Spatial Variations in Channel Morphology at Segment and Reach Scales, Middle Fork John Day River, Northeastern Oregon

Patricia F. McDowell

Department of Geography, University of Oregon, Eugene, Oregon

Like many montane rivers in the western U. S., the Middle Fork of the John Day River is characterized by alternating narrow- and wide-valley segments. Although the river has a low gradient (generally \( \leq 0.01 \)) alluvial channel, changes in valley width exert a clear influence on channel morphology. A spatial hierarchical model of channel morphology was applied to the Middle Fork to understand reach-level and segment-level patterns of morphologic variation. Channel unit data for a 55-km long section of the mainstem channel and detailed profiles at segment transitions where the valley width widens or narrows sharply were used in the analysis. Wide-valley segments, where not significantly modified by human activities, have higher sinuosity, 80% more pool area, and pools up to 40% deeper, on average, than narrow-valley segments. Going downstream from a wide-valley segment to a narrow-valley segment, channel morphology changes relatively abruptly from pool-riffle morphology, coarse pebble bed-material, and a gradient of less than 0.005, to plane bed morphology, cobble bed material, and a gradient of 0.005 to 0.010. Within one wide-valley segment, distinct reaches were delineated based on channel pattern and valley position. The more sinuous mid-valley reaches have several times more pool area, and pools more than 25% deeper, than the less sinuous valley-edge reaches. Segment-level differences appear to be related primarily to long term geologic controls, but these differences have been modified by human impacts. Observed reach-level differences are related to both geomorphic controls and human impacts. In this montane setting, the hierarchical spatial model is a useful way of analyzing and understanding spatial patterns of channel morphology and aquatic habitat.

1. INTRODUCTION

The Middle Fork John Day River (referred to as the Middle Fork; Fig. 1) is a medium-sized (fourth- to fifth-order) montane river system in which channel form is influenced by multiple controls, most notably variations in valley form and human impacts. The river flows through a series of alternating wide-valley and narrow-valley segments. These differences in valley width have influenced land ownership and use, with private ranch lands used for cattle pasture dominating in wide-valley segments, and national forest lands in narrow-valley segments. In wide-valley segments, the river channel is generally meandering but has been affected by placer mining, channel straightening, and bank stabilization.
stabilization. In narrow-valley segments, the channel is straighter but shows less direct modification by humans [McDowell, 2000]. Such irregular downstream variations are probably typical of many montane rivers in the western United States. Using the Middle Fork as a case study, this paper addresses the structure and controls of the spatial variations in channel morphology. The implications of these spatial variations for fish habitat and management goals will also be discussed.

A useful approach for analyzing spatial patterns of channel morphology is the hierarchical model in which the river channel is seen as nested elements of increasing scale from the individual pool to the watershed channel network [Frissell et al., 1986; Montgomery and Buffington, 1998]. This model also recognizes that controls of channel form are different at different scales. In this study, the hierarchical model is applied to the Middle Fork. The degree to which reaches and segments are distinct, and the controls of reach-level and segment-level differences in channel morphology will be examined.

1.1. The Spatial Hierarchy in Channel Morphology

Stream channel systems can be seen as a hierarchy of nested morphological units of increasing spatial scale: channel unit, reach, segment, and watershed channel network [Frissell et al., 1986; Montgomery and Buffington, 1998]. A channel unit is a short section of the reach (typically a few channel widths in length) with distinct bed morphology, such as a pool, glide, riffle, or cascade [Bisson and Montgomery, 1996]. A reach is a section of channel, containing tens to hundreds of channel units, that has relatively homogenous channel pattern, slope, sediment size, and bed morphology. A segment is a significant section of the drainage network, containing one or more reaches, that has relatively uniform valley slope and valley form. Segment boundaries are typically defined by a significant change in bedrock lithology, valley form, or drainage area (i.e., at the mouth of a major tributary) [Frissell et al., 1986]. The watershed channel network is composed of several to many segments.

The term reach has been used in two different ways. An ad hoc reach is a predetermined length of channel defined for use as a sampling unit (used by, for example, Kaufmann and Robison [1998] and Fitzpatrick et al. [1998]). An intrinsic reach is a discrete length of channel differing in morphology or size from adjacent reaches (used by, for example, Bisson and Montgomery [1996], Rosgen [1996], U. S. Forest Service [1996], Overton et al. [1997]). A finite number of non-overlapping intrinsic reaches comprise the entire length of the segment. In this paper, reach is used

Figure 1. Map of the Middle Fork John Day River study area, with valley segments.
primarily in the sense of intrinsic reach.

