**From: [Grays River Watershed: Geomorphic Analysis](#) prepared by Herrera Environmental Consultants, August 2005, for Pacific Northwest National Laboratory**

*Meanders*

Historical trends in the radius of curvature (rc) of meanders can be used to evaluate channel stability. For instance, stable meanders are typically characterized by a large rc value, whereas channel instability in the form of bank erosion and avulsion can occur as a meander bend tightens and meander amplitude increases. Temporal changes in rc values can also be used to forecast trends in bank erosion and the potential for channel avulsion.

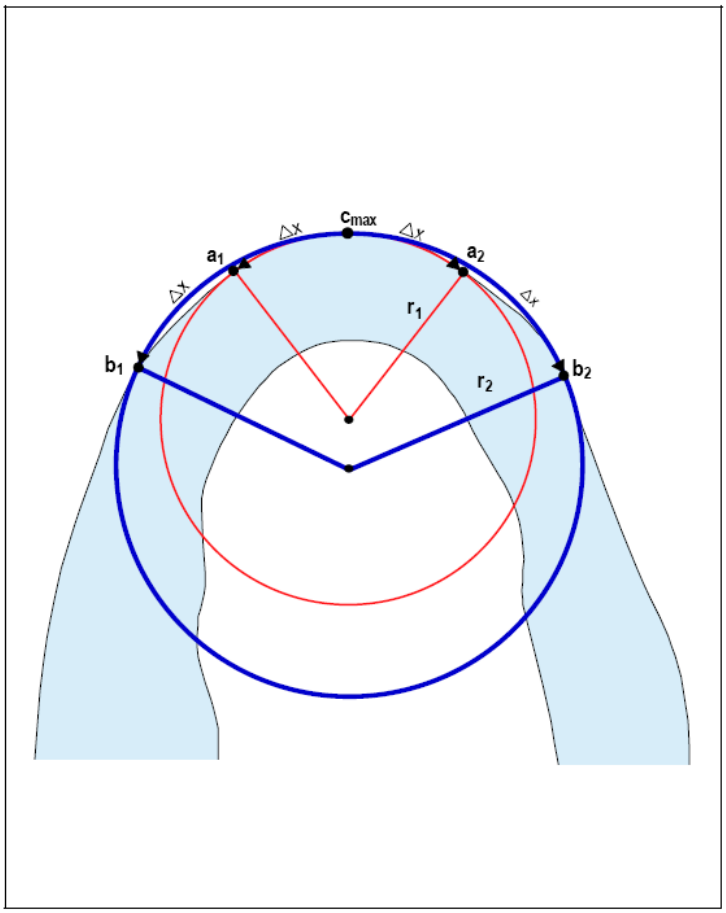


Figure 22. Schematic diagram of the measurement of radius of curvature of a meander bend (adapted from Nanson and Hickin 1983).

Temporal variations in meander geometry and channel stability of the Grays River response reach were evaluated in terms of the radius of curvature of channel meanders measured from historical aerial photographs, based on methods developed by Nanson and Hickin (1983). Channel width (w) was measured at several inflection points along the channel. The average channel width was then used as the length of an arc (Δx) placed around the outside of the meander bend, starting from the point of maximum curvature (cmax) (Figure 22). Two arcs with length Δx were traced on the outside of the bend to create points a1, a2, b1, and b2. Two circles were fitted through a1, cmax, and a2; and b1, cmax, and b2. The average of the radii of these two circles (r1, r2) is reported as rc of the meander bend.

The radius of curvature was measured for each of the five meander bends identified in the 1939–1996 aerial photographs and the three bends evident in the 2003 photographs. Bend 1 is located at the upstream extent of the Gorley subreach within the bedrock-confined segment. Bend 2 is located downstream of Bend 1 along the southern bedrock margin of the floodplain (Figure 23).

Bend 3 is located north of the Gorley property and includes the Crazy Johnson Creek subreach along the upstream segment of Bend 3 and the confluence with the West Fork at the downstream segment of Bend 3. The left bank along the inside of Bend 3 is defined by a gravel levee and rock revetment constructed in the early 1960s. The northern and western extents of Bend 3 are defined by bedrock along the valley edge in the vicinity of the West Fork confluence. The meander neck between Bends 3 and 4 is confined by levees on both sides. The outside (left) bank of Bend 4 is also armored with a gravel/rock revetment and a series of groin walls constructed between the 1982 and 1996 aerial photographs (Figure 23). Bend 5 is located upstream of the State Highway 4 bridge and is unconfined by levees but is partially confined by bedrock along the right bank.

