CHINOOK BEND CHANNEL MIGRATION MODELING STUDY
SNOQUALMIE RIVER, WASHINGTON

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Technical Report

Prepared for

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and

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2008

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EXECUTIVE SUMMARY

The King County Water and Land Resource Division (WLRD) and the Wild Fish Conservancy (WFC) are developing a project to remove an existing levee and existing revetments along the Snoqualmie River within the Chinook Bend Natural Area, near Carnation, Washington. The purpose of this project is to restore the ability of the river to migrate in this reach, with the expectation that renewed channel migration will improve in-stream and riparian habitat conditions. The possibility has been raised that this increased channel mobility in the vicinity of the project site could propagate downstream. This technical report describes a study intended to clarify the downstream channel response from the proposed projects.

This report describes a meander migration model, the data used as model input, different scenarios used to model channel migration, and model scenario results. Eight different scenarios (A-H) were modeled, comprised of 1) five scenarios to consider selected revetment removal (Scenarios A, B, E, F, G) 2) two scenarios to consider channel evolution after defined cutoffs at Chinook Bend (Scenarios C and D), and 3) one scenario to consider a possible avulsion on the floodplain downstream of Chinook Bend (Scenario H). The meander migration output data show the centerline evolution for simulated migration from 2005 to 2105.

Modeling was done to provide a conservative estimate, which would give a greater than average extent of expected migration for the time period modeled. This modeling provides valuable information about likely *patterns* of migration, and is not expected to give precise future channel locations or time periods under which changes may occur. The modeling shows that rather extreme developments at Chinook Bend such as cutoffs (scenarios C and D) do not result in large changes in the migration patterns downstream. In particular, the migration immediately downstream from Chinook Bend does not significantly increase in a southward direction when the channel cuts-off at Chinook Bend. The modeling also shows that if the channel were to avulse across the floodplain adjacent to Chinook Bend, there is an area where the avulsed channel would rejoin the 2005 channel pathway where there would be increased southward migration.

1.0 INTRODUCTION

The King County Water and Land Resource Division (WLRD) and the Wild Fish Conservancy (WFC) are developing projects to remove existing levees and existing revetments along the Snoqualmie River near the Chinook Bend Natural Area, near Carnation, Washington. The purpose of these projects is to restore the ability of the river to migrate in this reach, with the expectation that renewed channel migration will improve in-stream and riparian habitat conditions. The possibility has been raised that this increased channel mobility in the vicinity of the project site could propagate downstream. This report describes a study intended to clarify the downstream channel response from the proposed projects.

Large alluvial rivers have a tendency to migrate laterally over time. Meander migration, consisting of bank erosion on the outside bank of curved channels and point bar and flood plain building on the inside bank, is a key process altering the landscape. The meander migration process is a function of flow, channel form, and bank characteristics. To consider the downstream consequences of local channel migration patterns, it is helpful to simulate channel migration.

The current study was conducted by Dr. Eric Larsen with support from WLRD and WFC staff. Dr. Larsen used a modeling technique that he developed to predict future channel migration based on existing conditions and on records of historical channel behavior. WLRD and WFC staff provided Dr. Larsen information regarding existing and historical channel conditions, from which simulations were developed to explore whether downstream consequences might relate to various channel and revetment alterations being considered.

The area covered by this study is the channel and floodplain of the Snoqualmie River from River Mile 17 to River Mile 23 (USGS 1993 Carnation 7.5 minute quadrangle). This report presents the results of modeling runs which were designed to simulate river migration behavior in the study reach for a 100-year period under the following eight scenarios

a. Existing conditions (Figure 4).
b. Existing conditions plus removal of levee and revetments on Chinook Bend site (Figure 6).
c. Existing conditions plus removal of levee and revetments on Chinook Bend site plus the formation of an “upper” cutoff at Chinook Bend. (Figure 7).
d. Existing conditions plus removal of levee and revetments on Chinook Bend site plus formation of a “lower” cutoff at Chinook Bend (Figure 8).
e. Existing conditions with removal of all river facilities in study reach (Figure 9).
f. Removal of revetments on the Stillwater site: with “Stillwater” revetment removed (Figure 10).
g. Removal of revetments on the Stillwater site: with “Stillwater” and “Gainsford” revetments removed (Figure 11).
h. Removal of revetments on the Stillwater site plus formation of a cutoff at Chinook Bend and channel avulsion across the floodplain (Figure 12).

The report first describes the meander migration model and the data used for developing the calibration and the scenario predictions. It then describes the input data used for the simulations, the calibration data and results. The simulation scenario results are shown and there is a discussion of those results.

2.0 METHODS

2.1 Study Area

Figure 1 shows the Snoqualmie River from River Mile 17 to River Mile 23 (USGS 1993 Carnation 7.5 minute quadrangle) that was used for this study. The area in the white box is the entire area for which the model was run. Because meander migration of a local area depends on the conditions immediately upstream (Larsen 1995), the reach upstream of Chinook Bend was included in the model runs. The area in the blue box is the reach that was used for calibration. The area of concern (in the red box) is Chinook Bend and the river reach immediately downstream from that is the area of most concern.

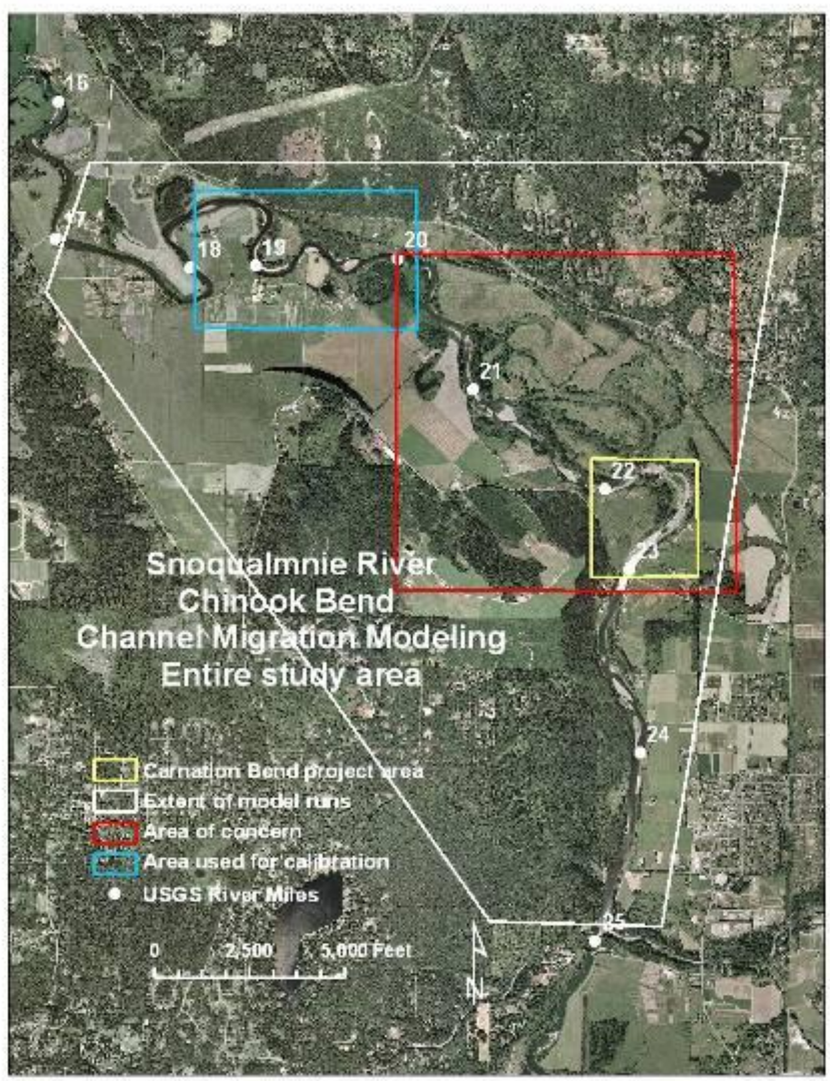

Figure 1 Snoqualmie River study segment

2.2 Meander Migration Model[1]

The approach taken to understand the future channel movement near the site of revetment removal is to model its future migration. As done for reaches of the Sacramento River (Larsen and Greco 2002, Larsen et al. 2004, Larsen 2006, Larsen et al. 2006a, Larsen et al. 2006b, Larsen 2007, Larsen et al. 2007), channel migration is simulated using a channel migration model, described below, that is based on mathematical-physical algorithms for flow and sediment transport.

The meander migration model and earlier variations of it produced by Johannesson and Parker (1989), have been used to predict and analyze the channel migration of a range of rivers, including rivers in Minnesota ((Parker 1982, Johannesson and Parker 1985, MacDonald et al. 1991) in New York (Beck et al. 1984), and the Mississippi River (Larsen 1995). Johannesson and Parker (1989) used the model to predict wavelengths of meandering rivers with results comparing favorably to laboratory and field data. Pizzuto and Meckelnburg (1989) confirmed the relationship between migration rates and velocity (Equation 1) assumed by the model. Howard (1992, 1996) used a version of the model to simulate floodplain sedimentation and morphology associated with meander migration. Furbish (1991) has used similar equations to describe the formation of complex meander sequences. A version of the model was used to examine conditions affecting meander initiation and growth (Sun et al. 1996).

