^{0.45}$/4.48 | Ptolemy 1993 |
| *winter* | If $C_P$ < 0.15: 0.20+($C_P$)/0.15*0.8<br>If $C_P$ > 0.15: 1.0 | USFWS 1988; Bjornn 1971;<br>Bustard and Narver 1975;<br>Hartman 1965;<br>Swales et al. 1985 |

$W$ = wetted width of unit in meters.
$L$ = length of unit in meters
$D$ = depth in meters (maximum in pools; mean in riffles)
$B_{Pr}$ = Proportion of substrate in riffles that is comprised of boulders
$D_R$ = Mean depth of riffles within the reach
$R_P$ = Proportion of surface area of reach comprised of riffle and rapid habitat types
$F_P$ = Proportion of substrate in riffles that is comprised of fines
$C_P$ = Proportion of substrate in the stream comprised of cobbles

from a set of Oregon coastal streams, so the scalar value for *dep* would be set to 1.0 for the average depth in the Oregon coastal streams that were sampled. Depths greater than average would receive a scalar >1, and depths shallower than average would receive a scalar <1. The sequence of calculations is illustrated in Figure 1, and the formulas and range of values for each of these scalars are given in Table 1 and Figure 2. To estimate smolt output at capacity, the parr capacity is multiplied by an overwinter survival rate, which is assumed to be density independent.

Substantiating evidence for the functions used in the UCM has been described by Cramer and Ackerman (2009, this volume). Here we describe the logic for translating that evidence into quantitative functions describing steelhead habitat.

### *Model functions*

*Standard Fish Densities (den).*—Rearing densities for different channel unit types from Johnson et al. (1993) were chosen to represent the *den* term in equation (1) (Table 1). Johnson et al. (1993) presented findings from

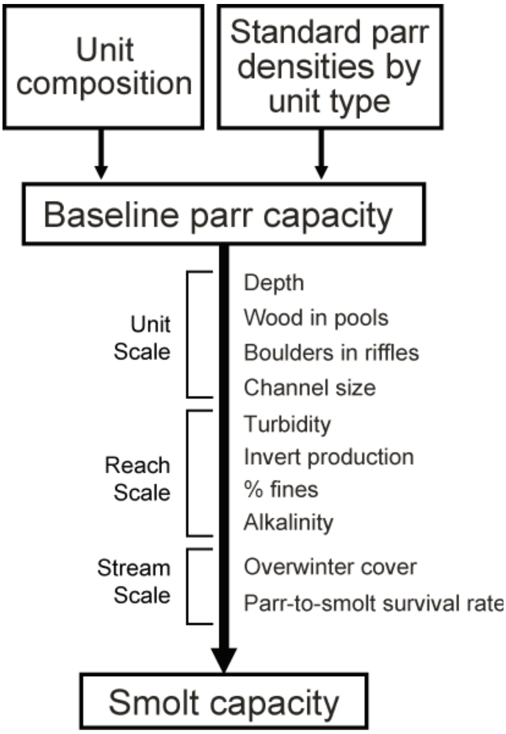

FIGURE 1. Diagram of the sequence of functions within the UCM.

19 coastal Oregon streams that were sampled over multiple years and were fully seeded. These densities are referred to in the UCM as the "standard densities" and the streams from which they were derived are termed the "standard streams." These "standard densities" were applied to all seven watersheds, and the various scalars in equation (1) then adjusted these densities to be appropriate for the habitat features in each channel unit, reach, and watershed, as described below.

*Channel Size (chnl).*—Large river channels tend to support much lower densities of rearing parr per area than smaller channels (Johnson 1985; Jepsen and Rodgers 2004) due primarily to the preference of steelhead parr for shoreline areas, and to the head and tail sections of pools within larger channels. Bjornn and Reiser (1991) showed that counts of age-0 chinook increased with pool surface area up to pool sizes of 200 m$^2$. Beyond this pool size, there was no further increase in the number of fish counted. Data from the Sandy River, Oregon, suggest that calm areas (velocity <0.15 m/s) tended to form in mid-sections of pools longer than four channel widths, and 80% of pools were under that length (Cramer et al. 1998). We have observed that such calm areas are seldom used by juvenile steelhead, so we set the UCM to only assign pool area for the pool length up to four channel widths.

Fish use of the mid-river portion of wide river channels is limited (Beechie et al. 2005). Direct underwater observation data from the Salmon River (tributary to the Sandy River, Oregon) and the Clackamas River, Oregon, indicate there is a stream size at which channel geometry and hydraulics result in less favorable habitat for juvenile salmonids in midstream, and that this difference depends on the type of channel unit (pool, riffle, or glide) (O'Neal and Cramer 1999; Romey et

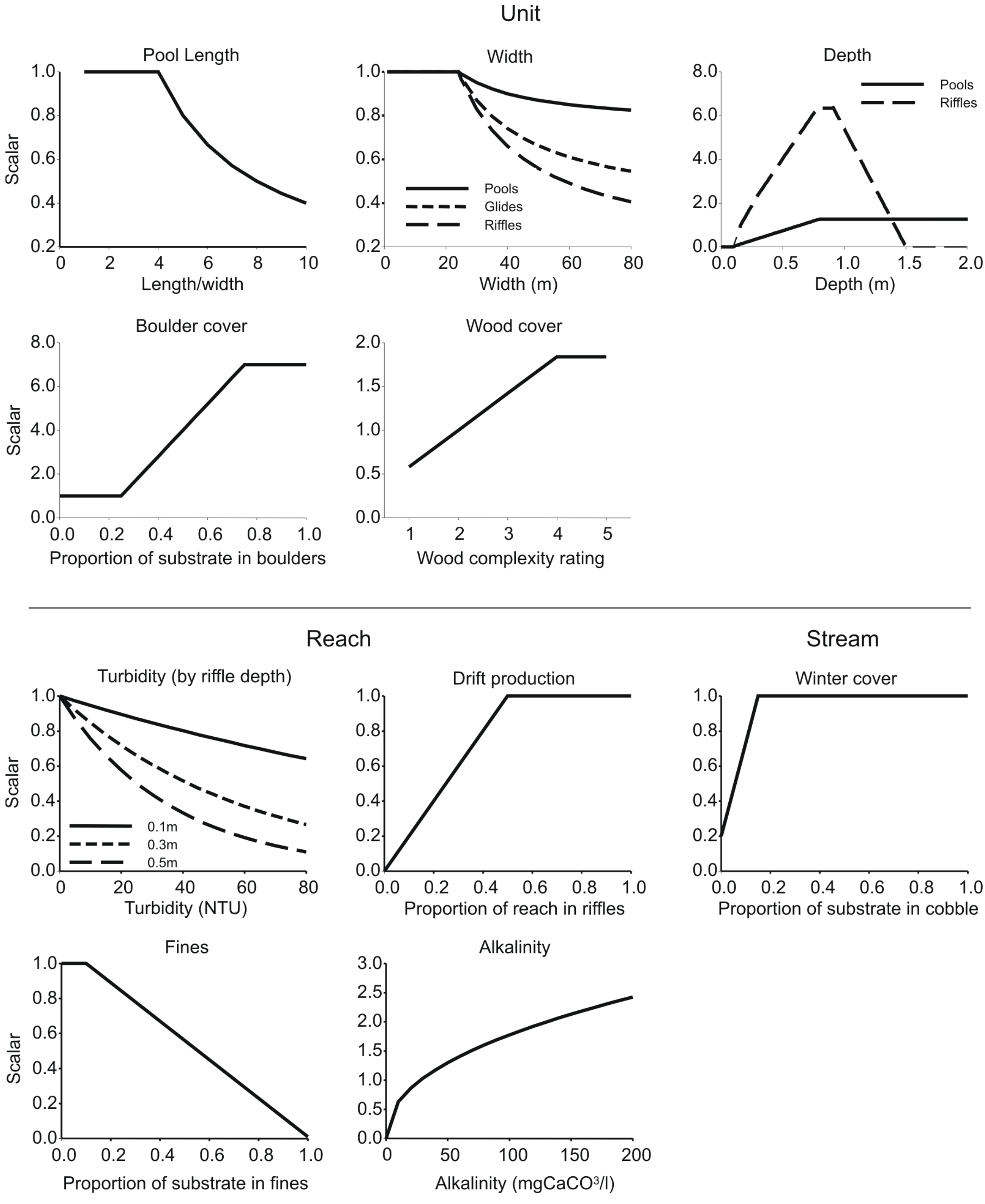

Figure 2. Habitat preference relationships applied within the UCM for scaling standard parr densities to those expected under the specific habitat features in a given stream.

al. 2001). In the smaller of the two rivers, the Salmon River, the mean channel width was 21 m and steelhead parr counts in the midstream lane, averaged for 16 channel units, was significantly ($P < 0.05$) greater than from either of the side lanes. However, in the Clackamas River where mean channel width was 40 m, the midstream lane consistently produced much lower counts of steelhead than the side lanes ($P < 0.01$) in riffles (15% of side lanes) and glides (35% of side lanes). Accordingly, the UCM incorporates these findings into the *chnl* scalar of equation (1), by assigning densities in the midstream portion of large channels (>12 m from shore) that are 15% of the standard in riffles, 35% of the standard in glides, and 75% of the standard in pools (Table 1; Figure 2).

*Depth (dep).*—The depth scalar accounts for the effect of depth on juvenile steelhead use independent of cover. In a study of a Washington stream in which cover from wood, vegetation, or boulders was absent, Beecher et al. (1993) found that steelhead parr strongly avoided areas with depth <0.15 m, and their use increased with depth from 0.15 to 0.76 m, with no change in depth preference beyond 0.76 m. Preference of steelhead parr for a similar range of depths was confirmed in separate studies by Everest and Chapman (1972), Fausch (1993) and Dambacher (1991). Bisson et al. (1988) and Roper et al. (1994) also reported that steelhead parr use increased with depth in wadable streams.