Table 20. Radii of curvature for each Grays River meander bend measured for the period of record (1939–2003).

| Bend Number | Radius of Curvature (meters) | | | | | |
|---|---|---|---|---|---|---|
| | 1939 | 1966 | 1970 | 1982 | 1996 | 2003 |
| 1 | 247 | 458 | 417 | 427 | 648 | 672 |
| 2 | 202 | 314 | 195 | 194 | 168 | a |
| 3 | 120 | 132 | 272 | 142 | 91 | a |
| 4 | 112 | 124 | 132 | 119 | 131 | 216 |
| 5 | 79 | 74 | 95 | 112 | 99 | 103 |

a. Bends 3 and 4 were cut off by the 1999 avulsion events.

Meander geometry was also evaluated from trends in bend curvature by normalizing the radius of curvature by the channel width (rc/w). Normalizing the radius of curvature by width allows for a scale-independent comparison of results with prior studies. In a study of the Beatton River in British Columbia, Nanson and Hickin (1983) showed that the meander migration rate (bank erosion) is greatest where rc/w falls between 2.5 and 4 (Figure 25). Bank erosion is considerably less for rc/w outside this range. Bagnold (1960) found that when rc/w falls below a threshold of 2, the formation of large eddies generates flow resistance that inhibits bank erosion and continued

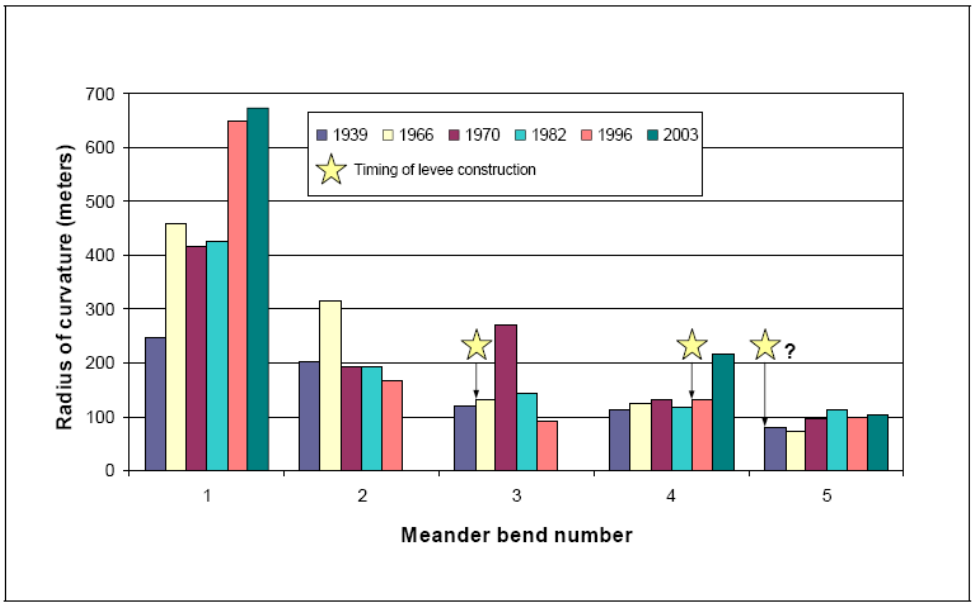


Figure 24. Average radius of curvature for five meander bends on the Grays River, Washington, during the period of record (1939-2003).
Note: Meander Bends 3 through 5 have been influenced by levee construction. The timing of levee construction is indicated by stars.