The meander migration model assumes that the local bank erosion rate is proportional to a local velocity factor such that:

$$M = E_o u'_b \qquad (1)$$

where M is the bank erosion rate (m/year), E_o is a dimensionless bank erodibility coefficient of the order 10^{-8}, and u'_b (m/s) is a velocity factor equal to the difference between the velocity near the bank and the reach-average velocity. u'_b and E_o are described in the following subsections.

2.2.1 Modeled velocity

The crux of the model as applied here is the calculation of the velocity field. This is done in a coordinate system that follows the path of the channel centerline. The downstream variation of the vertically-averaged downstream velocity at each model node is expressed as the sum of the reach-average downstream velocity U and a velocity "perturbation" u' (the local deviation from the reach-average velocity) that varies across the stream. The reach-average downstream velocity U is constant for the study reach and is the quotient of the characteristic discharge (explained below) divided by the characteristic cross section area of the channel. The velocity perturbation near the channel bank u'_b is the velocity factor in Equation 1. Nodes are spaced one half-channel width apart. Analyses show that this spacing captures the processes responsible for determining the velocity distribution. The analytic solution for the velocity results from simultaneous solutions of six partial differential equations representing the fluid flow field and bedload transport, which determine channel behavior (Johannesson and Parker 1989). The downstream and cross-stream conservation of momentum are expressed using a

[1] This section is taken and slightly adapted from Larsen and Greco, 2002.

version of the "shallow-water equations." Downstream bedload transport calculations are based on Engelund and Hansen (1967), and cross-stream bedload transport is related to downstream transport using a relation derived by Ikeda (1982) that is well described in Parker and Andrews (1985). The conservation of fluid and sediment mass is represented with traditional conservation-of-mass equations (e.g. Furbish 1997). The near-bank velocity perturbation (u'_b) calculated by these equations peaks somewhat downstream from the meander-bend apex. Therefore, the simulated meanders tend to migrate downstream and in the cross-stream direction, as occurs in natural streams (Hooke and Redmond 1992). The final expression for velocity is the result of a convolution integral (Furbish 1988). The mathematical expression for this indicates that the velocity at a given point is the result of the local conditions and the integrated effects of conditions upstream.

Local velocity varies with discharge, so the model requires an estimation of a characteristic discharge that mimics the integrated effect of the variable natural flow regime. In effect, this assumes that bank erosion resulting from the cumulative effect of discrete individual flow events can be modeled as a continuous process (Howard 1992). The rationale is the same as that used in traditional geomorphic analyses that relate channel form and processes to the "bankfull" or "dominant" discharge (Wolman and Leopold 1957, Wolman and Miller 1959). For this study we have chosen the two-year recurrence-interval flow as the characteristic discharge. Accordingly, it is not intended that the model simulate the effects of particular flow events, but that it produce estimates of *long-term* rates of erosion or channel migration. Assuming a single continuously-acting characteristic discharge that produces continuous and gradual erosion is a useful simplification (Howard 1992). Large events produce large erosion responses, and near-bank water level fluctuations produce bank collapse. Usable theoretical models do not exist for these processes. To reduce error in calibration and prediction that can be introduced by these discrete events, it is best to use a calibration period that is as long as possible. Nonetheless, inaccuracies may arise due to assuming that bank erosion is continuous. In this study, calibration was done over a 28 year period.

2.2.2 Bank erosion coefficient in the model

Although the model analytically calculates the velocity field in some detail, it represents bank erodibility by an empirically estimated coefficient. Bank erosion processes could be modeled mathematically (Thorne 1982, Hasegawa 1989a, b), but precisely estimating the input values for these expressions would require impractical amounts of field data. As Equation 1 indicates, the rate of erosion is a product of the erodibility coefficient and near-bank velocity. Hasegawa's (1989a) analysis suggests that bank erosion is related to five factors in addition to the near-bank velocity. These are the 1) longitudinal flow velocity, 2) longitudinal rate of change of bed elevation, 3) relative depth of bed scour, 4) relative magnitude of the transverse component of near-bottom fluid flow velocity, and 5) relative bank height. Hasegawa uses an order of magnitude analysis to show that the first four of these five factors are much smaller in magnitude than the near-bank velocity and can be ignored. The fifth, relative bank height, is also commonly ignored (e.g. Howard 1992).We assumed that its influence could be subsumed in the coefficient-velocity model. This means that the variability that is theorized to occur with bank height is accounted for in the calibration. As long as the bank height does not change significantly in the time period of modeling, the calibration should account for it. At this time, we are not able to include it explicitly in the meander migration model.

The simulations reported here use a dimensionless bank erodibility coefficient that varies spatially along the study reach, according to calibrated values. In calibrating the model for this study, a value for forest land was first established based on observed historical migration into forested land (refer to Figure 3, and report section 3.1). The non-forest land (agricultural land and relatively bare ground) was set to be approximately twice as erodible as the forest land, an assumption that was validated by work on the Sacramento River (Micheli et al, 2004).

2.2.3 Input variables for the model

The model requires the following six input values reflecting the hydrology of the watershed and the hydraulic characteristics of the channel: initial channel planform location, characteristic discharge, reach-average median particle size of the bed material, width, depth, and slope. The reach-average width and depth are measured at the characteristic discharge, and slope is the average water surface slope for the reach. Using these data, the model calculates other parameters required to predict channel migration. For a detailed description of the calculation process, see Johannesson and Parker (1989). Hydraulic data were taken from a study of the Snoqualmie (Booth et al. 1991). Centerlines were developed from aerial photos provided.

2.2.3.1 Channel planform centerlines

Delineating river channel centerlines depends on the magnitude of discharge (Q) chosen to define the edges of the channel from which the centerline is derived. High flows create wider channels with less sinuous centerlines than low-discharge flows (Brice 1977). Methods of defining channel edges range from visual estimates using channel planform maps and aerial photographs, to detailed hydrodynamic modeling using digital elevation models. This study used orthographic photography to estimate channel centerlines based on a subjective judgment of the extent of the two-year flow. Channel edges were estimated and centerlines were drawn one half-channel width (2-yr recurrence interval width) from the cut-bank (outside of bend) of the channel. When there were mid-channel bars, an estimate was made if these bars would be inundated at the two-year flow, in which case, the centerline was drawn over the mid-channel bar.

2.2.3.2 Discharge

We chose 28,750 cfs (814 cms m^3s^{-1}) as 2-yr recurrence interval discharge (Table 1) based on Snoqualmie River data (Booth et al. 1991)[2]. The hydraulic data from the Booth et al report was derived from a USGS gage in the current study reach. Independent estimates of the 2-yr flow based on recurrence interval analysis of the Carnation gage gave a similar value (Bethel Pers. Com.2008). 287750 (814 cms) was chosen to be consistent with the other hydraulic data described in the next section.

2.2.3.3 Width, depth, slope, and particle size

The meander migration model requires input of reach-average width, depth, slope, and particle size at the two-year recurrence interval flow. These values were taken from the same data source as the discharge (Booth et al. 1991).

[2] This choice of discharge data is supported by flow frequency estimates published by USGS, which give a 2-year flow of 30,100 at USGS Gage number 12149000, with 95% confidence limits that include the model run in their range (27,400 – 33,000 cfs). These figures were taken from Sumioka et al 1998, which are available on line at http://wa.water.usgs.gov/pubs/wrir/flood_freq/tables.html.

The width and depth at the two-year recurrence interval flow must be hydraulically consistent with relationships that describe flow in open channels. We used Manning's equation which assumes uniform, steady flow, to check the initial estimates of the width and depth input data (Table 1). Manning's n roughness relationship (Henderson 1966) is:

$$U = 1.49/n\ R^{2/3} S^{1/2} \qquad (2)$$

where U is the reach-average downstream velocity (ft/s), n is the Manning's roughness coefficient, R is the hydraulic radius (ft), and S is the reach-average friction slope (ft/ft).

FLOW PARAMETERS	
Q	28750 cfs
H (depth)	18 ft
B (width)	236 ft
S (slope)	0.0004
Ds	35 mm
Manning's n	0.03

Table 1 Model input parameters

2.3 Model assumptions

The mathematical modeling of physical processes inherently assumes simplifications of reality. In our model, we make the assumptions that:

- Channel reach-average width, depth and slope are constant.
- Water surface and river bed are straight lines from one bank to the other.
- Any riprap in place or emplaced in the channel will function in its current location.
- Riprap does not degrade or erode ($E_0 = 0$).
- Based on our calibration, progressive channel movement predicted by the model will correspond to the integrated long-term effects of many years of different bank erosion rates.
- Reach-average grain size is constant.
- Reach-average Manning's n is constant.