Although steelhead parr prefer increasing depth in riffles up to 0.8 m, there is also evidence that this preference declines as riffle depth exceeds 0.9 m (Bovee 1978; Conner et al. 1995). Conner et al. (1995) found that the range of depths preferred by juvenile steelhead grew smaller as velocity increased, and that juvenile steelhead only preferred deep areas where velocity was moderate. Hydraulic forces dictate that mid-depth velocities in riffles will increase as depth increases, due to the reduced influence of friction with the streambed. Thus, increasing velocity is likely the cause of reduced preference by steelhead parr for depths >0.9 m., We accordingly assumed parr densities would decrease at depths >0.9 m in riffles. The "*dep*" scalar increases linearly with increasing depths of 0.1–0.8 m in pools and riffles, and decreases linearly at increasing depths from 0.9 m, to a value of 0 at depths >1.5 m in riffles (Table 1; Figure 2). We found no clear correlation of steelhead parr densities to depth in other unit types, so we made no depth adjustment for other unit types.

The weighting factor for depth preference in the UCM was set at 1.0 for the average depth in the streams from which standard densities were derived by Johnson et al. (1993). However, Johnson et al. (1993) did not report depth, so the standard depth was defined as the mean of those reported by Oregon Department of Fish and Wildlife (ODFW) (online data, 2005b) for channel units in 10 of the streams sampled by Johnson et al. (1993).

*Cover (cvr).*—The UCM accounts for the effects of cover (cvr term in equation (1)) on steelhead capacity by relating availability of wood in pools and glides, and boulders in riffles, to steelhead densities (Table 1; Figure 2). Cramer and Ackerman (2009) further describe the evidence from key studies used to establish the UCM functions for cover.

Boulders provide important cover for steelhead parr in riffles (Don Chapman Consultants 1989; Dambacher 1991; Ward and Slaney 1993). Two approaches were developed to use existing stream survey data to account for the effect of boulder cover in riffles on steelhead capacity. In cases where only the dominant type of substrate was recorded, boulder dominance received a multiplier of 6.0, and other substrates had a multiplier of 1.0 (based on data of Johnson 1985). If substrate was recorded as percentage composition, then the multiplier was 1.0 for <25% boulders, and increased linearly up to 7.0 when boulders composed 75% of substrate. Boulders composed 25% of substrate in the streams from which standard densities were derived.

While boulders are the key form of cover in riffles, woody debris provides the most important form of cover in pools and glides (Bustard and Narver 1975; Johnson et al. 1993). The scalar for effects of woody debris cover was based on findings from Johnson et al. (1993), as described in Cramer and Ackerman (2009). The UCM uses inputs of wood complexity rated for each channel unit on a scale of one to five, with fish densities increasing as the wood score increased (Table 1; Figure 2). The wood cover scalar was calibrated to a value of 1.0 for the median wood complexity score of 2.0 observed in pools and glides of the standard streams.

*Productivity (prod).*—At the reach scale, there are stream productivity factors (*prod*) that influence all units of a reach in common. The UCM scales the effects of productivity on parr capacity based on four factors: turbidity (*turb*), invertebrate habitat (*drift*), fine sediments (*fines*), and stream alkalinity (*alk*). That is:

(2) $prod_i = turb_i \cdot drift_i \cdot fines_i \cdot alk_i$

where:

*turb* = turbidity during summer low flow (measured in NTUs),

*drift* = percentage of reach area in fastwater habitat types that produce invertebrates,

*fines* = percentage of substrate in riffles composed by fines, and

*alk* = alkalinity during summer low flow (measured as mg/l $CaCO_3$).

Before being used to calculate $prod_i$, each of these variables were converted to a scalar with a value of 1.0 corresponding to the mean or median value of the variable in the standard streams.

Turbidity (*turb*) influences productivity by reducing light penetration, which reduces primary production. Cramer and Ackerman (2009) review published evidence for biological production in streams that links sunlight to primary production, then to invertebrate production, and finally to salmonid production. In the UCM, any reduction in primary production during the low flow season would reduce steelhead capacity by the same percentage. A relationship described by Lloyd et al. (1987) was used to predict the effect of turbidity on primary production (Table 1; Figure 2), accounting for increasing attenuation of light with water depth. Mean riffle depth is used for the value of depth in the equation, because riffles are the primary location in the stream that produces most invertebrates that salmonids feed on (Hawkins et al. 1983; Rader 1997). The maximum depth we applied was 0.5 m, because velocity increases with depth in riffles, and may limit invertebrate production. If turbidity data were not available, and the stream was regarded to be a typical clear stream, the turbidity scalar was assumed to be 1.0.

The UCM uses the percentage of area in fastwater habitats (riffles, rapids, and cascades) as an index of invertebrate production (*drift*) (Cramer and Ackerman 2009). Juvenile salmon and trout feed predominantly on invertebrate drift in streams (Rader 1997), and Hawkins et al. (1983) demonstrated that salmonid density in 13 streams was correlated to invertebrate density in riffles (collector-gatherers), but not to invertebrates typically found in pools. Waters (1962) found that trout consumption of mayflies per surface area in pools (0.45 g/m$^2$) exceeded the production of mayflies per area of riffles (0.28 g/m$^2$) where the drifting mayflies were produced, which indicated that at least 60% of the stream area had to be riffles to produce the abundance of mayflies that were consumed in the pools. This finding was the basis for the assumption in the UCM that invertebrate food supply limits production in a stream reach if fastwater habitat types compose less than 50% of the surface area of the reach. We assumed that food capacity to support salmonids dropped linearly as the percentage of fastwater habitat types dropped below 50%, and we assumed that a minimum of 10% food capacity was retained even where fastwater habitat types were absent (Table 1; Figure 2). These assumptions were corroborated by observations in low-gradient streams of the Willamette Valley where abundance of salmonids was positively correlated to the percentage of area in riffles over the range of 4–50%, with salmonids composing less than 1% of fish in streams that had less than 11% riffle (Waite and Carpenter 2000).

The findings of Bjornn et al. (1977) were used to establish a UCM scalar that reduces stream capacity for parr rearing as fine sediments (*fines*) reach 10% or higher of substrate in riffles (Table 1; Figure 2). Density of juvenile steelhead in summer and winter was reduced by more than half when enough sand was added to fully embed the large cobble substrate in an experimental stream (Bjornn et al. 1977).

Alkalinity (*alk*) is a commonly measured analyte in streams that is useful as a surrogate of nutrient concentrations. Ptolemy (1993) found a positive relationship between total alkalinity and salmonid abundance across 226 streams in British Columbia and confirmed the relationship with data from 37 streams in six countries ($R^2 = 0.86$). We used the relation developed by Ptolemy (1993) to scale the effects of stream productivity to the median alkalinity of 28 mg/l $CaCO_3$ in midsummer for Oregon coastal streams from which standard parr densities were derived (Table 1; Figure 2).

### *Overwinter survival*

The UCM predicts the capacity of age >1 parr, but these parr must still survive through the winter before they undergo parr-to-smolt transformation and migrate to sea the next spring. Many studies have demonstrated that steelhead typically seek refuge in the winter within the interstices of cobble and boulder substrate (Hartman 1965; Bjornn 1971; Bustard and Narver 1975; Swales et al. 1986; and USFWS 1988). Several studies have demonstrated that steelhead presmolts will migrate from an area in the fall where cobble-boulder substrate is in short supply, but these fish typically find appropriate winter habitat further downstream (Bjornn 1978; Tredger 1980; Leider et al. 1986). Thus, the model uses availability of cobble substrate throughout the stream network as an index of winter capacity for steelhead parr (*winter* in equation (1). The UCM assumes that 15% of substrate comprised by cobbles is sufficient to support the numbers of parr surviving the summer, and winter capacity would drop linearly to a minimum scalar value of 0.20 if cobbles were absent (Table 1; Figure 2).

The overwinter capacity scalar is subsequently multiplied by the expected winter survival for age >1 parr to complete the translation of parr capacity into smolt capacity. Overwinter survival of steelhead parr is typically between 35 and 65% (Chilcote et al. 1984; Reeves et al. 1990; Tautz et al. 1992; Ward and Slaney 1993; Kiefer and Lockhart 1999). We assumed 50% survival to convert parr capacity to smolt capacity, unless data for a specific basin led us to assume otherwise.

### *Test basins*

Capacity estimates from the UCM were corroborated through comparison to observed parr and smolt production from seven steelhead-producing basins (referred to as test basins) of varied habitat characteristics and locations throughout Oregon (Figure 3). Though the UCM predicts parr capacity during summer low flow, abundance of juvenile steelhead is most often sampled when they emigrate from a stream as smolts in the spring. The abundance of smolts reflects the cumulative effects of all freshwater limitations to production, and thus is a useful index of carrying capacity. Our application of the parr-to-smolt survival rate described earlier facilitated comparisons of UCM estimates to juvenile steelhead production.

Watershed areas ranged from 26 to 1,420 km$^2$ (Table 2). One of the basins (Hood River) was strongly influenced by glacial meltwaters during summer, three basins drained arid watersheds to the east of mountain ranges (Trout Creek, Catherine Creek, and Little Butte Creek), and three basins were in a wet coastal region (Cummins Creek, Tenmile Creek, and Little North Fork Wilson River). Either parr or smolt production of steelhead had been estimated by the ODFW in these watersheds using direct sampling methods for five to 11 years (Table 2).