Channel morphology can be analyzed at the channel unit, reach, or segment scales. For example, geomorphologists commonly characterize channel pattern at the reach scale, whereas downstream hydraulic geometry analysis is done at the watershed scale, spanning significant increases in drainage area that occur across multiple segments. Geomorphologists have long recognized the morphological distinctness of channel units, but little attention has been paid to whether and how much channel morphology varies at the reach and segment levels. Geomorphologists have not, until recently, considered variation in channel morphology across spatial scales. Using the scale-explicit framework of reaches and segments should help to identify the major controls of channel morphology at different scales. Frissell et al. [1986] and Montgomery and Buffington [1998] argued that the characteristics and processes controlling channel morphology change as scale changes. They suggested that, when moving from channel units to reaches to segments, the dominant controls of channel form and habitat are expected to shift toward phenomena that operate at larger spatial and temporal scales.

In the case of the Middle Fork, initial observation suggested that channel units are likely controlled by local factors such as flow structures and hydraulic conditions at bankfull stage, large woody debris, and individual manmade structures (bridges, bank stabilization or instream structures), whereas reaches are likely defined and controlled by differences in mass movement inputs, bounding landform, bank material, and riparian vegetation. Human impacts, such as land-use effects, channelization, and diversion, were expected to be expressed mainly at the reach level. Segment-level differences are likely associated with controls such as bedrock geology and valley form. The specific goals of this study are to (1) determine whether morphologically distinct segments and reaches are present in the Middle Fork, (2) identify the controls of channel form and habitat characteristics at the segment and reach levels, and (3) determine the scale(s) at which human impacts on channel morphology are expressed.

The hierarchical spatial model is also useful for understanding aquatic ecology and for river management. At the unit level, steep, fast-water channel units (such as rapids and riffles) are generally important for reaeration, invertebrate production, and fish spawning, whereas flatter, slower water units (various types of pools) provide resting and holding habitat, lower summertime water temperatures, and better cover from predators than adjacent units [Bisson et al., 1982; Hawkins et al., 1993; Bisson and Montgomery, 1996]. Important ecological interactions occur at the reach scale across multiple channel units. For example, over the course of a day, fish will use adjacent pools, riffles, and other units for different activities. Frissell et al. [1986] argued that the spatial hierarchical model provides a framework for representative sampling and monitoring in aquatic ecosystems. Methods of assessing current status and predicting sensitivity to disturbance or potential for recovery are typically applied at the reach scale [Maddock et al., 1995; Rosgen, 1996; Montgomery and Buffington, 1998; Thorne, 1998]. Land ownership and management units within federal lands typically vary at the reach or segment scale.

1.2. Downstream Changes in Channel Morphology

In contrast to the hierarchical model of nested reaches and segments described above, many previous researchers in geomorphology have emphasized progressive downstream changes in channel morphology, controlled by downstream changes in water and sediment inputs (for example, Schumm [1977], Church [1996]). The most familiar example of this view is downstream hydraulic geometry analysis [Leopold and Maddock, 1953], in which channel dimensions are described as a function of increasing discharge or drainage area. In ecology, the river continuum model [Famote et al., 1980] emphasizes progressive downstream changes in physical-habitat structure and aquatic-ecosystem structure.

Although valid for lowland rivers, the progressive downstream change model may be less appropriate in montane rivers. Many montane or bedrock-influenced alluvial rivers have relatively abrupt changes in form and pattern that are independent of drainage area (see for example, Heritage et al. [1999]; Grams and Schmidt [1999]). The most obvious control on these irregular spatial patterns is valley width. Valley form influences channel morphology through direct bedrock influence on the channel, or more indirectly through secondary processes. In many rivers, channels in narrow-valley segments are continuously or intermittently flowing on bedrock. Compared to alluvial channels, bedrock-influenced channels tend to have relatively high gradients, low sinuosity, limited capacity for morphological adjustment, and limited pool development [Montgomery et al., 1996; Montgomery and Buffington, 1998; Tinkler and Wohl, 1998; Wohl, 1998]. Even where bedrock influences are not present, however, the effects of mass wasting processes and peak flow events are different in narrow and wide valleys. Mass wasting from valley walls and debris flows from tributaries have a stronger influence on channel form in narrow-valley segments than in wider valleys, often adding boulders and woody debris
to the channel and constricting the channel [Grant and Swanson, 1995]. Differences in valley width may control spatial patterns of erosion during geomorphically effective floods. Wide valleys can decrease the peak discharge for a given event through decreased velocity in overbank flows that results in temporary storage of some of the runoff [Woltemade and Potter, 1994]. Even for a given discharge, narrow-valleys have higher stage, stream power, and shear stress than wide valleys [Miller, 1995]. These two effects combine to produce greater stream power and shear stress in narrow-valleys, conditions that are reflected in floodplain structure [Nanson and Croke, 1992] and presumably also in channel form. Alluvial channels in narrow-valleys may be expected to have steeper channel gradient, lower sinuosity, and coarser bed material than in wide valleys.