These assumptions have proven to be acceptable in previous applications of the model (Larsen 1995, 2006; Larsen and Greco 2002; Larsen et al. 2004; Larsen et al. 2006a, 2006b, 2007). In particular, variation in particle size throughout a study reach will not account for substantial errors in calibration and prediction. The effect of the changing grain size in the study reach is partially accounted for in the calibration process. In essence, the effects of the changing grain size are captured in the calibration, and, to some extent, are then transferred to the prediction period through the calibrated coefficients. In addition, the model is not overly sensitive to changes in particle size. In the same way, the changing slope in the study reach is partially accounted for in the calibration process.

2.4 Model Calibration

The meander migration model hinges on numerical terms that describe two opposing forces: the forces created by flowing water impinging on the bank, and the resistance of the bank material to those forces. The model calculates flow velocities causing the impinging forces and uses an empirically calibrated bank resistance coefficient to represent the resisting forces. The model predicts local migration as the product of a near-bank velocity u'_b and an erosion coefficient E_o. Our calibration procedures used measured migration (M) and calculated near-bank velocities (u'_b) to back-calculate local bank-erosion coefficients (E_o) at points along the channel margin.

2.4.0 Historic migration rates

Analyses of historic centerlines from the 1870's to the mid 1930's show significant changes in the channel location due to rapid progressive migration and also channel avulsion. From the mid-1930's to the present, the rates of change due to both mechanisms were significantly less (Bethel Pers. Com.2008), perhaps due to the influence of upstream landsliding in the earlier time period.

The river showed significant movement in the early time period based on a GLO (Government Land Office) 1870 map that shows channel movement (Bethel Pers. Com.2008). Eyewitness accounts and existing topography show that, near River Mile 26.3 (upstream of Chinook Bend) there was a massive landslide along the river in the early 1930's. It appears that the hillslope failed and moved the river further east. The slide introduced a large slug of sediment into the river immediately upstream of the Chinook Bend site. This could have caused the large movement in the river downstream, which is not typical progressive meander migration. This is a possible reason for the more dramatic changes in that period of time. This study focuses on lateral channel migration by application of a meander migration model whereas avulsion was a major mode of past channel movement, particularly in the study area. Our calibration, and subsequent modeling, is based on the migration rates observed after the large changes took place. This is the most appropriate assumption for future migration.

It is important to recognize that all findings of this modeling exercise assume that the modeled migration patterns are based on calibrations of movement in the more recent period (1936 to 1964).

2.4.1 Calibrating the erosion coefficient

To calibrate the erosion coefficient, one must know where the channel planform centerline was located during two separate time periods. For calibration, 1936 and 1964 were chosen, two years for which centerlines could be accurately defined and during which we assumed that there was minimal bank revetment in the area of calibration. The bank erosion coefficient calibration consists of adjusting the coefficient in the simulated migration until the simulated migration from 1936 to 1964 matches the observed migration in the same time period.

On freely meandering rivers with few anthropogenic or geologic controls (such as the Mississippi River before man's influence) one can calibrate erosion coefficients so that observed and simulated migrations match in great detail (Larsen 1995). However, an exact calibration for our study reach was difficult because the reach includes areas that were constrained and did not experience much migration.

In consultation with King County, it was decided to choose an area where the migration of part of the river showed obvious progressive migration into an area with vegetation. The main purpose of this was to establish a bank erosion coefficient for vegetated areas. Figure 3 shows the area where the river had a downstream limb of a meander bend that moved in a way that suggested that the migration was the direct result of the interaction of the eroding forces of the flow and the resisting forces of the bank material (influenced by vegetation).

There are two revetments in the calibration area. The revetment near River Mile 18.75 is composed of old car bodies. The age of this revetment is not clear, but it is located along the highway at a location where the river is effectively limited from migrating due to the adjacent valley wall, and it was modeled as restrained in the calibration. The revetment located upstream near River Mile 19 was built in 1965, outside of the calibration period and was therefore not modeled as restrained in the calibration (Bethel Pers. Com.2008).

The calibration sought a general agreement of bend shape near the limb of the bend that appeared to move in progressive migration rather than perfect point-by-point agreement between the locations of the observed and simulated channel centerlines where the channel was not in the area chosen to match. The greatest concern was to find an area that seemed to be migrating in a way that resulted from the water forces interacting with the bank characteristics, rather than an area where the migration pattern was largely due to bank restraints. While the calibrated simulated migration between 1936 and 1964 (Figure 3) does not precisely match the observed channel centerline for that period, the pattern and rough magnitude of channel movement on the downstream limb of the bend is simulated to match the observed migration. In particular, the magnitude of simulated and observed channel migration matches well at this location. Upstream and downstream from this area were small "partial" cutoffs that the calibration did not attempt to model. Although the calibration is generally in agreement for our study site, any calibration is essentially subjective and relies on the judgment of the modeler.

The model calibration for this project was more problematic than for some other river systems where the model has been used, which influences the confidence in the resulting model results. The channel in this reach did not meet some model assumptions. For example both the slope and D_{50} decrease significantly through the model reach. Also the period of useable record was limited. We expect that these factors will influence the model results to some degree, but that the model results do answer the main question addressed by this work. General patterns of migration should suggest what the Snoqualmie will do in the future in this area; we would have less confidence in point by point agreement in future channel migration. Based on the best information available, it was judged that the migration pattern that was predicted was reasonable for this type of alluvial system, and that the predictions were useful in assessing the main question of the study – how would the downstream migration patterns change when changes in bank characteristics (i.e. revetment removal) were made upstream.

King County Staff and the modeler Eric Larsen conferred in the following line of establishing calibration:

1. Initial calibration attempts at Chinook bend proved to yield limited information because of the channel restraints in place. It was decided to move to another area.

2. Calibration in the final area of calibration was decided to be useful because the chosen area showed a migration pattern that appeared to be the result of typical bank retreat due to fluvial forces.
3. 1936 and 1964 data were chosen in the calibration area, because this time period was judged to have minimal riprap.
4. The erosion coefficient for the forested area in this location was transferred to the study reach for the first simulations.
5. Based on the professional experience of County Staff and Eric Larsen, a value for the coefficient of friction, which is used as a typical calibration adjustment method in this model, was chosen which gave more channel migration than the original coefficient and was judged to be geomorphically appropriate (it conserved channel sinuosity more than the other). Because using this coefficient resulted in more migration, it was considered somewhat conservative.

2.4.2 Heterogeneous Erodibility Surface

A heterogeneous erosion surface can be created using the geographic information system (GIS) ArcGIS 8.3 (ESRI 2003) and imported into the river meander migration model. The erodibility surface was developed by spatially combining a GIS dataset of vegetation, described above, with a GIS dataset of channel revetment, and a dataset describing a geologic constraint.

Values in the merged dataset represent erodibility potential based on both land cover and revetment data. This dataset, or erodibility surface, is then imported into the migration model with areas of natural vegetation being given one value of erodibility, while agricultural or bare lands are given another value, and geologically constrained areas and revetment were given a value of zero.

An erodibility potential surface was created based on digitizing areas that were forested, and areas that were not vegetated. Areas that were non-forested were initially valued as twice as erodible as non-vegetated areas (a ratio of 2 to 1), based on past experience and published studies (Micheli et al. 2004). During calibration this was adjusted slightly to a ratio of 2.3 to 1). The erosion potential coverage is shown in appendix 4 (Figure 21).

2.4.3 Revetment Coverages

The effect of revetment was simulated by modifying the erosion potential grid, using a GIS revetment dataset from the King County Water and Land Resource Division (WLRD) (Eastman, pers.com. 2008). The revetment was buffered by approximately one half channel width and combined with the erosion potential grid (ESRI 2003); areas within the buffered revetment were given an erosion potential value of zero (i.e., non-erodible). In addition to the revetment areas being given an erosion potential of zero, there was an outcrop of nonerodible till downstream from Chinook Bend that is erosion resistant. This area was modeled as a hard point. A GIS coverage of the till outcrop provided by King Co. (Landau, Pers. Com.2008) was buffered and given an erosion potential of zero.

For the purposes of modeling the downstream effects of changes at Chinook Bend with the Stillwater scenario" (Scenario F, Figure 10), the downstream levee is most influential bank restraint. It was modeled as non-erodible.