Habitat data that were inputs to the UCM were obtained from surveys by ODFW and U.S. Forest Service (USFS) using their standard protocols (Table 3). Steelhead distribution in these basins was defined using 1:100K data from the ODFW Fish Distribution Data Development Project (ODFW 2005a, online data). Water quality data were obtained from the Oregon Department of Environmental Quality (ODEQ 2006, online data). In some basins, habitat data did not provide complete coverage for the range of steelhead rearing

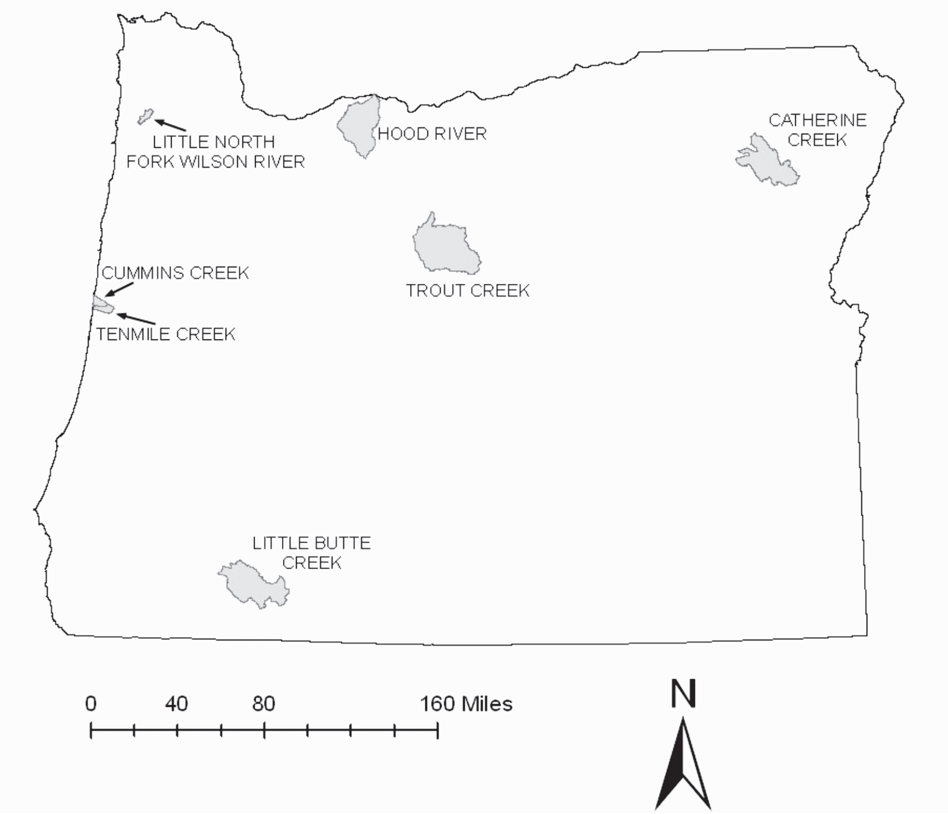

Figure 3. Map displaying relative location of test watersheds within Oregon.

TABLE 2. Drainage area and estimated abundance of juvenile steelhead in watersheds used to test the UCM. Tenmile and Cummins Creek population estimates are in terms of parr. Remaining watersheds are in terms of smolts.

| Watershed | Watershed Area ($km^2$)[1] | Years of Population Estimation | Minimum Population | Average Population | Maximum Population |
|---|---|---|---|---|---|
| Tenmile Creek[2] | 60 | 1991–1995 | 12,180 | 15,270 | 19,784 |
| Cummins Creek[3] | 26 | 1996–2000 | 4,798 | 5,743 | 7,171 |
| Little North Fork Wilson River | 52 | 1998–2004 | 3,524 | 10,108 | 20,686 |
| Little Butte Creek | 966 | 1998–2004 | 15,634 | 21,801 | 27,425 |
| Hood River | 912 | 1994–2004 | 4,936 | 14,242 | 27,193 |
| Trout Creek[4] | 1,420 | 1998–2004 | 11,643 | 25,888 | 51,199 |
| Catherine Creek[4] | 267 | 1997–2001 | 10,377 | 13,029 | 19,865 |

[1] Approximation of watershed area above downstream migrant trap.

[2] Population was monitored in 1996-2000, but ODFW (who conducted sampling and population estimates) determined that production estimates in those years were unreliable.

[3] Population was monitored in 1991-1995, but data indicated the basin was underseeded in those years.

[4] Population estimates reflect smolts normalized to age 2. See subsequent methods section.

TABLE 3. Sources of outmigrant and habitat data used within the UCM test basins.

| Basin | Outmigrant Data | Habitat Survey Data |
|---|---|---|
| Tenmile Creek | Solazzi et al. 2002 | Pers. comm., Steve Johnson, ODFW |
| Cummins Creek | Solazzi et al. 2002 | Pers. comm., Steve Johnson, ODFW |
| Little North Fork Wilson | Dalton 2001; Pers. comm. | ODFW online data 2005b, Tim Dalton, ODFW |
| Little Butte Creek | Vogt 2004; Pers. comm., Jay Doino, ODFW | ODFW online data 2005b |
| Hood River | Olsen 2005 | ODFW online data 2005b; Unpublished data, US Forest Service, Mt. Hood NF. |
| Trout Creek | Pers. comm., Tom Nelson, ODFW | ODFW online data 2005b; Unpublished data, US Forest Service, Ochoco NF. |
| Catherine Creek | Reischauer et al. 2002 | ODFW online data 2005b; Unpublished data, US Forest Service, Wallowa-Whitman NF |

distribution. Typically, unsurveyed habitat was at the upper extent of steelhead presence and in small tributaries. In these situations, we assigned parr per meter values predicted by the UCM from the surveyed reach that we judged to be most similar. Similarity was judged by such factors as gradient, watershed area, valley form, channel form, flow, elevation and precipitation. Most often, this judgment led to use of the nearest reach with similar width and gradient.

In some instances, measurements of some habitat attributes were not directly applicable to the UCM. For instance, substrate composition was only classified into dominant and sub-dominant types in some reaches. In this particular situation, habitat data from streams around Oregon were used to draw correlations between dominant/sub-dominant substrate types, and the percentage of substrate most likely represented by those classifications. If a clear basis could not be derived to translate existing survey data into the inputs called for by the UCM, then no adjustment was made for the function (e.g., wood complexity data were not collected in Trout Creek). This practice assumes that the unmeasured factor value was equal to the average from the standard streams. Basin coverage of habitat data to supply inputs for the UCM was generally good. The reaches that accounted for over 90% of the capacity predictions were fully surveyed in all test streams except Little Butte Creek and Trout Creek, where 81% and 69% of the predicted capacities were generated from the reaches that had been surveyed.

Directly sampled production data from each test basin was examined for evidence that juvenile production reached capacity (full seeding) in some of the years sampled. Evidence of full seeding with juveniles was deduced from high smolt production in some years relative to that expected based on watershed area (Cramer and Ackerman 2009), or consistency in smolt production across several years. Only Catherine Creek in the Grande Ronde Basin appeared not to have reached full seeding.

In Tenmile Creek and Cummins Creeks, both direct ocean tributaries in Oregon, the size of the summer rearing population of parr was estimated via snorkeling and electrofishing surveys by the ODFW between 1991 and 2000. In Tenmile Creek, only population estimates from 1991 to 1995 were included in the analysis, because those were the only years ODFW deemed the estimates sufficiently reliable (Steve Johnson, ODFW, personal communication). In Cummins Creek, we used parr population estimates for 1996 to 2000 in our analysis, because smolt abundance was high and stable compared to lower, but increasing abundance during 1991 to 1995. Parr estimates for these two basins were converted to estimates of smolt production by assuming 50% survival from parr to smolt.

Hood River was the only basin tested where we assigned other than 50% for overwinter survival. Glacial influences in Hood River resulted in a high volume of fines, which embedded the available cobble and restricted overwinter cover. High percentages of fines in the substrate have been implicated in stimulating emigration and reducing overwinter rearing densities for salmonids (Bjornn et al. 1977; Bjornn 1978; Hillman et al. 1987). Accordingly, we applied a 35% par–smolt survival rate to the Hood basin as was done by Underwood et al. (2003).

We defined observed capacity as the 80th percentile of population estimates for each watershed. The 80th percentile was chosen to ensure that the estimate represented years in which production was maximized, yet avoided positive bias that could result if we used only the year of greatest production, which may have resulted from unusual circumstances.

## Results

### *Range of habitat features tested*

A wide range of habitat features used in the UCM were represented across the test basins. The UCM was populated with data from 190 reaches across seven basins. For most habitat attributes, there was a severalfold range in the median values between reaches within each basin (Figure 4). Only a few notable differences existed between basins including: the proportion of pools, the proportion of fines in riffles, and alkalinity (Figure 4). The percentage of pools was generally higher, and the percentage of fines was lower in coastal basins than elsewhere. The percentage of stream surface area composed by pools, riffles, rapids, and glides was consistent between the three coastal basins, and more variable among the interior and glacial basins (Table 4). Alkalinity was higher in the interior basins than in coastal or glacial basins. Hood River basin, although having a full range of channel sizes from small tributaries to the main river, included the widest channels, lowest proportion of pools, deepest riffles, and the highest percentage of fines. Wood complexity rarely exceeded a score of 2.0 in any of the basins, and only reached a median of 2.0 in the Cummins Creek basin, where landslides and habitat restoration had recently introduced substantial quantities of large wood.

### *Observed and predicted smolt capacity*

Direct sampling of parr or smolt production in test basins showed variability between years (Figure 5). Repeatability of high juvenile production was a criterion for determining full seeding of capacity. Production for the highest three years ranged less than 25% within each basin, except in Trout Creek and Catherine Creek. In Trout Creek, unusually high smolt abundance in 1998 resulted from exceptionally rapid growth in 1997, followed by an unusually high percentage (64%) of age-1 smolts in 1998. Most smolts have been age 2 in other years (T. Nelson, ODFW, Madras, OR, personal communication). Thus, the unusually high abundance of smolts in 1998 was not regarded as evidence of unmet capacity in other years. No such event occurred in the highest year of smolt production in Catherine Creek and spawner abundance was