2. STUDY AREA

The John Day River is a tributary of the Columbia River, with headwaters in the Blue Mountains of Oregon. The Middle Fork John Day River is one of three main headwater branches of the John Day system. This paper focuses on the mainstem of the Middle Fork from Big Creek upstream to the junction of Summit Creek and Squaw Creek, including about 55 km of channel length (Fig. 1). The Middle Fork and other headwaters branches of the John Day system provide significant spawning and rearing habitat for both resident and anadromous salmonid fishes. The John Day system, the largest watershed in the Mid-Columbia Basin, lies above only three of the Columbia River dams and is itself one of the longest free-flowing rivers in the United States. Within the Middle Fork, anadromous steelhead (Oncorhynchus mykiss) and bull trout (Salvelinus confluentus) are listed as threatened under the Endangered Species Act, and spring chinook salmon (O. tshawytscha), a species of special concern, also use the study area for spawning and rearing habitat. Although spring chinook in the Middle Fork are not listed under the Endangered Species Act, present populations are estimated to be only 20 to 50% of their historic (ca. 1800 A.D.) numbers. The section of the Middle Fork studied in this paper is the zone used for spawning and holding (occupance during the period of several weeks after the fish return to the spawning site but before spawning begins) by spring chinook [Torgersen et al., 1999].

The Middle Fork is typical of many montane rivers in the western United States in its relief, vegetation, and land use. Drainage area is 915 km² at the downstream end of the study area. The elevation is about 2300 m above sea level on the northern drainage divide. Valley floor elevations range from 1300 m at the upstream end of the study area to less than 1000 m at the downstream end. The geology of the watershed includes both Mesozoic metamorphic rocks and Tertiary volcanic rocks, all relatively resistant to weathering and erosion compared to softer lithologies in this region. Located in the Blue Mountains ecoregion [Clarke and Boyce, 1997], the uplands of the watershed are forested with Ponderosa pine and other conifers, and the valley bottom is a mosaic of forest and meadow. Large woody debris loading is low (less than 40 pieces per km) throughout most of the study section, and it therefore has little influence on channel morphology (except in one segment, discussed in section 4.2).

For most of its length, the mainstem channel of the Middle Fork is alluvial with a bed dominated by coarse gravels to cobbles. Pool-riffle and plane-bed channel reach types predominate. Bankfull width ranges from about 25 m at the downstream end of the study area to less than 10 m at the upstream end. Individual pools and riffles are commonly two to four bankfull widths in length, but their sizes vary widely. Riffles 10 to 50 bankfull widths in length were identified throughout the system; the longer riffles are in effect plane-bed reaches.

3. METHODS AND DATA SOURCES

Fourteen valley segments, labeled A (downstream) to M (upstream), were defined a priori on the basis of changes in valley width evident on topographic maps [Frissell et al., 1986; Church, 1996] (Fig. 1). Specific placement of segment boundaries was guided by tributary confl uences and cultural features (bridges, mine tailings), in addition to changes in valley width. After identification of segment boundaries, U. S. Geological Survey digital raster graphic files of 1:24,000-scale topographic maps were used to measure drainage area for each segment and valley width at 200 m intervals along the main channel. A reach-level analysis was conducted within segment E. The channel in segment E was divided into six intrinsic reaches based on pattern and channel morphology recognizable in aerial photos.

Independently of segment and reach identification, channel unit data for the entire study area were obtained in a field survey in late summer 1996, following standard stream inventory procedures [U.S. Forest Service, 1996; Bisson and Montgomery, 1996]. More than 1000 channel units were identified in the 55-km long section of mainstem channel. Data recorded for each channel unit included unit type (pool, riffle, etc.), length, wetted width, average water
depth, maximum water depth for pools, presence of woody debris, and presence of channel modifications such as bank stabilization with rip-rap. These data, which represent physical habitat characteristics during summer conditions (low flow), were used to examine segment-level and reach-level variations in channel morphology and habitat characteristics. Because summer water temperatures in the Middle Fork are predominately above optimal or even limiting temperatures for anadromous salmonids, and abundant and deep pool habitat is particularly important for the survival of these fish [Torgersen et al., 1999], analysis focused on pool characteristics.