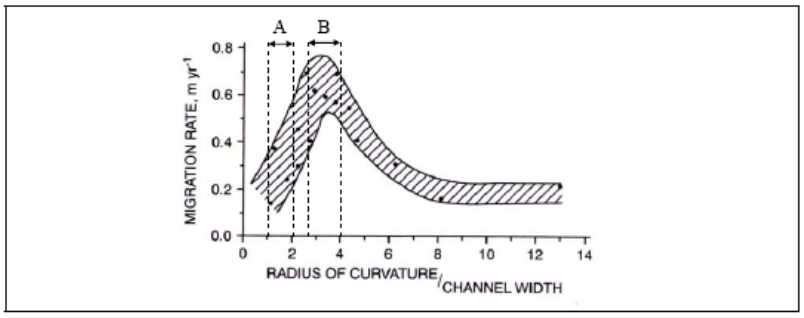


**Figure 25. Meander migration rate versus bend curvature ($r_c/w$) for the Beatton River, British Columbia (Nanson and Hickin 1983), illustrating optimal range of channel avulsions for $1 < r_c/w < 2$ (A) and maximum migration rate for $2.5 < r_c/w < 4$ (B).**

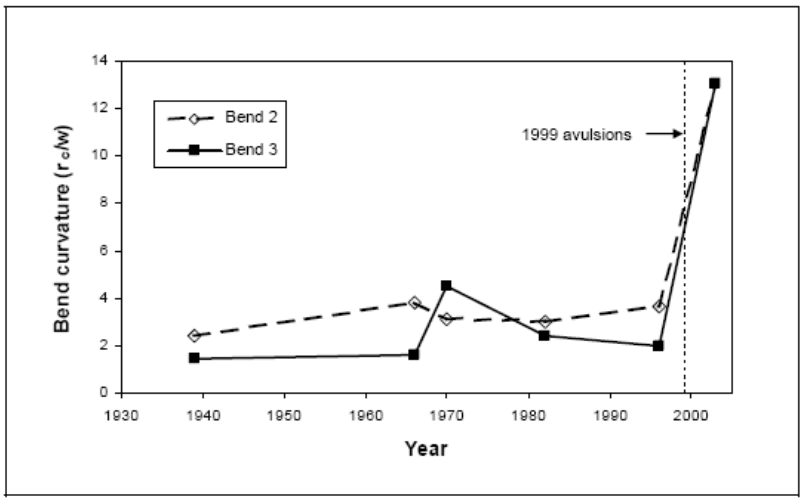


**Figure 26. Temporal variation in meander bend curvature relative to the 1999 avulsions in the Grays River, Washington.**

meander migration, thereby shifting channel adjustment from bank erosion to avulsion between meander bends. Results from similar studies indicate that the decline in bank erosion in tight meander bends, where rc/w is less than 2, can lead to a channel avulsion through a chute or neck cutoff of the meander. In a study of Welsh rivers, Lewis and Lewin (1983) found that the maximum frequency of chute and neck avulsions coincided with rc/w between 1 and 2.

Historical trends in bend curvature for Bends 2 and 3 leading up to the 1999 avulsions on the main stem Grays River are presented in Figure 26. Although rc/w in Bend 2 fluctuated about the upper envelope of the critical range, rc/w in Bend 3 (the site of the larger avulsion) declined to 2.0 (or possibly lower) prior to the 1999 avulsion. Based on a comparison with similar studies, the reduction in rc/w through Bend 3 from 1970 to 1996 may have contributed to the 1999 avulsion.

## Sinuosity

Sinuosity of the main stem Grays River was calculated from the ratio of channel length to straight-line valley length (a channel flowing along the centerline of avalley has a sinuosity of 1). Channel and valley lengths were measured in GIS from the digitized historical channels for the period of record (1939–2003). The historical trends in sinuosity are presented in Figure 27. Results indicate that sinuosity of the main stem declined steadily from 1.37 to 1.33 between 1939 and 1966. Meander growth after 1966 caused a rapid increase in sinuosity to 1.46 by 1982.