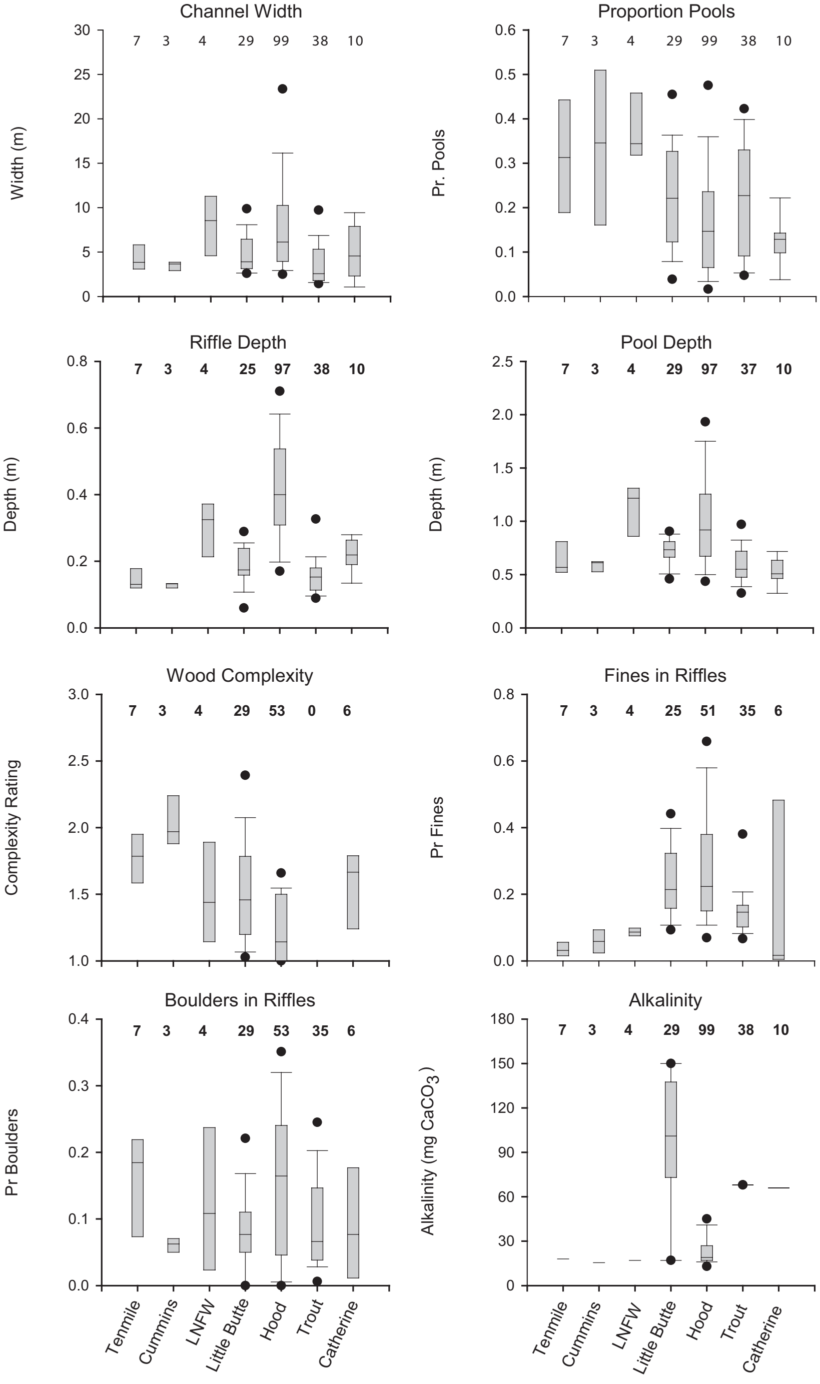

FIGURE 4. Habitat attributes associated with each basin where UCM capacity estimates were made. Plots constructed using mean values from reaches within each basin where data for a particular attribute were available. Box is defined by 25th 50th, and 75th percentiles, whiskers represent the 10th and 90th percentiles, and points represent 5th and 95th percentiles. Sample size (*n*) is located above each box and varies between plots because data on all attributes was not collected in every reach.

TABLE 4. Habitat unit composition of test basins. Values represent the mean value from all reaches incorporated into the UCM.

| | % Glide | % Pool | % Rapid | % Riffle |
|---|---|---|---|---|
| *Coastal Basins* | | | | |
| Tenmile Creek | 7% | 41% | 22% | 28% |
| Cummins Creek | 3% | 41% | 31% | 24% |
| Little N. Fk. Wilson | 14% | 40% | 12% | 26% |
| *Interior Basins* | | | | |
| Little Butte Creek | 9% | 38% | 23% | 24% |
| Hood River | 2% | 16% | 54% | 19% |
| Trout Creek | 6% | 30% | 8% | 50% |
| Catherine Creek | 3% | 13% | 38% | 45% |

believed to be low compared to historic levels (R. Carmichael, ODFW, La Grande, OR, personal communication). Therefore, direct estimates of smolt production in Catherine Creek did not qualify for estimating observed carrying capacity. Estimates of observed capacity for the six qualifying test basins are given in Table 5.

Parr capacity predictions from the UCM ranged from 5,127 in Cummins Creek (the smallest of tested watersheds) to 91,505 in the Hood River basin (Table 5). These capacities expressed in terms of smolts were 2,563 and 23,843 respectively. Because parr in the Hood River basin were assigned lower winter survival (35%) than other test basins (50%), predicted smolt capacities in Little Butte Creek and Trout Creek were greater than for Hood River basin (Table 5). Basin-wide averages for predicted densities at parr capacity ranged from 5.4 parr/100 m$^2$ in the Hood River to 11.0 parr/100 m$^2$ in Catherine Creek (Table 5).

Smolt capacities predicted by the UCM were highly correlated to observed capacities across the six test basins that had evidence of full seeding ($R^2 = 0.88$; $P < 0.005$) (Figure 6). However, watershed area by itself was equally well correlated to observed capacities across the six test basins ($R^2 = 0.88$; $P < 0.005$; Figure 7), and the UCM predicted capacity was also correlated to basin area ($R^2 = 0.92$). Predicted capacities in the three largest basins all exceeded the 80th percentile of observed juvenile production, indicating there may be a tendency for the UCM to over-predict capacity in larger basins. Deviations of predicted from observed capacities were modest for five of the six basins, ranging from –22 to + 34% (Table 5). Only in the Little North Fork Wilson basin did predicted capacity (3,957) deviate substantially from observed capacity (14,797; –73%).

Observed parr abundances were most consistently near the predicted capacity in Cummins and Tenmile creeks, where parr abundance was slightly above or below the predicted value in a balanced number of years (Figure 5). These were the only two basins in the test set for which juvenile production was estimated directly for age-1+ parr, rather than for smolts. Thus, no assumption about overwinter survival was necessary for these basins, but in all other basins, an assumed winter survival rate had to be assigned to the parr capacity estimate to calculate smolt production the following spring.

In two of the six basins analyzed, Little Butte Creek and Hood River, the observed annual parr abundance, derived from smolt sampling, fell below the UCM predicted capacity in all years sampled. If we assumed winter

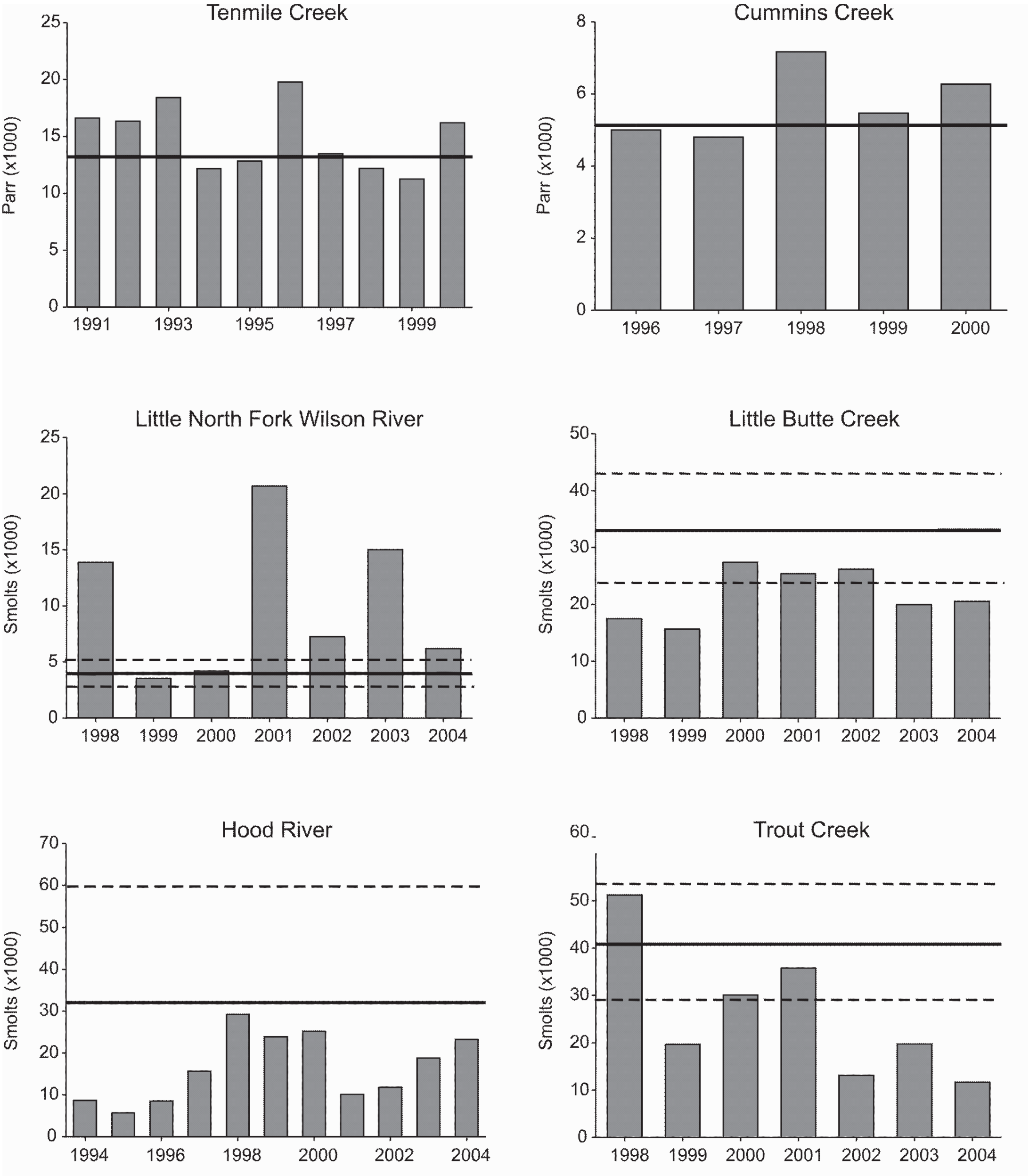

FIGURE 5. Annual estimates of steelhead parr or smolts produced in each test basin. Data from sources in Table 3. Solid horizontal line represents the UCM capacity estimate based on a 50% $S_{ow}$ (35% in Hood River). Dotted lines represent the range of the UCM capacity estimates assuming a 35–65% $S_{ow}$.