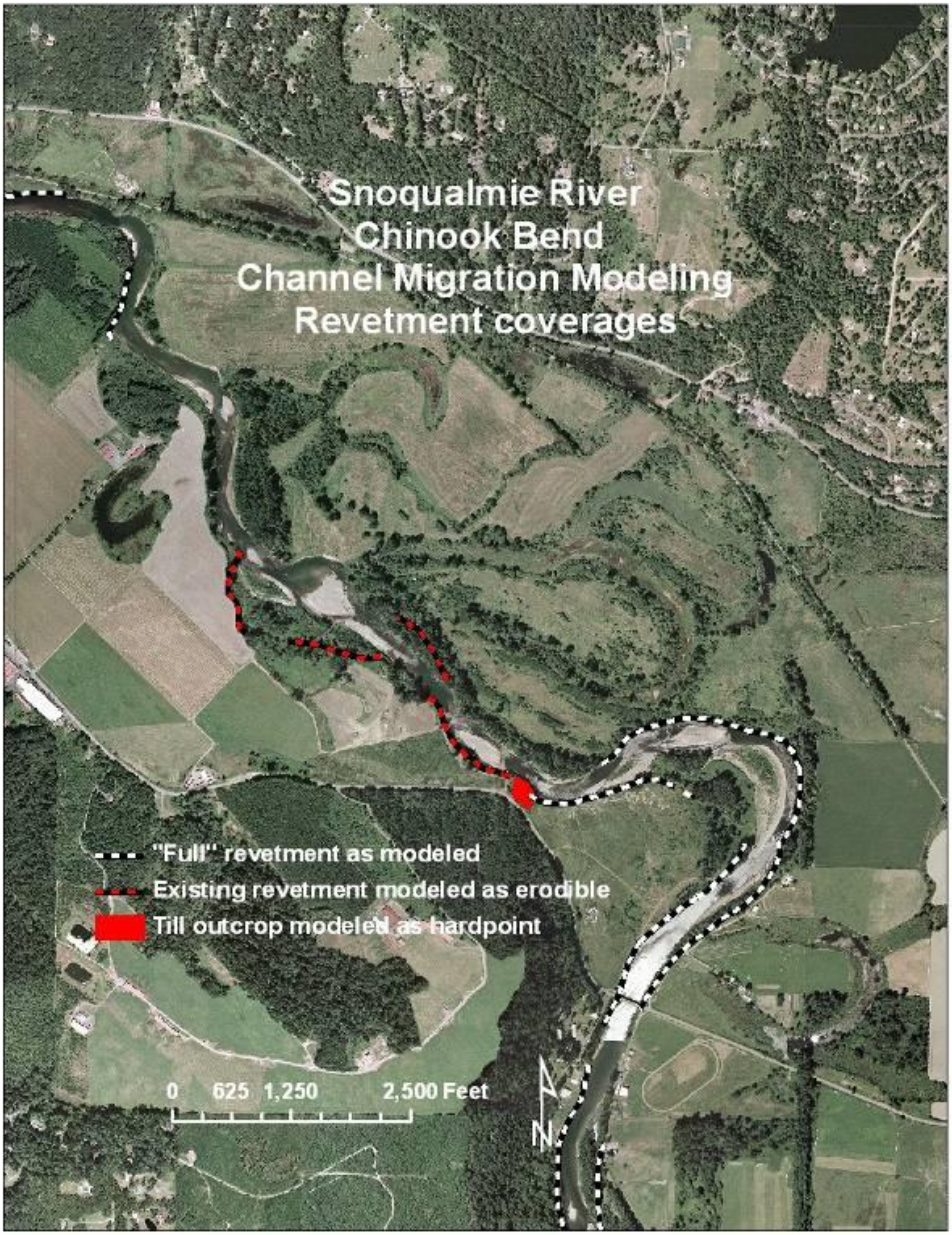

Figure 2 Revetment coverage modeled

The baseline revetment field is shown in figure 2. The original revetment coverage estimate included four lengths of revetment downstream from Chinook Bend. These were judged (Bethel, pers. com., 2008) to have erosion potential and were excluded from the revetment field used for modeling.

Different revetment scenarios were developed from this base revetment coverage. Each of these is described in the results for the appropriate scenario.

2.5 Model runs with conservative assumptions

Calibrating in one area and applying it to a different area may introduce errors in migration rates in the modeled area. In order to estimate possible ranges of migration that would occur in the modeled area, we chose to do a conservative estimate that would show a greater than average channel migration. A coefficient internal to the model was adjusted to give a conservative estimate of migration. A comparison between the model application using strictly calibrated model values and using a conservative estimate of the coefficient of friction is shown below under Scenario A. This change does not affect the original calibration of the model.

In the final runs, four revetment locations were assumed to be erodible (Section 2.4.3 and Figure 2), a procedure which also provides a more “conservative” estimate of channel migration because it assumes no hardness in these locations, when in reality, there is some hardness there. It is possible that this assumption could have implications for the modeling along the banks opposite these under-represented revetments. However, the modeling, for example of Scenario A (Figure 4), shows that the unrestrained migration is not extensive in this area, and therefore suggests that modeled migration along the banks opposite these under-represented revetments would not differ in a way that would have major implications.

The model with the conservative assumptions was chosen as the working model also because it appeared more reasonable in terms of migration patterns. In particular, this model tended to conserve sinuosity and not reduce it. Using the calibration from another area of the river was effective in giving values for the erodibility of the landscape, in particular, forested areas versus non-forested areas, which was a prime reason for calibrating in this area. Because it was not performed in the actual area near Chinook Bend, it is likely that the calibration did not precisely capture the processes that control the evolution of sinuosity.

2.6 Limitations and Interpretation of Model Results

This section describes limitations of the meander migration model or caveats regarding the interpretation of expected model results.

2.6.1 Models and Simulations

As with other simulation models (e.g. Montgomery and Dietrich 1992, Sklar and Dietrich 2004), the meander migration model is an effective tool to predict patterns of landscape evolution. All large-scale geomorphic models are simulations that estimate future conditions, but they are not intended for precise predictions of small scale site-specific land alterations. For example, one would not expect that a particular point on the landscape would experience *exactly* 15.7 meters (arbitrary example) of bank erosion at a precise spot in a prescribed time interval. Simulations may, however, indicate future patterns, for example, one could simulate that one scenario would result in 35% more land reworked (arbitrary example) than another scenario.

2.6.2 Tributary Influences

Although it has been suggested that bends at or just downstream from stream tributary confluences migrate faster due to sediment input, analyses show that this pattern is not always the case (Larsen et al. 2006a). In a study of bank erosion and stream power (Larsen et al. 2006a), areas with the highest mean average erosion rates are not located near confluences near tributaries. Although these data suggest that tributary inflow may not be a large influence on migration rate in some areas, the influence of tributaries is only implicitly modeled in the meander migration model, by means of calibration. Other patterns of migration, such as high migration rates where a bend occurs immediately downstream of long, straight, historically stable reach, are modeled explicitly by the model because they are primarily determined by the flow patterns related to the planform. “Implicit” in this context means that tributary influence is accounted for indirectly when the model is calibrated in that specific location. “Explicitly” in this context means that the equations that govern the model account for this process.

2.6.3 Effect of sediment accumulation on channel pattern

The migration model does not explicitly model how a channel may change position in response to sediment build up. In the modeling exercise here, some of the possible effect of this at Chinook Bend was accounted for by the assuming different channel locations after the levees are removed. There can be a “fire nozzle” effect where the channel shifts location from year to year in response to the buildup of sediment. Another place where this may have some impact is downstream of Chinook Bend near River Mile 21.25. It is similar to the effect of a delta, where a channel shifts periodically on the delta. This is not modeled by the channel simulations, but can be partially taken into account as described above.

3.0 RESULTS AND DISCUSSION

The model output consists of images of channel centerlines superimposed on an aerial photo of the area of concern. The images show the existing (in 2005) or assumed, in the case of assumed cutoff events, location of the channel in the first time period (2005) and the modeled channel centerline (2105) after 100 years of channel migration. Each image also shows the revetment that is assumed in place for the model run in question.

Table 2 lists the scenarios and describes the revetment and assumed cutoff configuration for each scenario. The revetment scenario described as “existing” is the one described in Section 2.4.3, which excludes the four that were judged to be erodible.

Following the table, the output image for each scenario is presented and each one is described and briefly discussed.

Scenario number	Description	Location of initial channel	Modeled years	Revetment	Cutoffs
A	Run with existing conditions.	2005 existing location.	2005-2105	Existing (adjusted) revetment field in place.	None.
B	Same as A, but with the two inner (left-bank looking downstream) revetments at Chinook removed.	2005 existing location.	2005-2105	Existing (adjusted) revetment field in place and the two inner revetments at Chinook Bend are removed.	None.
C	Model of evolution after "upper cutoff" at Chinook Bend.	Initial channel 2005 in assumed "upper cutoff" location.	2005-2105	Existing (adjusted) revetment field in place and upstream inner revetment at Chinook Bend removed.	Chinook Bend assumed upper cut-off location.
D	Model of evolution after "lower cutoff" at Chinook Bend.	Initial channel 2005 in assumed "lower cutoff" location.	2005-2105	Existing (adjusted) revetment field in place and the two inner revetments at Chinook Bend are removed.	Chinook Bend assumed lower cut-off location.
E	Model of channel evolution with no revetment on the entire channel.	2005 existing location.	2005-2105	No revetment.	None.
F	Model of channel evolution with the revetment removed on the Stillwater site.	2005 existing location.	2005-2105	Existing (adjusted) revetment field in place except it is altered at the Stillwater site (a small piece is removed.)	None.
G	Same as F, but with the Gainsford revetment removed.	2005 existing location.	2005-2105	Existing (adjusted) revetment field in place except it is removed at the Stillwater site and at the Gainsford revetment site.)	None.
H	Model of channel evolution starting with Stillwater channel avulsion into the floodplain. The upper cutoff at Chinook is assumed as a starting postion.	2005 assumed location of avulsion into oxbow on floodplain. Also the assumed "upper cutoff" location in Chinook Bend.	2005-2105	Existing (adjusted) revetment field in place and the two inner revetments at Chinook Bend are removed.	Chinook Bend assumed upper cut-off location. Assumed channel avulsion into oxbow on floodplain.