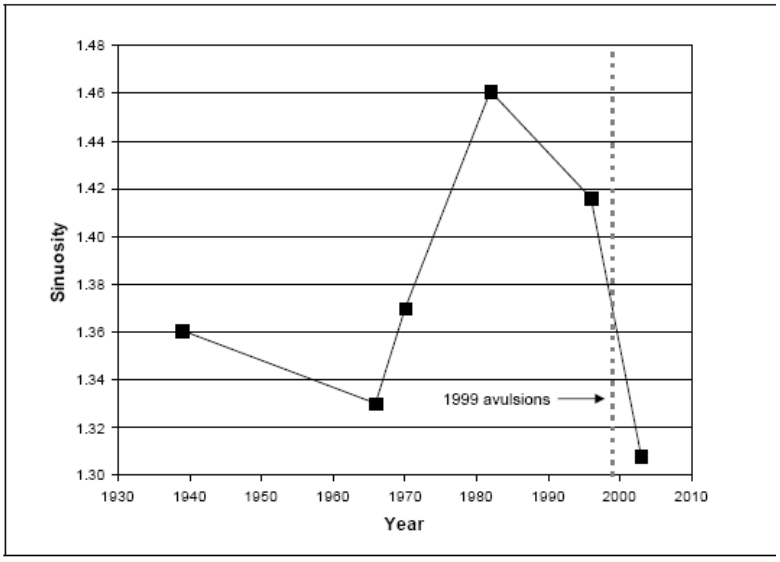


**Figure 27. Temporal variation in sinuosity of the main stem Grays River.**

Thereafter, sinuosity decreased rapidly to 1.42 by 1996 and declined further to 1.31 by 2003 following the channel avulsion event of 1999.

The reduction in sinuosity through 1966 is consistent with the trends predicted by Equation 4 following an increase in sediment supply from timber harvest. The increase in sinuosity during the 1970s followed the construction of levees in the 1960s. The levees locked portions of the channel into their 1960s alignment and focused migration to shorter, unconstrained segments, where meander growth between 1966 and 1982 increased sinuosity. Sinuosity declined sharply after the 1999 avulsions as a result of channel shortening.

*Vertical Channel Adjustment*

Vertical changes in the elevation of alluvial surfaces caused by the 1999 avulsion were assessed by comparing profiles and cross-sections constructed along the channel alignments delineated from the 1996 and 2003 aerial photographs (see Figure 21). Longitudinal profiles were constructed using surface elevations at the edge of water in the 2004 PNNL survey of the response reach (Figure 28). Cross-sections were also constructed from topographic data derived from this survey (Appendix I). In Figure 21, the 2003 profile extends from Bend 1 at the upstream end of the Gorley subreach to the bridge at the downstream end of the Highway 4 subreach. The 1996 profile extends from point A, crosses the 2003 alignment at point B, and joins the 2003 profile at point C.