Table 5. UCM predictions of parr and smolt capacity at the assumed over-winter survival ($S_{ow}$) in test basins, compared with observed capacity based on direct estimates of juvenile production. The observed capacity represents the 80th percentile of observed production estimates (Table 2). The observed capacity and prediction deviations are based on parr for Tenmile and Cummins creeks, and based on smolts for the remainder of the basins.

| Basin | Predicted Parr Capacity | Predicted Parr/100m$^2$ | Assumed $S_{ow}$ | Predicted Smolt Capacity | Observed Capacity | Prediction Deviation |
|---|---|---|---|---|---|---|
| Tenmile Cr. | 13,253 | 6.7 | 50% | 6,676 | 16,974 | –22% |
| Cummins Cr. | 5,127 | 7.0 | 50% | 2,562 | 6,452 | –21% |
| Little N. Fk. Wilson | 7,913 | 6.4 | 50% | 3,957 | 14,797 | –73% |
| Little Butte Creek | 65,982 | 8.1 | 50% | 32,991 | 26,024 | +27% |
| Hood River | 91,505 | 5.4 | 35% | 32,026 | 23,843 | +34% |
| Trout Cr. | 81,575 | 9.9 | 50% | 40,787 | 34,620 | +18% |
| Catherine Cr. | 47,787 | 11.0 | 50% | 23,894 | -- | -- |

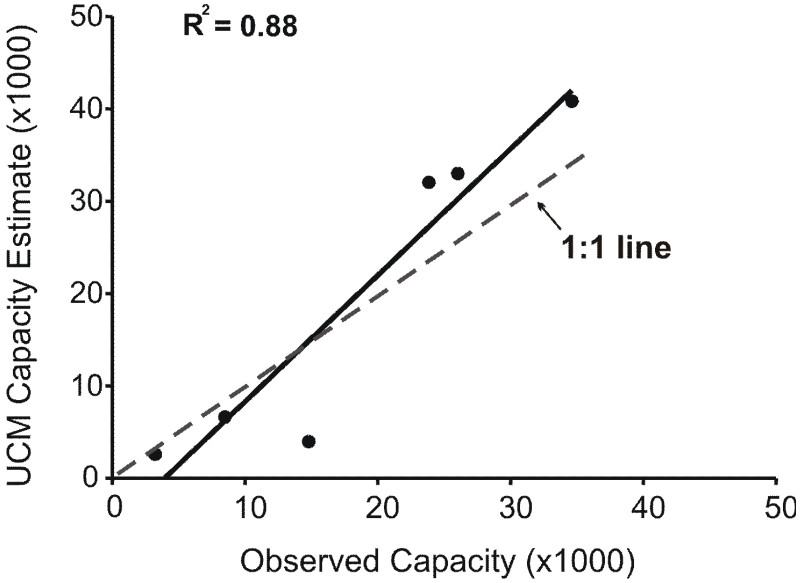

FIGURE 6. Relationship of predicted to observed smolt capacities for the six test basins. Catherine Creek excluded from the comparison because it was not believed to be fully seeded. Solid black line is least-squares regression line. The dashed gray line indicates 1:1 relationship.

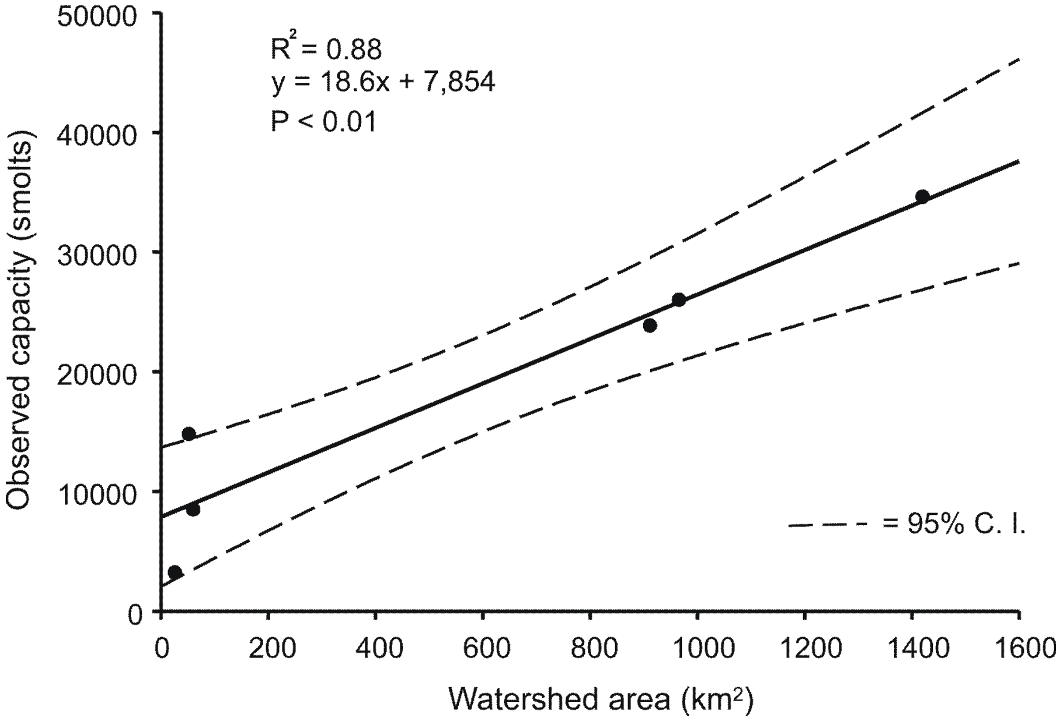

FIGURE 7. Regression of observed smolt capacity on watershed area in the six test basins.

survival was 35% in Little Butte Creek, then estimated parr abundance reached the UCM predicted capacity in three of seven years (Figure 5). The Hood River was the only test basin for which smolt sampling indicated parr abundance was less in all years sampled than that predicted by UCM, assuming the low range of winter survival (35%). In contrast, smolt abundance exceeded the predicted capacity in six of eight years sampled in the Little North Fork Wilson River, and deviations from predicted capacity were greatest there for any of the test basins (Table 5).

### *Distinction of habitat quality*

The UCM provided a quantitative measure of habitat quality by predicting the density of parr or smolts that a given basin, or stream reach within the basin, could support. Although basin area was highly correlated to observed smolt production, the UCM predicted that four of the seven test watersheds had widely differing habitat quality between reaches. Only the three coastal watersheds had consistent habitat quality, as indicated by the low variability in predicted density among reaches, compared to the interior basins (Figure 8). All of the interior and glacial basins had some low quality reaches that would support less that 0.01 smolts/m$^2$, and high quality reaches that would support greater that 0.06 smolts/m$^2$. Median values of smolt density at capacity were about 50% higher in interior basins than those for coastal basins.

### *Prediction sensitivity to habitat factors*

*Differences between basins.*—Alkalinity (*alk*) had a greater effect on capacity predictions than any other model term (Figure 9). Alkalinity strongly distinguished watersheds in dry, interior climates from those in wet, coastal climates. The adjustment for alkalinity substantially increased predicted capacities for Trout, Catherine, and Little Butte creeks, while slightly decreasing capacities in the other four basins. Predictions of basin capacity were moderately influenced by *dep* and *cvr*, with *dep* having more influence (Figure 9). The depth scalar for all basins exceeded 1.0, indicating that depths in the test basins were generally greater than in the standard streams. The cover scalar had mixed effects on model outcomes. Cover quality was better in Cummins Creek, Trout Creek, and Catherine Creek, but lower in other test basins than for the standard streams (Figure 9).

The attributes, *turb*, *drift*, and *fines*, generally had small effects on most predictions, but notable effects in specific watersheds. The Hood River was the only glacially turbid stream tested, and the predicted effect of turbidity there was to reduce capacity by 21% (Figure 9). The largest effect of *drift* on capacity predictions was to reduce capacity approximately 10% for three of seven watersheds (Figure 9). The proportion of fines in the substrate was only high enough in the Hood River Basin to have a notable negative effect (–15%) on predicted capacity (Figure 9). Fines averaged 26% in riffles in the Hood River basin, but only ranged from 2 to 17% in other test basins (Table 6).

*Differences between reaches.*—More variation in habitat features was expressed between reaches than between basins, so we examined the effect of reach-level attributes on predictions of smolt capacity and density in 137 reaches where all, or nearly all, habitat attributes were evaluated in surveys. Stream surface area within a reach had the greatest influence on predicted reach capacity, but was not related to habitat quality (parr capacity/m$^2$). Reach surface area ranged from under 5,000 m$^2$ to over 270,000 m$^2$, a 50-fold difference, among all reaches studied. Predicted habitat quality (parr/m$^2$) varied substantially by 15-fold between reaches, but the range of predicted capacities was still driven by the 50-fold range in stream surface area between reaches.

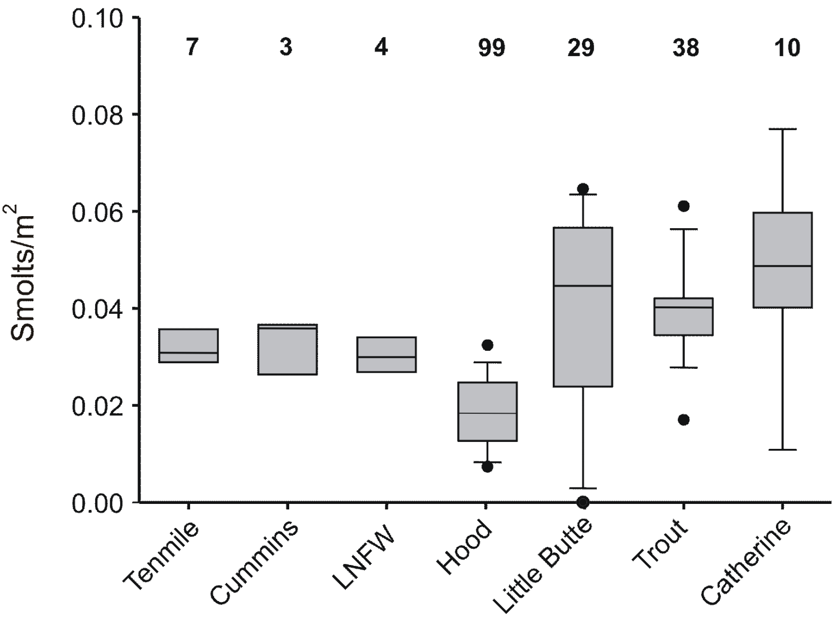

FIGURE 8. Predicted smolt capacity densities among reaches within each basin. Sample size (*n*) is labeled above each box. Box is defined by 25th 50th, and 75th percentiles, whiskers represent the 10th and 90th percentiles, and points represent 5th and 95th percentiles.