Table 2 Scenario descriptions

Note: In the revetment column, “adjusted” refers to the fact that four of the existing revetments were modeled as if they were not present.

3.1 Model Calibration

Choice of the location of model calibration was discussed in methods. The calibration results are described below.

3.1.1 Calibration: Centerline Agreement

Calibration in the upstream segment (RM 18 to 20) (Figure 3) was performed starting with the observed 1936 and 1964 channel centerlines. The red line is the 1936 observed channel centerline; the blue line is the 1964 observed channel centerline; the yellow line is the 1964 modeled channel centerline. The agreement between the observed (blue) and simulated (yellow) 1964 channels was visually assessed as adequate in the area chosen for detailed calibration. Upstream from the calibration area, there is a bend whose apex points northward toward a road. Near the apex of that bend, there is not good agreement between the modeled (yellow) and observed (blue) centerlines. This appears to be an area that experienced a "partial cutoff" across the tip of the point bar. This type of event is not modeled by the meander migration model. Although statistical methods could be used to assess calibration agreement with observed migration, those methods can "force" agreement in areas where migration patterns are not controlled by channel planform and internal hydraulics, but by other factors such as anthropogenic changes. Using a visual assessment has proven to be an effective means of calibration (Larsen and Greco 2002, Larsen et al. 2006b).

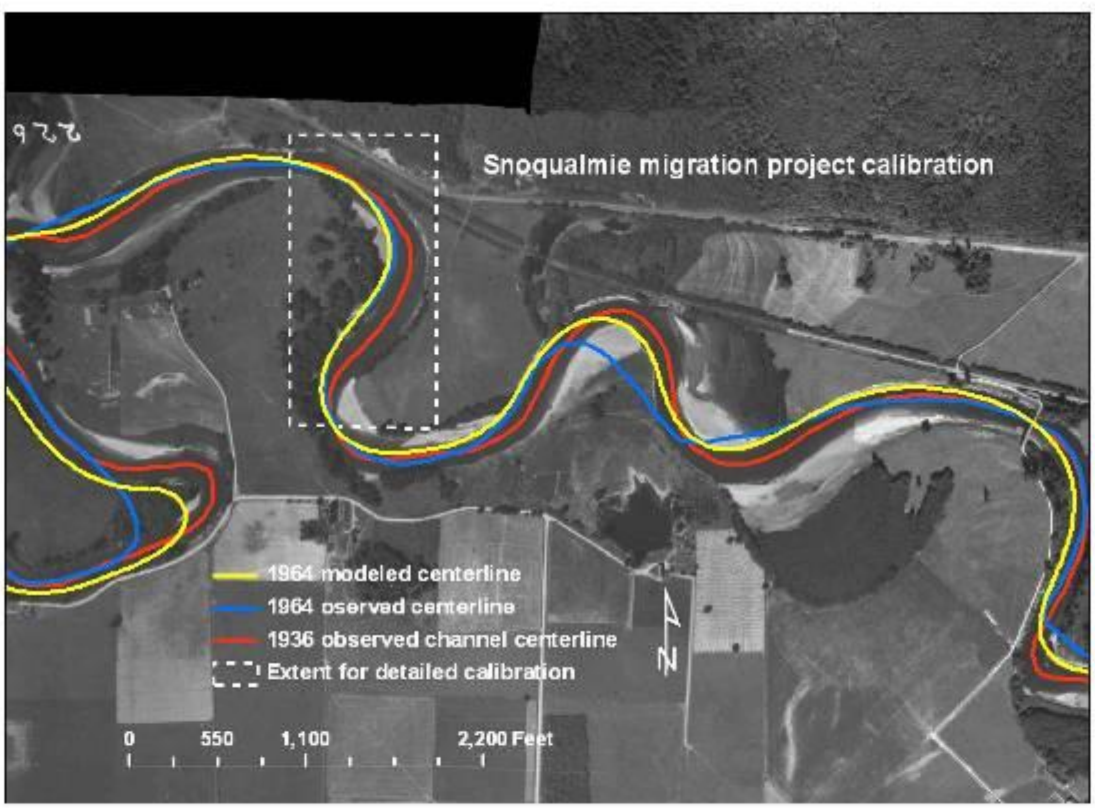

Figure 3 Calibration

3.2. Model Scenarios

Scenario A: Simulations with existing conditions

Scenario A (Figures 4 and 5) shows 100 years of migration with the conditions that exist currently. There are 4 revetment fields that were excluded from this figure (red lines in Figure 2) for reasons discussed above. The figures show limited lateral migration at Chinook Bend, no cutoffs, and moderate lateral migration downstream from Chinook Bend.

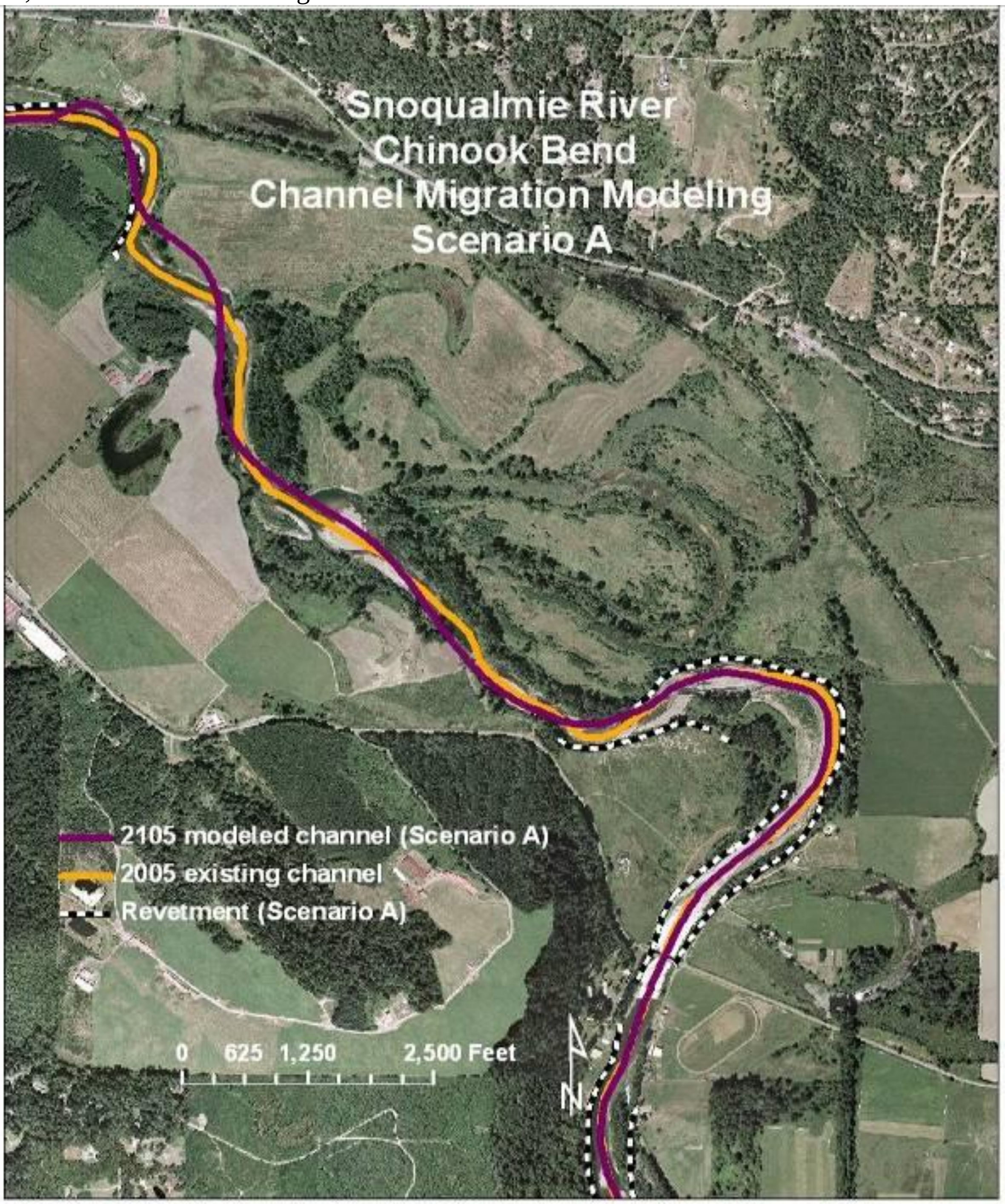

Figure 4 Chinook Bend migration Scenario A

Simulations comparing strictly calibrated and conservative output

The assumptions and rationale for a conservative approach are described in section 2.5 above.