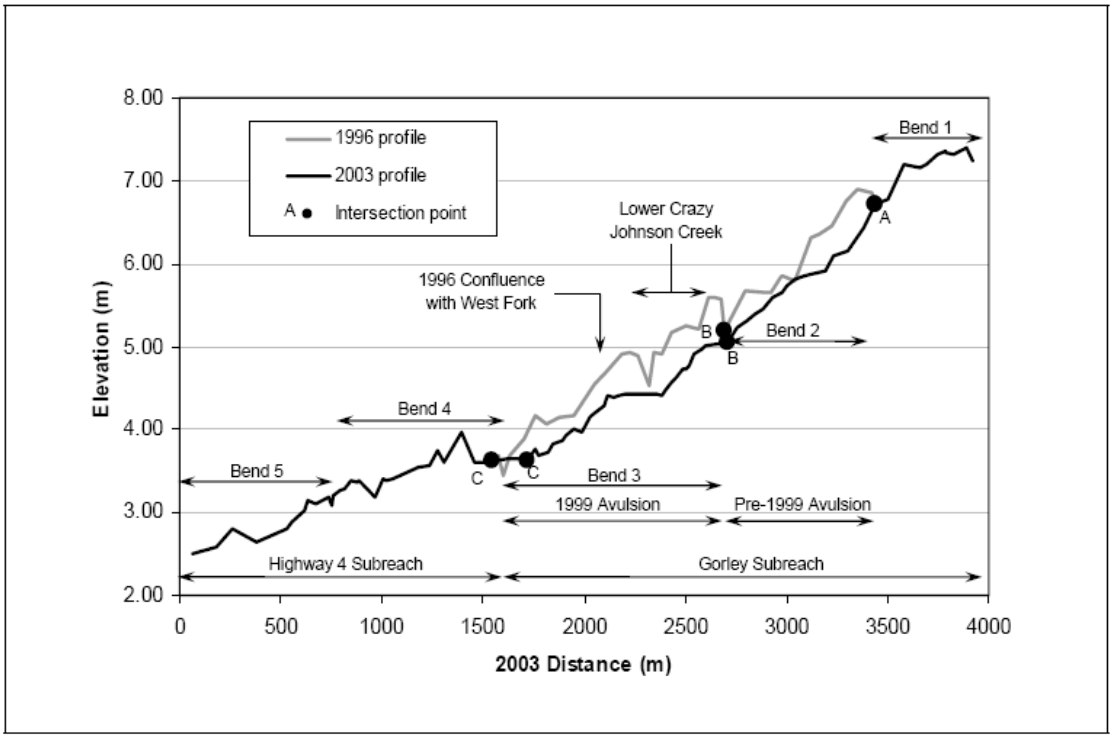


**Figure 28. Channel profile of the Grays River response reach from State Highway 4 to the bedrock canyon.**

The 1999 avulsions decreased the length of the main stem by approximately 117 meters (the offset at point C in Figure 28) and increased the reach gradient from 0.16 percent to 0.18 percent. Most of the channel shortening and increase in gradient occurred through Bend 3. Subsequent meander development in the

new channel above point C since the 2003 aerial photograph has increased the channel length through Bend 3.

A comparison of the 1996 and 2003 profiles in Figure 28 suggests that the 1999 avulsions were triggered either by aggradation downstream of points A and B along the old (1996) channel alignment, or by levee failure and relocation through Bend 3 to an ancient channel alignment at a lower elevation, or by a combination of these two mechanisms. Field reconnaissance confirms the recent deposition of sediment along the 1996 alignment downstream of point B. A comparison of the profiles indicates up to 0.6 meters of aggradation along 1,900 meters of the river between 1996 and 2003. Based on the average width of the active channel in 1996 (100 meters), this change in bed elevation represents the deposition of approximately 114,000 cubic meters (194,000 tons) of sediment during this 7-year period, or approximately 10 percent of the estimated 1.5 million tons of sediment delivered to the entire channel network of the upper Grays River watershed (but not necessarily routed to the lower response reach) during this same period. Observations of historical channel conditions are summarized in Table 21.

**Table 21. Summary of historical observations for the main stem Grays River.**

| Location | 1939–1966 | 1966–1970 | 1970–1982 | 1982–1996 | 1996–2003 |
|---|---|---|---|---|---|
| Between Bend 1 and Bend 2 | Wide active channel; north bank migrates south. | No significant change in channel position. | Active channel narrows. | Active channel widens to the north. | Secondary channel to the south is abandoned. |
| Bend 2 | Inside bank retreats south; side channel to Crazy Johnson Creek abandoned. | Minor shift to north of outside bend of active channel. | Active channel width decreases; thalweg translates to north of vegetated island; secondary channel forms south of island. | Thalweg moves to the south; north alignment becomes secondary channel; dense vegetation on mid channel island. | Thalweg abandons south channel and avulses to the north through vegetated island. |
| Bend 3 (upstream) | Thalweg contacts bedrock point and migrates south; vegetated island forms southeast of bedrock. | No significant change in channel location. | Meander translates downstream and contacts bedrock; radius of curvature tightens and flows through Crazy Johnson Creek. | Thalweg abandons small radius of curvature in north bend and erodes through vegetated island; flow splits between Bends 2 and 3. | Bend abandoned during large avulsion through levee and Gorley property. |
| Bend 3 (downstream) | Thalweg migrates northwest against bedrock at West Fork confluence; levees constructed along inside bend and between Bends 3 and 4 in early 1960s. | Migration rate to northwest decreases; midchannel islands densely vegetated. | Channel continues to erode to the west; radius of curvature tightens; sinuosity increases. | Split flow captures Crazy Johnson Creek and West Fork Grays River and joins main stem between Bends 3 and 4. | Bend abandoned by large avulsion; West Fork confluence with main stem moves to Bend 4; channel shortened by 177 meters; slope increases. |
| Bend 4 | Inside bend retreats south across point bar. | No significant change. | Channel erosion to the south in the downstream portion of Bend #4. | Levee and groin wall constructed by 1996 along outside (left) bank. | No significant change. |
| Bend 5 | Small high-flow channel at tight bend in pasture; erosion inside the downstream bend; no change in alignment at bridge | Tight north bend abandoned and vegetated; no significant change in channel at bridge. | Bend migrates to the northeast (slightly upstream); no significant change in reach at bridge. | Channel erodes to the north into 1996 alignment; no significant change in reach at bridge. | Upstream reach of bend migrates across point bar to northeast; no significant change in reach at bridge. |