In the first calculation step of the UCM, the surface area for each type of channel unit is multiplied by the standard parr density for that unit type. We refer to this initial stage of calculations as the "base capacity" predicted by the model. The base capacity density (parr/m$^2$) in test reaches increased as a function of the percentage that pools composed of the stream surface area (Figure 10). The expected parr density at base capacity approached 0.04 parr/m$^2$ as the proportion of pools in a reach approached zero, and increased up to 0.13 parr/m$^2$ at 70% pools, the highest percentage observed. This is a three-fold range in the densities predicted at this initial calculation step. Baseline capacity densities were higher in coastal Oregon watersheds, where pools comprised 40–41% of habitat, compared to 13–38% of the habitat in interior and glacial basins (Table 4).

Sensitivity of capacity density predictions to functions within the UCM were determined by adding each UCM factor in stepwise fashion to the UCM calculation, and computing the proportionate change in the fish density prediction with each new factor added (Figure 11). We refer to this accumulating product of scalars as the cumulative density multiplier. The median value of this multiplier accumulated for all habitat factors in the UCM was 1.09 (little different than the base density of $(\Sigma\ arean_{jk} \cdot den_j)/\Sigma\ area_k)$), but ranged up to 3.0 for the 90th percentile of reaches and down to 0.2 for the 10th percentile (Figure 11). Alkalinity produced the greatest difference in the density multiplier between reaches, ranging from 0.8 to over 2.0 (Figure 11). The percentage of fines was the second most influential factor, and generally reduced the density multiplier, ranging from 1.0 down to 0.5. Lesser effects from pool and riffle depths tended to increase the multiplier, while channel width, wood cover (lack thereof), and fines tended to reduce it. Boulder cover, drift availability and turbidity usually produced scalars near 1.0, and only

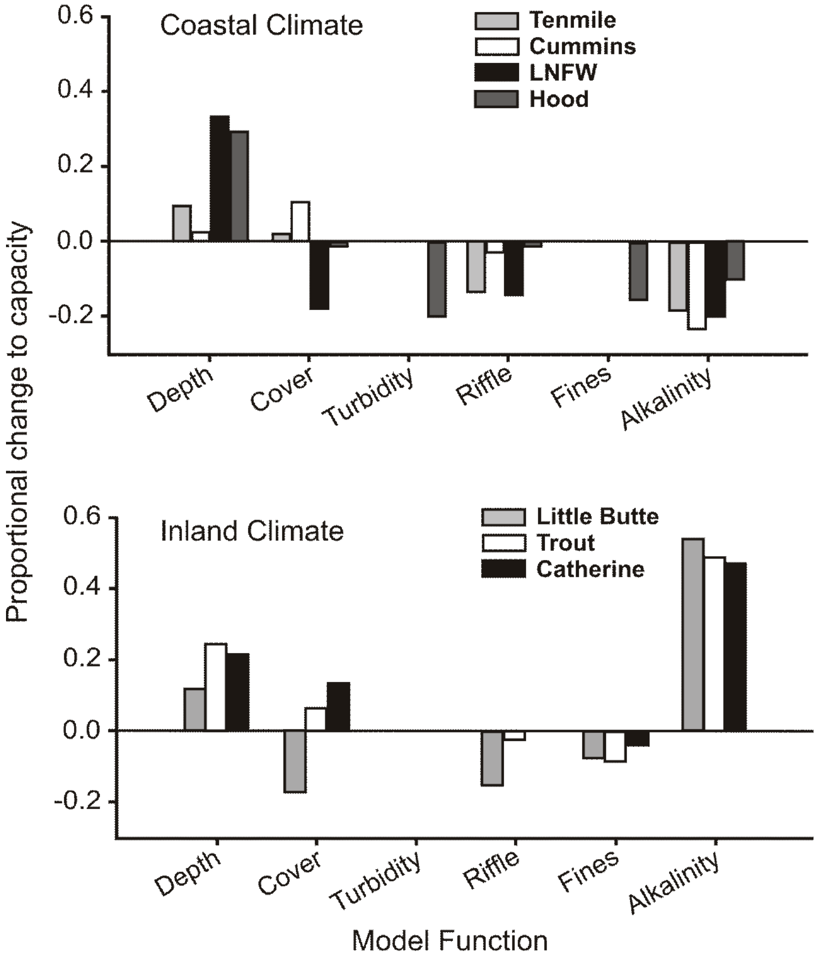

FIGURE 9. Response of UCM predicted capacity within each test basin to each habitat attribute.

had notable effects in a few reaches. The multiplier for winter cover had no effect in any of the reaches surveyed.

## Discussion

### *Accuracy of prediction*

Parr capacities predicted with the UCM using habitat measurements at the channel unit level showed a high correlation ($R^2$ = 0.88) to direct estimates of smolt production in six test watersheds of widely different size and habitat characteristics. This finding suggests that the UCM predictions of smolt capacity are reasonably accurate at the basin scale, but we also found that basin area by itself was similarly correlated to observed smolt production ($R^2$ = 0.88). Thus, the high correlation of predicted and observed smolt capacities should not be regarded as validation of the UCM. Such validation will require comparison of predicted and observed parr or smolt per unit area (i.e., fish densities) between reaches representing a wide range of predicted capacity densities. Data on parr densities in each reach were not available for four of our six

TABLE 6. Habitat attributes of test basins. Note: In some reaches, habitat substrate was surveyed as dominant and subdominant substrate types. Those classifications are not included in this table, but were included in model scenarios.

| Basin | Depth (m) Pools | Depth (m) Riffles | Wood Complexity (1–5) | % Fines in Riffles | % Boulders in Riffles | Alkalinity ($mgCaCO_3/l$) |
|---|---|---|---|---|---|---|
| Tenmile Creek | 0.6 | 0.1 | 1.9 | 2% | 22% | 18 |
| Cummins Creek | 0.6 | 0.1 | 2.2 | 8% | 10% | 16 |
| Little N. Fk. Wilson | 1.2 | 0.3 | 1.3 | 8% | 14% | 17 |
| Hood River[2] | 1.3 | 0.5 | 1.1 | 26% | 19% | 23[1] |
| Trout Creek | 0.6 | 0.1 | --[3] | 17% | 15% | 68 |
| Catherine Creek | 0.5 | 0.2 | 1.7 | 2% | 11% | 66 |
| Little Butte Creek | 0.7 | 0.2 | 1.4 | 14% | 7% | 89[1] |

[1] Several streams within the basin were assigned different values based on available data. Value is mean from streams included in the model. In other watersheds, a single value was applied to all streams within the basin.

[2] Estimate represents value from dominant steelhead producing reaches. Reaches listed in Table A12 of Underwood et al. (2003).

[3] No wood complexity data available for Trout Creek. Assumed no adjustment for wood complexity.

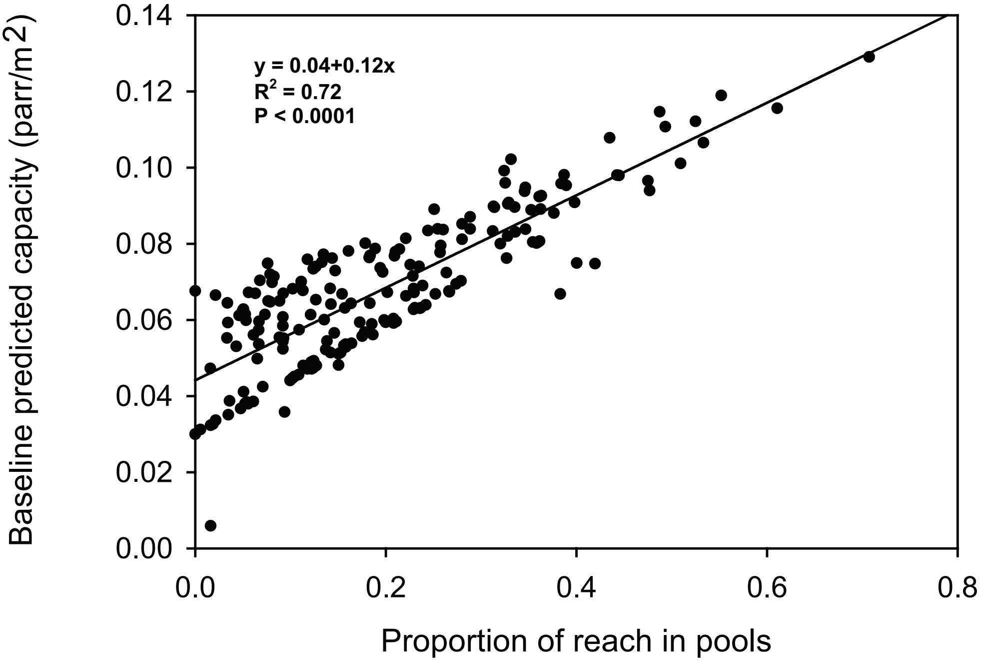

FIGURE 10. Relationship between the proportion of pools within a reach and the predicted base capacity in terms of parr/$m^2$. *n* = 190. The straight-line relationship among a large number of the observations in the lower left of the data array are reaches where only the pools were deep enough to support age >1 steelhead parr.