Channel planform was investigated using 1939 and 1990 aerial photos [U. S. Forest Service, 1939, 1990]. The aerial photos were scanned and rectified to the U.S. Geological Survey digital raster graphic files. The mainstem channel and side channels were digitized from the rectified 1939 and 1990 images. The channel unit data were linked to the 1990 stream channel using a dynamic segmentation procedure with GIS software [Environmental Systems Research Institute, 1996; Radko, 1997]. Channel length for each segment was calculated from unit lengths.

After identification of valley segments and initial analysis of segment-level differences, three segment transitions (ad hoc reaches spanning the boundary between two segments) were selected for detailed field study. At another transition where a continuous survey was not appropriate, noncontiguous, representative ad hoc reaches within each segment were surveyed. Each transition included one reach in the downstream part of the upstream segment, and the adjacent reach in the downstream segment. Longitudinal profiles were surveyed using an electronic total station, and bed-material size measurements [Wolman, 1954] were done at three representative riffles in each reach.

Data visualization with boxplots was used in the analysis [Cleveland, 1993]. Formal statistical tests (analysis of variance or covariance, or the equivalent nonparametric tests) were not used because at least one of the underlying assumptions (independence, normality, homogeneity of variance) is violated in each case, even after the variables are suitably transformed. For example, Bartlett’s and Levene’s tests for homogeneity of variance [Underwood, 1997] both indicate that the variance of average depth differs significantly across segments (p < 0.001 in both cases), and the results are the same for log transformed values of average depth. The non-normality and heterogeneity of variance are evident in the boxplots (presented in sections 4.2 and 6).

4. SEGMENT-LEVEL ANALYSIS

4.1. Description of Segment-level Differences in Valley Form

Valley segments in the Middle Fork study area are 1.3 to 8.5 km long (Table 1), and average valley width by segment ranges from 100 m to 400 m (Fig. 2a). There is no pattern of increasing valley width going downstream. Within each segment, valley width is variable, but many segment boundaries show a distinct shift in valley width. The study area has a distinct pattern of alternating wide- and narrow-valley segments, shown most clearly in segments E through I; channel morphology in these segments will be analyzed in more detail below.

At most segment boundaries, there is an abrupt transition (less than 400 m long) in valley width. The specific controls of these width changes are not evident, but lithologic change and fault structures probably control most segment boundaries. About one-half of the segment boundaries are related to geologic boundaries (Table 2; Brown and Thayer [1966]; Walker and MacLeod [1991]), but similar geologic changes also occur within segments and without any expression in valley width. There are relatively few faults mapped in the study area, and none of the boundaries is related to a mapped fault. Neither is there any apparent influence of geomorphic controls, such as terraces or tributary junctions, on valley width changes at segment boundaries.

In narrow-valley segments A through D, F, H, and J, valley width is 10 bankfull channel widths or less, and the channel is intermittently in contact with the valley wall, colluvial deposits, or the embankment of a county road built down the valley floor. Thus meanders do not develop fully. In the wide-valley segments, particularly segments G, I, K and N, valley width is 10 to 30 bankfull channel widths, and the channel is generally unconfined and not in contact with the valley wall. Even in the narrow-valley segments of the Middle Fork, however, the channel is an alluvial channel without significant bedrock control. Bedrock in the channel bed was observed at only a few isolated points in segments A, E, and L.

4.2. Differences in Channel Morphology

The spatial pattern of valley form described above is reflected in the channel morphology of the Middle Fork. Based on field inspection, wide-valley segments tend to be dominated by pool-riffle reaches. Narrow-valley segments have more plane-bed reaches, although they also contain

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pool-riffle reaches. Wide-valley segments are likely to have more fully developed meanders and broader floodplains. Sinuosity in 1939 (before substantial channel straightening and dredge mining) was about 1.5 in wide-valley segments E, G and I, and 1.2 in narrow-valley segments F and J (Fig. 2B). Narrow-valley segment H also had high total sinuosity in 1939, due to several reaches with two active channels. Marked decreases in sinuosity occurred between 1939 and 1990, due to channel straightening, loss of side channels, and road encroachment in a few places [McDowell, 2000]. The result of these human impacts is that the wide-valley segments today have sinuosity no higher than the narrow-valley segments (Fig. 2B).