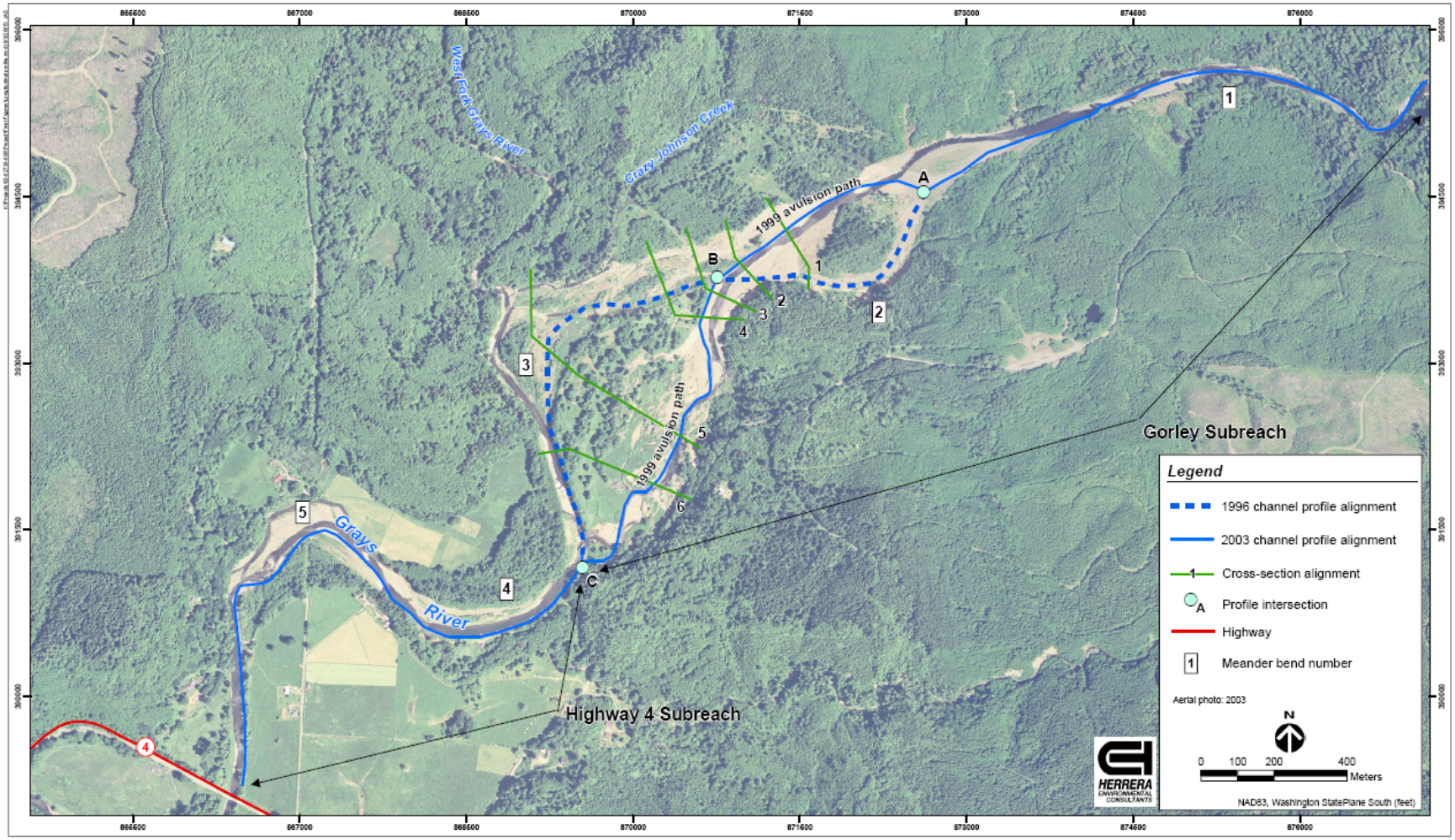


Figure 21. Avulsion paths and locations of longitudinal profiles and cross-sections based on 2004 PNNL topographic survey of the Grays River response reach (RK 18.5 to 22.5).