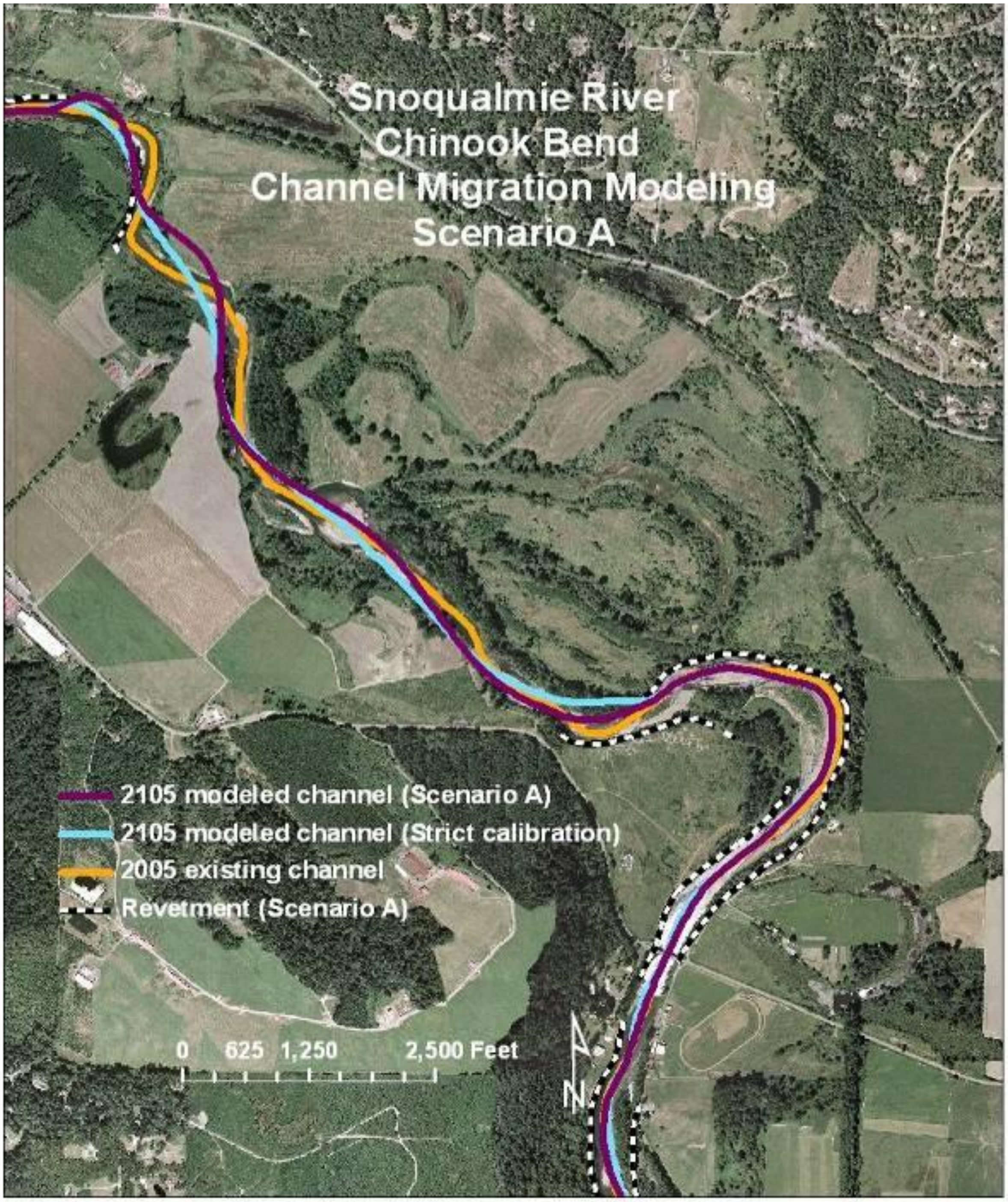

Figure 5 Chinook Bend migration Scenario A: strict and conservative assumptions

Scenario B: Simulations with Chinook Bend revetment removed

Scenario B (Figure 6) shows the migration with the revetment removed on the inside of Chinook Bend.

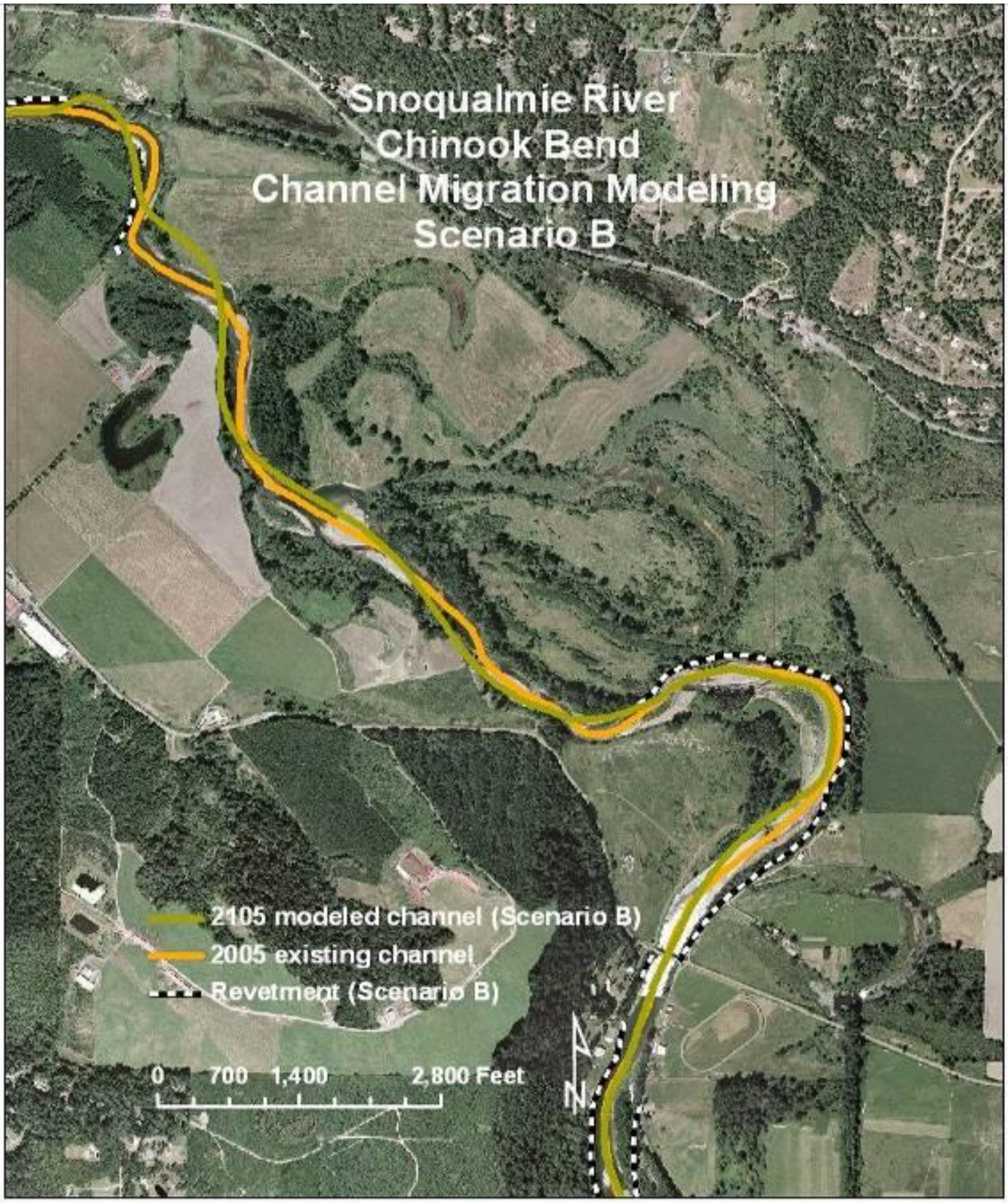

Figure 6 Chinook Bend migration Scenario B

Scenario C: Simulations with Model of evolution of "upper cutoff" at Chinook Bend