The wide-valley segments also tend to have higher pool area (Fig. 2C), although human impacts in some segments have modified this pattern. Of particular interest is the downstream sequence of segments I, H, G, and F that shows the strongly alternating pattern of pool area. Wide-valley segments G, I, and N all have more than 50 % of their channel area in pools during summer flow conditions. Apart from segment M, the narrow-valley segments have more of their low-flow channel area occupied by riffles and, in smaller proportion, glides. Narrow-valley segment M has anomalously high pool area, probably because of abundant large wood pieces in the channel. (Large woody debris loading is 137 pieces/km in segment M. Large woody debris loading is generally less than 40 pieces per km in other segments, and has little or no influence on channel morphology.) In the wide-valley segments (excluding segment E), the percentage of the channel area in pools is 80% or more greater than in the narrow-valley segments. Direct human modification of the channel (Table 1) has influenced pool abundance in segments C, E, G, J, and K. In wide-valley segment E, several sections of channel have been slightly straightened and rip-rapped, and several meanders have been cut off [McDowell, 2000].

<table>
<thead>
<tr>
<th>Segment</th>
<th>Segment length, km</th>
<th>Number of channel units</th>
<th>Drainage area at downstream end (km²)</th>
<th>Valley type</th>
<th>Land ownership and recent land use on valley floor</th>
<th>Major human channel modifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.05</td>
<td>50</td>
<td>915</td>
<td>Narrow</td>
<td>Private lands; limited grazing</td>
<td>Road encroachment</td>
</tr>
<tr>
<td>B</td>
<td>3.05</td>
<td>46</td>
<td>908</td>
<td>Intermediate</td>
<td>Mixed national forest and private; grazing</td>
<td>Channel straightening</td>
</tr>
<tr>
<td>C</td>
<td>4.40</td>
<td>71</td>
<td>886</td>
<td>Narrow</td>
<td>Mixed national forest and private; grazing and residential grazing</td>
<td>Placer mining, straight channel constructed</td>
</tr>
<tr>
<td>D</td>
<td>3.24</td>
<td>41</td>
<td>857</td>
<td>Narrow</td>
<td>Mixed national forest and private; grazing</td>
<td>None</td>
</tr>
<tr>
<td>E</td>
<td>8.49</td>
<td>112</td>
<td>662</td>
<td>Wide</td>
<td>Private lands; grazing, nature preserve</td>
<td>Channel straightening, rip-rap</td>
</tr>
<tr>
<td>F</td>
<td>3.20</td>
<td>53</td>
<td>580</td>
<td>Narrow</td>
<td>National forest; limited grazing</td>
<td>None</td>
</tr>
<tr>
<td>G</td>
<td>3.40</td>
<td>76</td>
<td>554</td>
<td>Wide</td>
<td>Private lands; grazing</td>
<td>Placer mining, straight channel constructed</td>
</tr>
<tr>
<td>H</td>
<td>8.34</td>
<td>191</td>
<td>465</td>
<td>Narrow</td>
<td>National forest</td>
<td>None</td>
</tr>
<tr>
<td>I</td>
<td>5.69</td>
<td>133</td>
<td>403</td>
<td>Wide</td>
<td>Private lands; grazing</td>
<td>Bank stabilization with barbs</td>
</tr>
<tr>
<td>J</td>
<td>1.50</td>
<td>32</td>
<td>317</td>
<td>Narrow</td>
<td>Private; former sawmill site</td>
<td>Channel straightening</td>
</tr>
<tr>
<td>K</td>
<td>1.31</td>
<td>45</td>
<td>171</td>
<td>Wide</td>
<td>Private lands; grazing</td>
<td>Channel straightening</td>
</tr>
<tr>
<td>L</td>
<td>1.52</td>
<td>40</td>
<td>150</td>
<td>Narrow</td>
<td>Private lands; grazing</td>
<td>None</td>
</tr>
<tr>
<td>M</td>
<td>4.21</td>
<td>143</td>
<td>140</td>
<td>Narrow</td>
<td>Mainly national forest; grazing</td>
<td>None</td>
</tr>
<tr>
<td>N</td>
<td>1.32</td>
<td>51</td>
<td>113</td>
<td>Wide</td>
<td>Private lands; grazing</td>
<td>None</td>
</tr>
</tbody>
</table>
segment E has pool area similar to narrow-valley segments, but it is probable that segment E had pool area similar to segments G and I before human alterations. Segments C and G both have channels created by dredge mining of placer gold deposits in the 1940s and 1950s; the dredged channels have moderately high pool area (gray circles on Fig. 2C). Segment G also contains a meandering channel that is now a side channel but was the main channel before dredge mining. This meandering channel has high pool area typical of wide-valley, meandering channels (black circle on Fig. 2C).