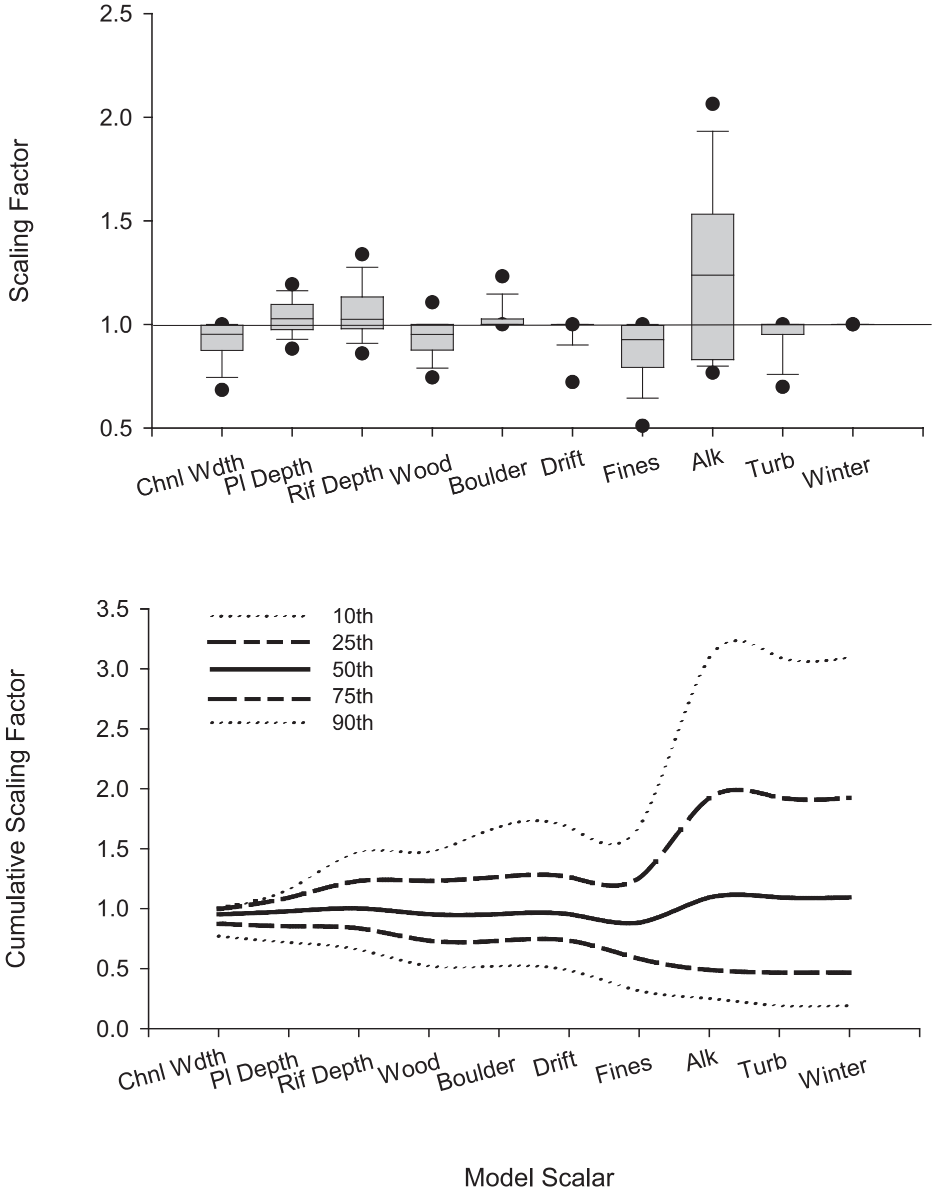

Figure 11. Effects of individual scalars on model outcomes. Top graph: each box represents the effect of that scalar on model outcomes independent of other scalars. Plot constructed by pooling data from all basins and all reaches where full suite of habitat data were available (*n* = 137). Box is defined by 25th 50th, and 75th percentiles, whiskers represent the 10th and 90th percentiles, and points represent 5th and 95th percentiles. Bottom graph: plot constructed from data in top graph by compounding 10th to 90th percentile scaling factors across all model scalars.

test basins. Though statistical procedures might be helpful to account for the separate effect of basin size on the fit of predicted to observed smolt capacity, our limited sample size of six basins with direct estimates of smolt production provides little statistical power to account separately for the effects of basin size.

However, by expressing these predictions in a per-unit-area scale, the overriding influence of reach area on basin predictions can be eliminated. Application of UCM to the test reaches demonstrated that the method could sharply distinguish habitat quality throughout the basin in terms of carrying capacity per unit area. The cumulative density multiplier in the UCM after all habitat factors were included ranged over 15-fold between reaches, from a high of 3.0 for the 90th percentile of reaches and to a low of 0.2 for the lower 10th percentile of reaches (Figure 11). Cramer and Ackerman (2009) presented evidence from a number of studies that demonstrate steelhead parr densities are strongly related to the habitat factors included in the UCM, and the habitat data from the test basins indicate that those factors important to steelhead were substantially different between some of the reaches in nearly every basin. In spite of the wide range of these habitat factors and the large differences they produce in predicted parr capacity between the 190 reaches analyzed in this study, the sum of these reach-level predictions still reflected the observed smolt production from the basin. Thus, the UCM prediction appeared to have accurately expressed both the heterogeneity of habitat quality in a basin, and the combined potential of those different habitat qualities to produce smolts from throughout the basin.

The results of our study support the notion that basin area is a reasonable predictor of carrying capacity for steelhead similar to that reported for other species (Underwood et al. 2003). Our results also demonstrate that much additional information about limiting factors and likely distribution of fish production in the basin can be gained from habitat measurements collected during typical state and federal stream surveys. Apparently, the averaging of a wide range of habitat qualities that exists between reaches within a basin leads to a central range of smolt densities that can be expected between basins. The predictions of the UCM for the test streams confirm this interpretation. As shown in Figure 11, the cumulative density multiplier, although ranging widely between reaches within a basin, still had a median value of 1.09; quite close to the 1.0 level that would indicate no difference compared with habitat quality in the streams from which standard parr densities were derived.

### *Sources of error*

The correlation of predicted to observed parr capacity ($R^2$ = 0.88) was surprisingly high given the substantial source of error introduced by back-calculating of summer parr capacity from estimates of smolt out-migration in four of the six validation streams. Predicted parr capacity was most consistently near the observed parr production in the two streams, Cummins and Tenmile creeks, where parr abundance was estimated directly from sampling of parr. In those two streams, observed parr abundances were slightly above or below the predicted capacity in a balanced number of years (Figure 5).

In addition to sampling variation, there are at least two sources of error that enter into the back-calculation to parr from smolt abundance. First, immigration or emigration of parr during fall is a common behavior among juvenile salmonids in pursuit of winter habitat (Cederholm and Scarlett 1981; Leider et al. 1986; Bramblett et al. 2002). Either event confounds our ability to determine actual parr capacity based on smolt population estimates. Second, differences in flow stability between streams can lead to substantial differences in overwinter survival, with peak flows reducing survival (Seegrist and Gard 1972), and stable flows allowing high survival (Mundie and Trabor 1983). We assumed a constant 50% overwinter survival in all years sampled, and in all test streams except Hood River, where we assumed a 35% overwinter survival. Overwinter survival was estimated annually during field studies in two of the test streams, Tenmile and Cummins creeks, and found to vary by two to three-fold (32–59% in Cummins Creek and 18–48% in Tenmile Creek; Solazzi et al. 2002). Clearly, this variation contributed to error in estimation of annual parr production in the test streams for which only smolt production was sampled.

Our analysis suggests that the UCM may slightly over-predict capacity in the larger basins (>900 km$^2$), such as Trout Creek, Little Butte Creek, and Hood River, or in highly alkaline basins such as Trout Creek and Little Butte Creek. In each of these basins, the observed smolt production for most sampled years fell below the predicted smolt capacity (Figure 5). The deviation of predicted from observed was not large in these streams (18–34%), but the consistency of the pattern warrants scrutiny as further data are gathered. It may simply be that capacity is fully reached in large basins less frequently, because the larger stream network increases the probability due to random variation that some of the reaches will not be fully seeded. However, two of the three larger test basins were also assigned large increases in predicted capacity (about 150%) due to high alkalinity (Figure 9). It is possible that the high correlation found by Ptolemy (1993) for salmonid densities to alkalinity across 226 streams may have been influenced by correlations of alkalinity to stream morphology. Alkalinity tends to increase as runoff per km$^2$ watershed area decreases, and such differences in water yield may influence the formation of channel morphology. For example, pools comprised 40–41% of habitat in coastal basins, compared to 13–38% elsewhere for our test streams. These possible confounding factors warrant further study, but the results from our test streams suggest that little increase in prediction accuracy will be achieved by improvements to the basin size and alkalinity functions.

Smolt yield in the Little North Fork Wilson was anomalously high compared to the capacities predicted by both the UCM and watershed size (roughly four times the expected yield), and may have been influenced by immigration of parr from the main stem Wilson River in the fall. Substantial immigration would result in over-prediction of summer parr abundance when back-calculated from the abundance of smolts departing the stream the following spring. The Little North Fork Wilson enters the mainstem Wilson River near the upper end of tidewater, where it is a last-chance opportunity for nonnatal rearing of juveniles that arrive in tidewater before they are ready to smolt. Local biologists have found no unusual habitat morphology in the Little North Fork to account for exceptional production of anadromous salmonids in that stream (Tim Dalton, ODFW, personal communication).

A clear understanding of the distribution of steelhead rearing within a basin network of channels is important in determining juvenile production potential. The distribution of salmonids within a watershed varies seasonally and annually. These variations are driven in part by flow, temperature, and competition (Welsh et al. 2001; Jacobs et al. 2001; Bramblett et al. 2002). Greatest accuracy in applying the UCM can be achieved by excluding channels that may be used for migration or spawning, but not for rearing. For example, the uppermost reaches where steelhead spawn within a basin may provide an insufficient water supply during summer for parr rearing, in which cases parr move further down in the stream network to rear. Likewise, lower reaches that serve only as migration corridors should also be excluded from assignment of rearing capacity. Lack of rearing in lower reaches of a basin may result from the influences of factors such as high stream temperature or an abundance of predators, which are not included in the UCM.