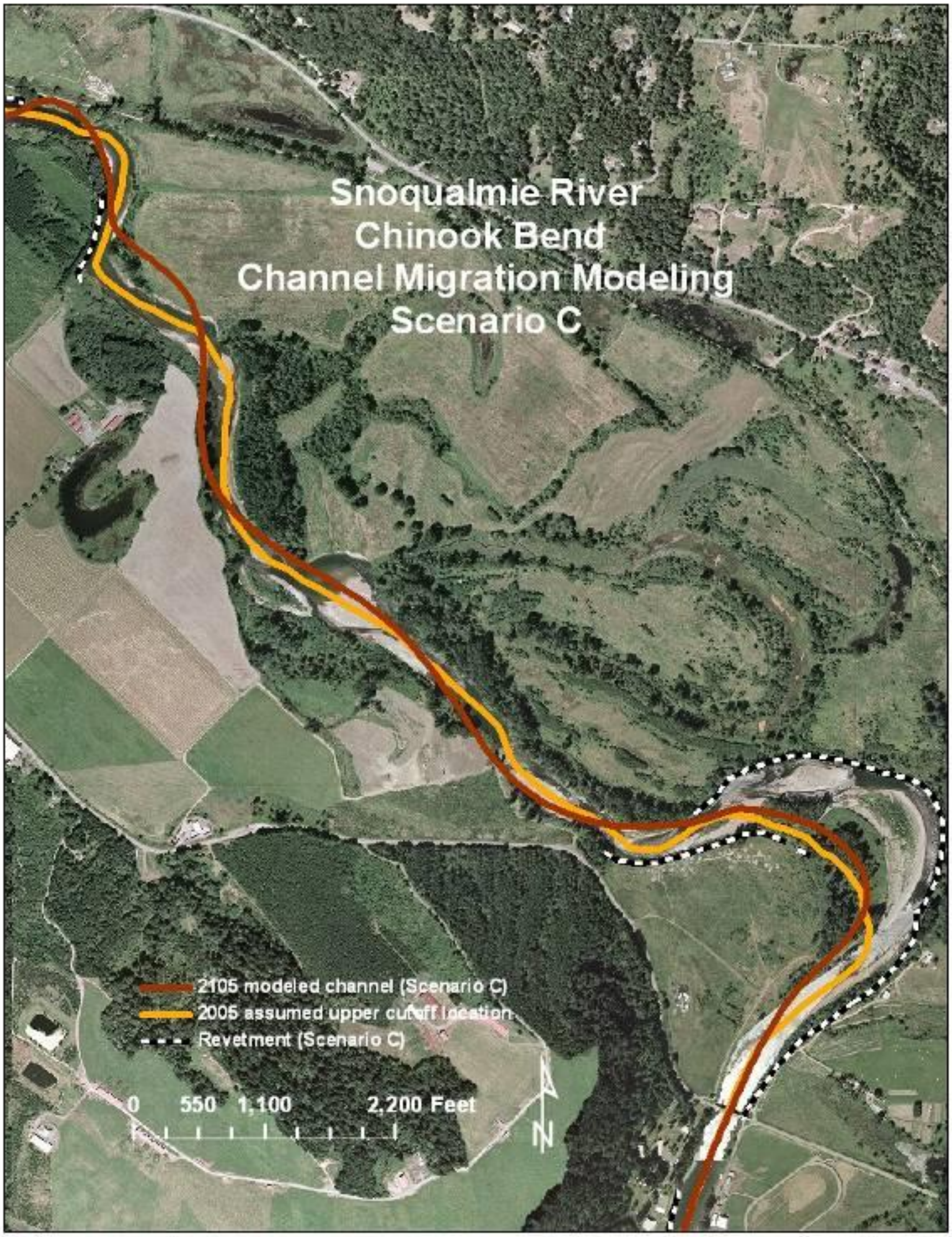

Figure 7 Chinook Bend migration Scenario C

Scenario D: Simulations with Model of evolution of "lower cutoff" at Chinook Bend

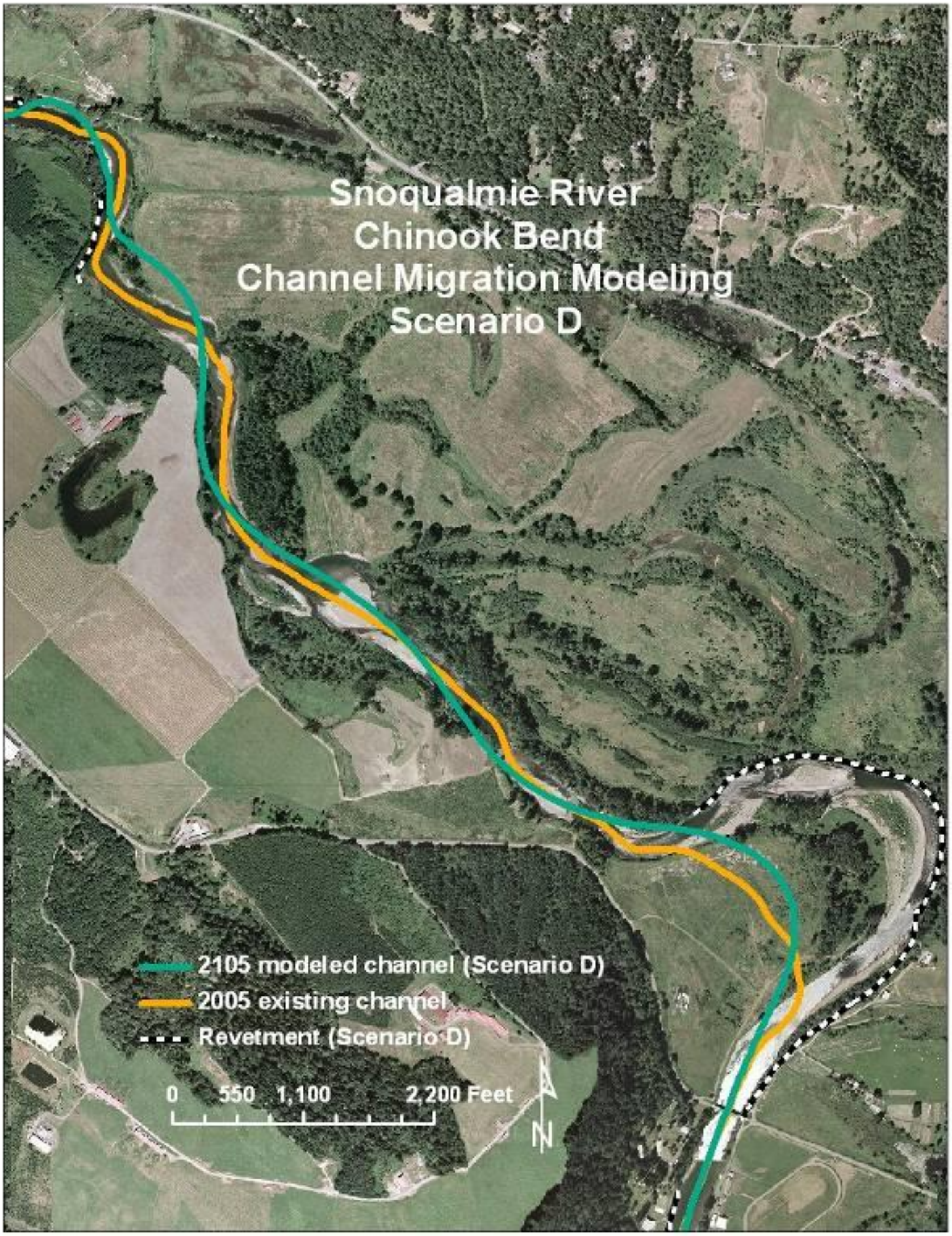

Figure 8 Chinook Bend migration Scenario D

Scenario E: Simulations with Model of channel evolution with no revetment on the entire channel

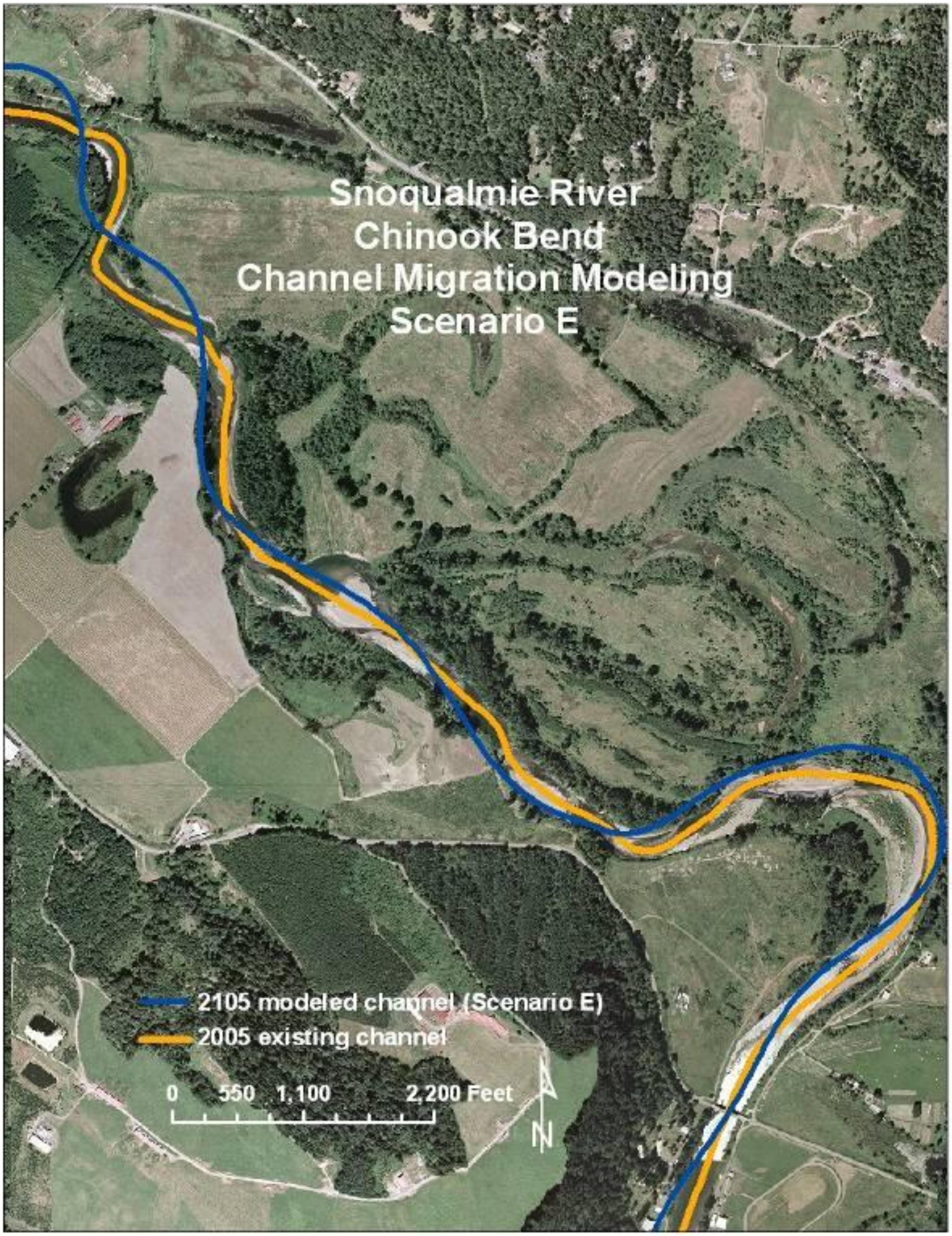

Figure 9 Chinook Bend migration Scenario E

Scenario F: Simulations with model of channel evolution with the revetment removed on the Stillwater site