Five alternating wide- and narrow-valley segments, E through I, were analyzed in more detail. The boxplots (Fig. 3A) show that maximum pool depth is greater in wide-valley segments than in adjacent narrow-valley segments. Although there is considerable overlap in the range of maximum pool depth across these five segments, in all three wide-valley segments (E, G, and I), the median value of maximum pool depth is greater than the 75th percentile for the narrow-valley segments (F, H). The magnitudes of differences between wide-valley and narrow-valley segments were evaluated by comparing the average values. Maximum pool depth is 20 to 30% greater in wide-valley segments than in narrow-valley segments. Along with its lower sinuosity and pool area compared to other wide-valley segments, segment E also has lower maximum pool depth than segments G and I. This may be due to human-caused channel straightening, particularly cutting off of some large meander loops and
loss of the large deep pools that typically form at meander bends. Average depth of pools was also compared, and it has a similar pattern to the pattern of maximum pool depth. Average wetted (summer flow) depth of all channel unit types (Fig. 3B) shows a similar but less distinct pattern; wide-valley segments tend to have channels 16 to 48% deeper during summer flow conditions than do narrow-valley segments. The pattern for wetted (summer flow) width (Fig. 3C) shows both downstream increase and alternation between wide-valley (I, G) and narrow-valley (H, F) segments. Narrow-valley segments have channels 18 to 37% narrower than adjacent wide-valley segments (except for segment E).

5. SEGMENT TRANSITIONS

To confirm observed differences between wide- and narrow-valley segments in the segment-average data, detailed total-station field surveys of adjacent ad hoc reaches in wide- and narrow-valley segments were done. At three sites, continuous surveys were made through the transition from wide- to narrow-valley or vice versa. At a fourth transition (segments H to G), a continuous survey was not appropriate because there was a short intervening reach strongly influenced by bedrock constraint and a bridge, so two nearby representative ad hoc reaches were surveyed. Longitudinal profiles of the noncontiguous reaches, in segments G and H, are shown in Fig. 4A. Segment H has a narrow valley, and segment G has a wide valley. The surveyed reach in segment G is on the meandering channel that was not dredge mined. The surveyed reach in G displays clear pool-riffle morphology, whereas the surveyed reach in segment H is a plane-bed reach with a few pools present. The surveyed reach in G also has a slightly lower slope and generally finer bed material than that in H. These two reaches are representative of the difference between narrow- and wide-valley segments.

For two of the three transitions with continuous surveys, channel morphology changes abruptly at the segment boundary. The downstream transition from wide-valley segment N to narrow-valley segment M corresponds to a decrease in pool depth, increase in slope and increase in bed-material size (Fig. 4B). Likewise, the downstream transition from wide-valley segment E to narrow-valley segment D also corresponds to a decrease in pools and an increase in slope and bed-material size (Fig. 4C). The detailed surveys at segment boundaries, therefore, show spatially abrupt changes in channel morphology that are consistent with the segment-level differences between wide and narrow valleys. The expected progressive downstream changes in channel morphology are reversed in these two examples.

The fourth transition survey, going from narrow-valley segment F downstream to wide-valley segment E (Fig. 4D) does not show a change in channel characteristics. Bed-material size and slope are relatively constant across the transition, and pools are relatively infrequent throughout the two reaches. The absence of channel change at this transition appears to be due to local geomorphic factors not captured in the process of delineating segments. Although the valley widens at the segment E/F boundary, much of the valley floor in this area is occupied by a large alluvial fan built by a major tributary, Big Boulder Creek (Fig. 5). Big Boulder Creek enters on the right side, and the Middle Fork mainstem channel occupies a narrow floodplain strip along the left valley wall. Consequently, the Middle Fork is effectively confined in the surveyed reach in E by the alluvial fan, creating narrow-valley conditions.
6. REACH-LEVEL ANALYSIS

Segment E was selected for an analysis of reach-level differences in channel morphology because it is a long, wide-valley segment with space to develop unconfined meanders. It also has had substantial human alteration of the channel and is therefore a good place to evaluate the relative influence of natural controls and human influences on reach-level morphology. The goals of the reach-level analysis were to determine whether there are morphologically distinct reaches within a segment, whether reach-level morphological differences are more or less distinct than segment-level differences, and what are the controls of morphological differences among reaches. Examination of the channel in segment E on aerial photos and in the field revealed that the most obvious differences in channel form were differences in channel pattern (well developed meanders vs. low sinuosity) and channel position (against the valley wall or in mid-valley), so these characteristics were used as the basis for delineating reaches. Six intrinsic reaches (Table 3), ranging from 500 to 3400 m in length, were identified on aerial photos. Reach E1 is at the downstream end of segment E, and reach E6 is at the upstream end.