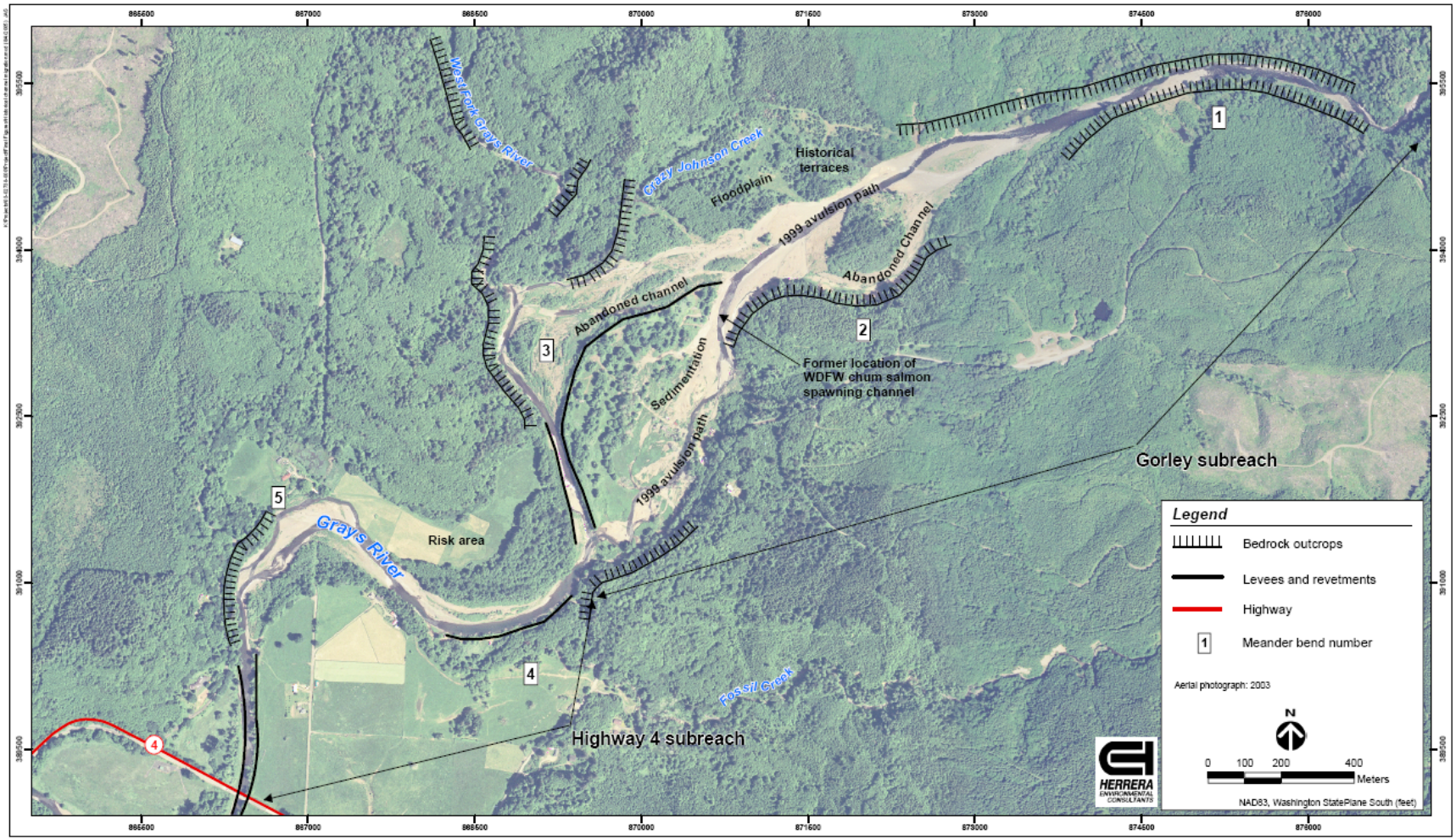


**Figure 23.** Bedrock and levee controls on channel migration in the Grays River response reach (RK 18.5 to 22.5).