### *UCM sensitivity to habitat factors*

The variation in reach scalar values for each habitat factor in all seven test basins provided a realistic and practical context for examining model sensitivity to the factors included. The wide range of values for each habitat factor between basins (Figure 4) provided a useful test for how the model responds to combinations of habitat features found in steelhead streams. Although the values for scalars ranged widely (with the exception of winter cover) the effect of averaging multiple factors across multiple reaches within a basin proved to be a strong homogenizing force on predicted density at capacity for a basin. Though scalar values for each of the eleven habitat factors ranged up to sevenfold between reaches within a basin, the density multiplier accumulated across all factors had a median value of 1.09 and ranged only four fold between the 25th and 75th percentile of reach values (Figure 11). As a result, the median reach value for predicted smolt density ranged only 2.5 fold between the seven test basins. Alkalinity had a greater effect on capacity predictions than any other model term, and its primary effect was to distinguish watersheds in dry, interior climates from those in wet, coastal climates (Figure 9). The percentage of surface area in pools accounted for up to a threefold range in the base parr densities between reaches, and up to 50% difference between basins. The factor of depth in pools and riffles tended to increase capacity densities by 20–30% in large basins compared with those in the smallest coastal basins, Cummins and Tenmile creeks (Figure 9).

Data from the test streams illustrate that specific habitat factors may only cause anomalies in habitat quality predictions in specific basins, while having little effect in others. As one example, the Hood River was the only glacially turbid stream tested, and the predicted effect of turbidity there was to reduce capacity by 21% (Figure 9). In another example, boulder cover had little effect in most streams, and had its largest effect in Catherine Creek, despite the low average proportion of boulders in riffles (11%). However, a high value of boulder cover in a small number of riffles (7% of the stream's habitat area) accounted for a 20% increase in the capacity prediction for the Catherine Creek basin. This second example illustrates the importance of applying model functions at the unit scale rather than using average habitat values at the reach or stream scale to estimate capacity. Even though a particular habitat factor may have little effect in most basins and reaches, it can still have an important effect in specific areas.

No specific measurements of velocity were included in the UCM, because velocity is not typically measured on stream surveys. Steelhead show strong velocity preferences related to their size, so the absence of specific velocity information undoubtedly contributes to error in the UCM prediction of carrying capacity. However, some effect of velocity is captured in the predictor through the densities assigned to different channel unit types. For example, steelhead are typically found in riffles at higher densities than juvenile Chinook (Bjornn and Reiser 1991), or coho (Nickelson 1998). Thus, higher densities for steelhead than other salmonids in riffles reflects in part their unique velocity preferences, in combination with their preferences for other habitat features.

### *Applications of the UCM*

Whether a proposed restoration strategy focuses on expanding stream habitats, improving fish passage, reducing the harvest fraction, or altering the use of hatchery fish, all of these strategies share a common need for accurate knowledge of a stream's capacity to produce the species of interest. The UCM offers the means to obtain such knowledge for many steelhead-bearing streams for which spawner abundance has not been monitored over the long term.

Both the UCM and basin area appear to offer rapid, accurate means to predict a stream's carrying capacity for steelhead. Traditional approaches to estimating carrying capacity have required 10–20 years of monitoring catch and spawner escapement, to statistically fit a stock–recruitment function such as the Ricker (1954) or Beverton and Holt (1957). Fits to these functions are generally mediocre, producing $R^2$ values in the range of 40–60%. For example, Chen and Holtby (2002) fit Ricker parameters for 83 populations of coho in British Columbia, and found the average model $R^2$ was 41%. While that approach will always remain useful, because it confirms real production of adult fish, basin area can be used to predict carrying capacity at least equally well with less than a few hours effort, and the UCM can be used with a few days to a few weeks of effort to distinguish habitat quality between reaches within a basin.

The novel information provided by the UCM about carrying capacity for steelhead in a stream is the present habitat value and limiting factors at specific locales throughout the basin. Further, the UCM quantifies stream carrying capacity in terms of stream features that can be targeted by habitat conservation/restoration actions, and makes it possible to predict changes in fish production that would result from changes to habitat features, even at the level of a single channel unit. Such an approach has been applied to coho by Nickelson and Lawson (1998) who used the habitat-based model of Nickelson (1998) to predict carrying capacity for coho in streams along the Oregon coast. Nickelson and Lawson (1998) then used a life cycle model to predict the future change in coho populations that would result from habitat improvements versus that which would result from allowing continued habitat degradation. They found that the fine-grained habitat information included in their model of coastwide populations, "provided insights into the dynamics of coho salmon population and the mechanisms controlling their distribution within a basin." Similarly, the UCM is well suited for application in life cycle modeling as a means to link habitat features and their modifications, even at the channel unit scale, to the performance of an entire population.

The UCM can be used to provide a common currency for expressing the effectiveness of various kinds of habitat conservation or restoration activities. Restoration effectiveness has often been expressed in terms of specific habitat features that have changed, such as pool surface area or wood complexity (e.g., Crispin et al. 1993; Johnson et al. 2005) The UCM would enable these changes to be expressed as predicted changes in parr rearing capacity. Restoration actions may cause gradual change in habitat characteristics, and some changes will be eliminated by floods or channel changes (Roni et al. 2002), so these factors must also be accounted for by explicit assumptions when using the UCM to predict probable future benefits of a restoration project. While monitoring of restoration success should include sampling of fish response, wide variation in salmonid abundances from year to year and out-of-basin influences pose significant statistical hurdles for detecting the magnitude of effects on fish (House 1995). Monitoring of stream habitat change can be used in conjunction with the UCM to provide earlier and reliable feedback on benefits realized from an action.

Additional uses of the UCM may include predicting the change in production potential that would be realized with elimination of man-made barriers, or with the addition of artificial side channels. At a larger scale, changes in watershed management could affect turbidity, fines, channel width, or channel complexity, and each of these changes can be specifically accounted for in the UCM to determine their effect on steelhead carrying capacity.

The UCM may also be used, in conjunction with other tools, to identify areas within a watershed where preservation or restoration may be targeted. For example, when paired with an approach such as that taken by Burnett et al. (2006), areas within a watershed can be compared in terms of both their intrinsic and current potential. Those areas where intrinsic potential is high, and there is great divergence between intrinsic and current potential, could be considered for restoration. Areas where current potential is near its intrinsic potential may be considered for conservation.

### *Possible enhancements to UCM*

The UCM was developed for streams in which water quality and species composition were in the range typical of steelhead streams. Further studies may provide the data needed to derive scalars that would adjust for violation of these assumptions and broaden the set of streams for which UCM would be applicable.

Many water quality factors such as temperature, dissolved oxygen, pH, etc. are not included in the model, but can have significant impacts on habitat capacity. For example, high summer temperatures may totally exclude steelhead from certain areas where the habitat is otherwise suitable. Incorporation of this into the understanding of stream capacity is important and should be dealt with when establishing the distribution of steelhead rearing. Additionally, increased nutrient levels beyond those accounted for in the alkalinity adjustment, such as nutrients derived from carcass additions, may offer improvement to capacity predictions.

Although the model assumes that summer habitat for parr limits steelhead production, recent studies have found that stream restoration techniques, particularly the addition of large wood, can enhance overwinter survival and increased production of steelhead smolts (Johnson et al. 2005). The UCM attempts to account for winter habitat through the inclusion of cobble availability, but the dynamics that determine winter capacity or survival are certainly more complicated than the availability of cobble. Further studies on winter habitat use and survival of juvenile steelhead may reveal a means to improve the accounting for differences in winter habitat.

Interspecific competition is an important phenomenon that is not accounted for in the UCM, and may substantially affect steelhead carrying capacity in some situations. Harwood et al. (2002) noted that interspecific competition for shelter (Gregory and Griffith 1996) can result in density-dependent use of refuge habitat (Armstrong and Griffiths 2001) and thereby have important implications in terms of carrying capacity. This may have specific implications to a stream's steelhead carrying capacity as competition with coho (*O. kisutch*) for summer habitat has been shown to cause steelhead to re-distribute themselves (Hartman 1965; Allee 1982). However, McMichael et al. (2000) found that competition between fish in the Yakima Basin was strongest between individuals of the *O. mykiss* species, but competition of steelhead with juvenile chinook and coho was negligible. Interspecific competitive interactions are highly complex, and whether or not they influence capacity depends partly on the life stage at which competition occurs. The streams used to test the UCM included varied species assemblages that covered the typical range for steelhead streams throughout Oregon. Thus, we expect that separate accounting for inter-species competition or predation may only lead to substantial change in predicted rearing capacity in a small fraction of steelhead-producing streams.

The UCM does not distinguish between capacity utilized by the different life-histories of *O. mykiss* that may rear and compete with one another in the same reach. Nonanadromous rainbow trout will compete with anadromous fish, and thus would share the available capacity when rearing in the same reach. Further, McMichael et al. (2000) found in the Yakima River that agonistic interactions were substantial between individual *O. mykiss*, regardless of whether they were resident or anadromous, and that the larger individuals were behaviorally dominant in over 80% of contests observed. Thus, larger resident rainbow trout will be competitively dominant, and will defend more habitat per individual than steelhead parr (Grant and Kramer 1990). To account for capacity consumed by nonanadromous *O. mykiss*, it will be necessary to account for additional habitat factors, and perhaps racial abundance.

## Conclusions

The UCM provides estimates of basin carrying capacity for steelhead that are consistent with observed smolt yields for basins widely different in size and character. The UCM predictions indicate that habitat quality ranges widely between stream reaches within a basin, and the method provides specific metrics to identify factors most limiting and most beneficial for steelhead capacity. Such predictions can be used to prioritize and justify investments in habitat restoration or conservation. Factors that limit production are often quite different between stream reaches and even between basins. Given the range of habitat characteristics observed in the test basins, the predictions of steelhead capacity are most affected by the percentage of stream area in pools, alkalinity, and percentage fines in the substrate. Further validation of the model should be pursued at the stream reach level to compare predicted and observed parr densities across a wide range of habitat quality.

## Acknowledgments

Much of the data we used on fish and habitat in test streams was collected by dedicated staff of ODFW and the USFS. We owe special thanks to Steve Johnson of ODFW who helped us obtain detailed data from their studies and answered our many questions about interpretation of their data. The Oregon Building Industry Association funded initial work on model development, and subsequent development was partially funded by both Bonneville Power Administration and Portland General Electric.

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