In segment E, reaches alternate between very low sinuosity reaches and moderate sinuosity reaches with alternating bars. Sinuosity is related to channel position and constraint by valley walls. The three longest reaches, E2, E4, and E6, all have low sinuosity and are located at or very near
to the valley edge (Table 3). E2 and E4 were significantly straightened by direct human action between 1939 and 1990 [McDowell, 2000]; large meander loops were cut off. These two reaches account for most of the loss in sinuosity in segment E (Fig. 2B). Reach E6 was already low sinuosity and located against the valley wall in 1939. In part of reach E6, however, old meander scars are visible on the 1939 and 1990 aerial photos, indicating that it did have higher sinuosity in the recent past. The other three reaches, E1, E3, and E5, are located in mid-valley positions, are bounded by floodplain deposits and have higher sinuosity (Table 3). All of the reaches in segment E are also significantly affected by bank structures (rip-rap and bank barbs) constructed of rock.

Reach-to-reach differences in channel morphology and habitat characteristics are significant in segment E. Pool area is 17% greater in reach E1, and several times greater in E3 and E5, than in the low sinuosity, valley-edge reaches (Table 3). In reach E5, many of the pools are associated with bank barbs (which tend to create scour and therefore force pools), but these pools are mainly located on meander bends where self-formed pools would be expected. In reaches E1 and E3, however, pools are generally self-formed, and few are associated with bank barbs.

Maximum pool depth is 26 to 39% greater, and average depth of all units is 11 to 44% greater, in reaches E1, E3, and E5 than in the low sinuosity reaches (Table 3). In reach E5, many of the pools are associated with bank barbs (which tend to create scour and therefore force pools), but these pools are mainly located on meander bends where self-formed pools would be expected. In reaches E1 and E3, however, pools are generally self-formed, and few are associated with bank barbs.

Figure 4. Channel longitudinal profiles and slopes (S) at segment transitions. The upper line is the water surface and the lower line is the channel bed. Elevations are tied to an arbitrary site datum. Triangles show locations of bed material samples. The median size in mm (D50) is shown for each sample. (A) Noncontiguous ad hoc reaches near the segment H-G boundary. (B) Transition of segments M to N. (C) Transition of segments D to E. (D) Transition of segments E to F.
be associated with a shift to plane-bed channel type and with increased riffle area, but the reasons for the width difference are not clear.

7. DISCUSSION AND CONCLUSIONS

The Middle Fork displays a distinct alternating pattern of wide- and narrow-valley segments, and morphologically distinct reaches are present within segment E. The segments contain tens to hundreds of channel units, and the reaches contain up to a few tens of channel units, consistent with the hierarchical spatial model of channel morphology [Frissel et al., 1986; Montgomery and Buffington, 1998]. Clear differences in channel morphology and habitat characteristics are evident between wide- and narrow-valley segments. Wide-valley segments without major human modifications have higher sinuosity, more pool area, and deeper pools than narrow-valley segments. Wide-valley segments with the most intense human modifications of the channel have channel morphology similar to that of narrow-valley segments. Detailed surveys at segment transitions show that the channel morphologic changes from wide-valley to narrow-valley segments occur abruptly. Going downstream from a wide-valley to a narrow-valley segment, the alluvial channel becomes slightly steeper and coarser in bed material, and bed morphology changes from pool-riffle to plane bed. Thus, even the moderate valley width changes observed in the Middle Fork, without bedrock control on the channel, can produce reversals of typical downstream patterns of channel morphology and habitat characteristics [Leopold and Maddock, 1953, Vannote et al., 1980].

Reach-level differences in channel morphology are also distinct in segment E. Compared to the less sinuous valley-edge reaches, the more sinuous mid-valley reaches have two to five times more pool area, and the pools are deeper by 25% or more. The valley-edge reaches have channel characteristics similar to narrow-valley segments. In the Middle Fork, segment-level differences in channel morphology are about equal in magnitude to reach-level differences within segment E.

The specific causes of the observed spatial variations in channel morphology in the Middle Fork are complex. Segment-level differences in channel morphology appear to originate primarily in natural controls. Human influences have, to a certain extent, overwritten the effects of natural controls. Land use has been more intensive, and therefore it has had more impact on channel morphology, in wide-valley segments than in narrow-valley segments. Reach-level differences in segment E are due to a combination of natural controls (channel position) and human influences (straightening, bank structures). In this study, there are not

Table 3. Reach characteristics in segment E

<table>
<thead>
<tr>
<th>Reach</th>
<th>Length (m)</th>
<th>Number of channel units</th>
<th>Channel position and Morphology</th>
<th>Sinuosity&lt;sup&gt;a&lt;/sup&gt; 1989</th>
<th>Structures&lt;sup&gt;b&lt;/sup&gt; (% length of units)</th>
<th>Area in pools (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>934</td>
<td>17</td>
<td>At valley contraction; mid-valley; pool-riffle</td>
<td>1.35</td>
<td>36.9</td>
<td>29.8</td>
</tr>
<tr>
<td>E2</td>
<td>1654</td>
<td>19</td>
<td>At right valley footslope; plane bed with some pools</td>
<td>1.00</td>
<td>49.8</td>
<td>25.5</td>
</tr>
<tr>
<td>E3</td>
<td>939</td>
<td>21</td>
<td>Crossing valley; pool-riffle</td>
<td>1.33</td>
<td>54.4</td>
<td>50.2</td>
</tr>
<tr>
<td>E4</td>
<td>1054</td>
<td>19</td>
<td>At left valley footslope; pool-riffle</td>
<td>1.06</td>
<td>41.8</td>
<td>9.7</td>
</tr>
<tr>
<td>E5</td>
<td>519</td>
<td>9</td>
<td>Mid-valley; pool-riffle with forced pools at bank barbs</td>
<td>1.14</td>
<td>59.5</td>
<td>65.7</td>
</tr>
<tr>
<td>E6</td>
<td>3390</td>
<td>27</td>
<td>At left valley footslope; plane bed</td>
<td>1.01</td>
<td>56.7</td>
<td>12.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Total sinuosity (including length of side channels with water at low flow conditions)

<sup>b</sup> Structures include rip-rap and bank barbs.
clear differences in the controls of channel morphology at reach- and segment-level.

Torgersen et al. [1999] found that habitat use by spring chinook in the Middle Fork is unevenly distributed at both the channel unit level and reach level. Pools, particularly deep pools, are intensely used by adult salmon for holding. Pools typically are relatively cool, and in much of the study area, deep pools are the only form of cover available. Analyzing ad hoc 1-km long reaches, Torgersen et al. found that chinook selected relatively cool reaches with low W:D ratios and more abundant and deeper pools. In the present analysis, these characteristics are found to be associated with wide-valley segments, and with mid-valley reaches within segment E. Segment-level and reach-level patterns of channel morphologic variation therefore are potentially important for fish habitat.

The results of this study show that channel morphologic characteristics that are important for fish habitat have uneven spatial patterns. Channel morphology varies in a non-progressive manner from segment to segment and from reach to reach. This heterogeneity in geomorphic characteristics creates large to small patches of more favorable habitat for salmonids. For example, wide-valley segments have higher habitat potential, in that they have the ability to develop more and deeper pools than narrow-valley segments. Some reaches within wide-valley segments, however, may have fewer and less deep pools, with pool characteristics similar to narrow-valley segments. In segment E of the Middle Fork these reaches with reduced pool area and depth were associated with human modifications and valley edge positions. The best of the wide-valley segments and reaches may provide models of “restoration potential” [Torgersen et al., 1999].
Recognizing the spatial scale of these morphological segments and reaches is also important for aquatic habitat management and for planning projects to improve aquatic habitat. Reach to reach differences in channel morphology are important, and reaches are potentially useful as small scale management units. Management prescriptions and restoration projects should be designed at the reach level.

Acknowledgments. This research was supported by The Environmental Protection Agency Water and Watersheds Program, grant R-824774-01 to University of Oregon. Bruce McIntosh and Christian Torgersen of Oregon State University provided the stream inventory data. Steven Jett, Hudson Henry, Jennifer Pierce and Andrew Mowry of University of Oregon assisted in GIS analysis and field work.

REFERENCES


Environmental Systems Research Institute, ARC/INFO GIS version 7.0.4, Environmental Systems Research Institute, Inc., Redlands, Calif., 1996.


U.S. Forest Service, Umatilla National Forest Project no. F. S. 6-21, symbol BTU [aerial photos], scale 1:20,000, 1939.


Patricia F. McDowell, Dept. of Geography, University of Oregon, Eugene, OR, 97403-1251