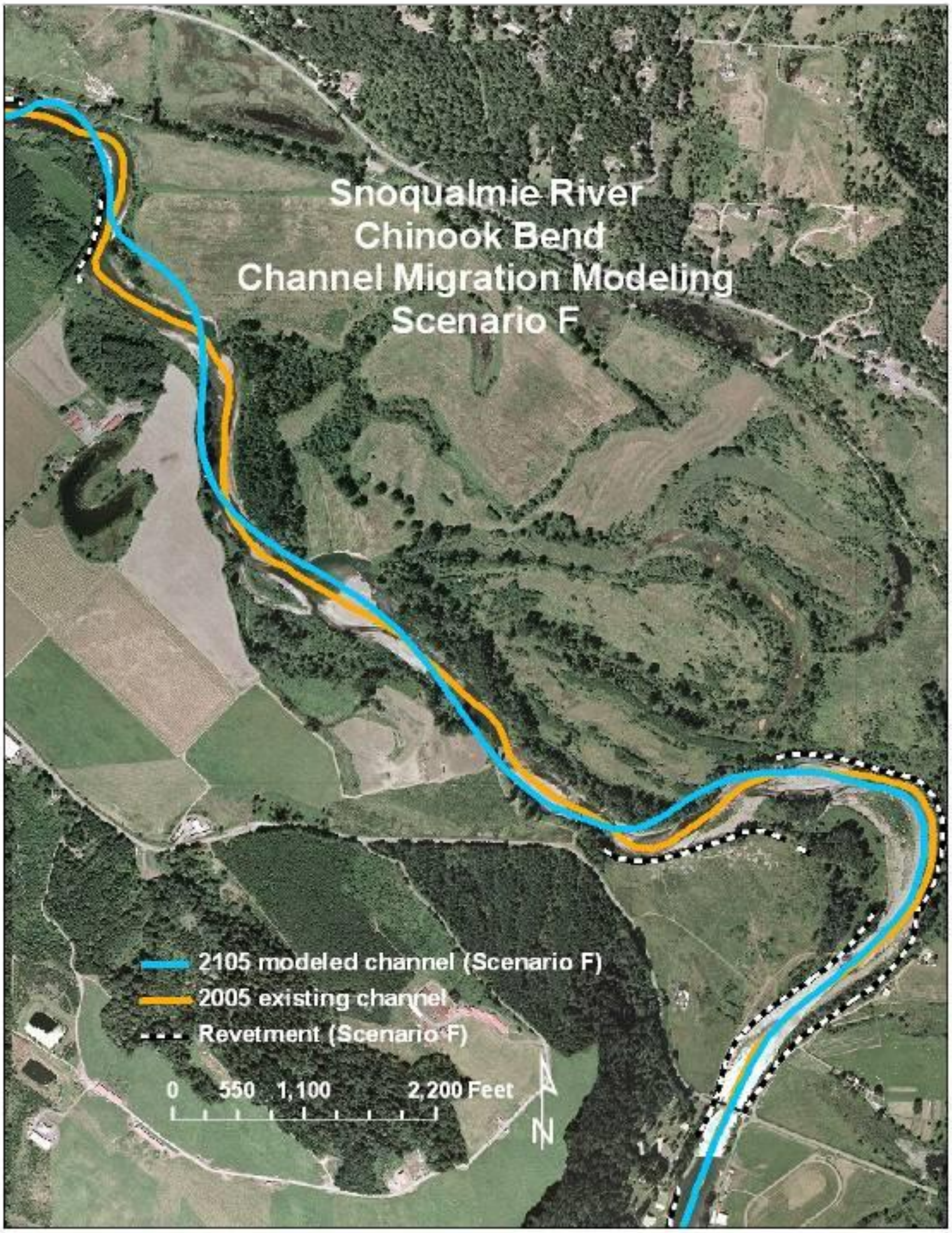

Figure 10 Chinook Bend migration Scenario F

Scenario G: Simulations with Gainsford revetment removed

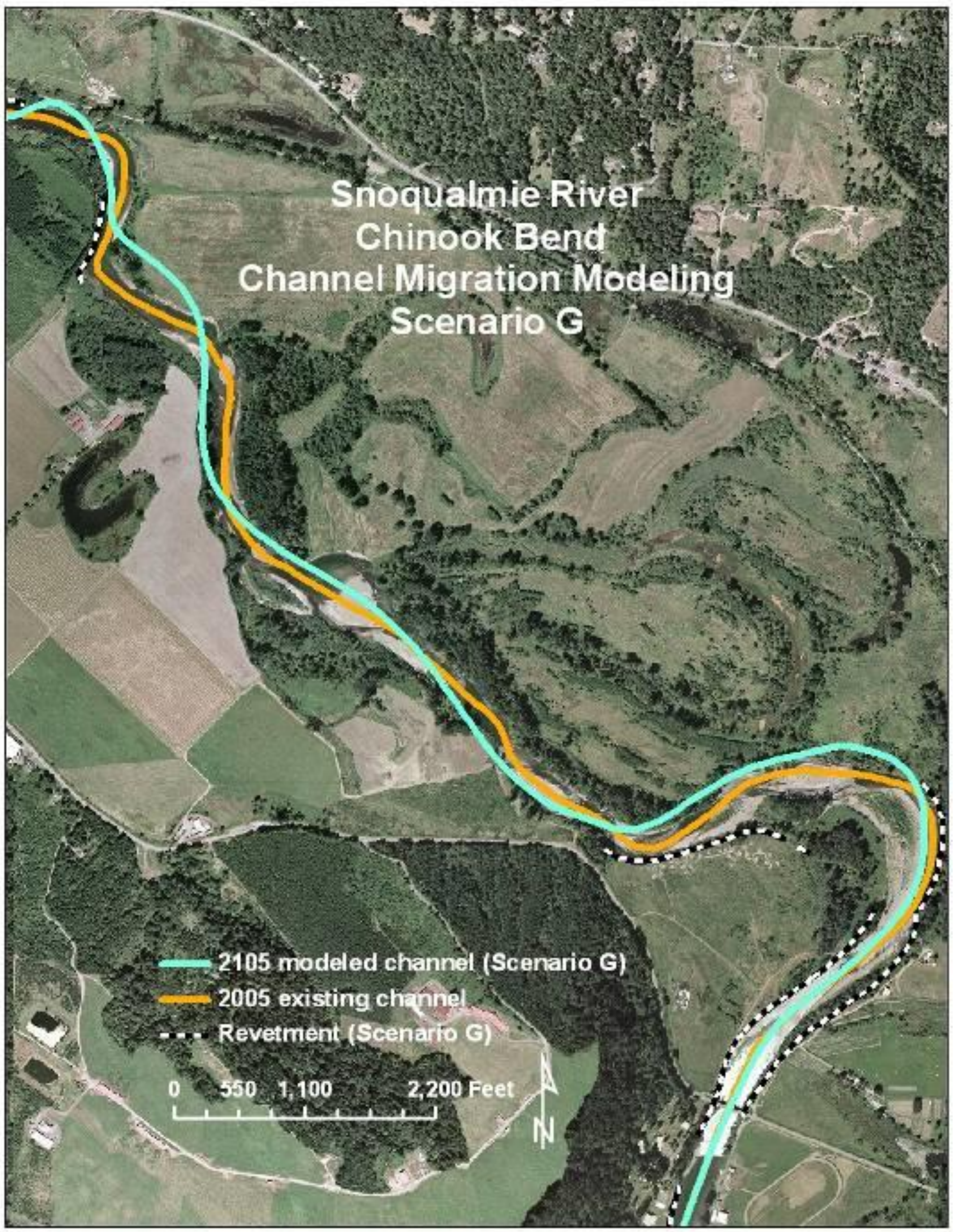

Figure 11 Chinook Bend migration Scenario G

Scenario H: Simulations with channel avulsion into abandoned meander loop

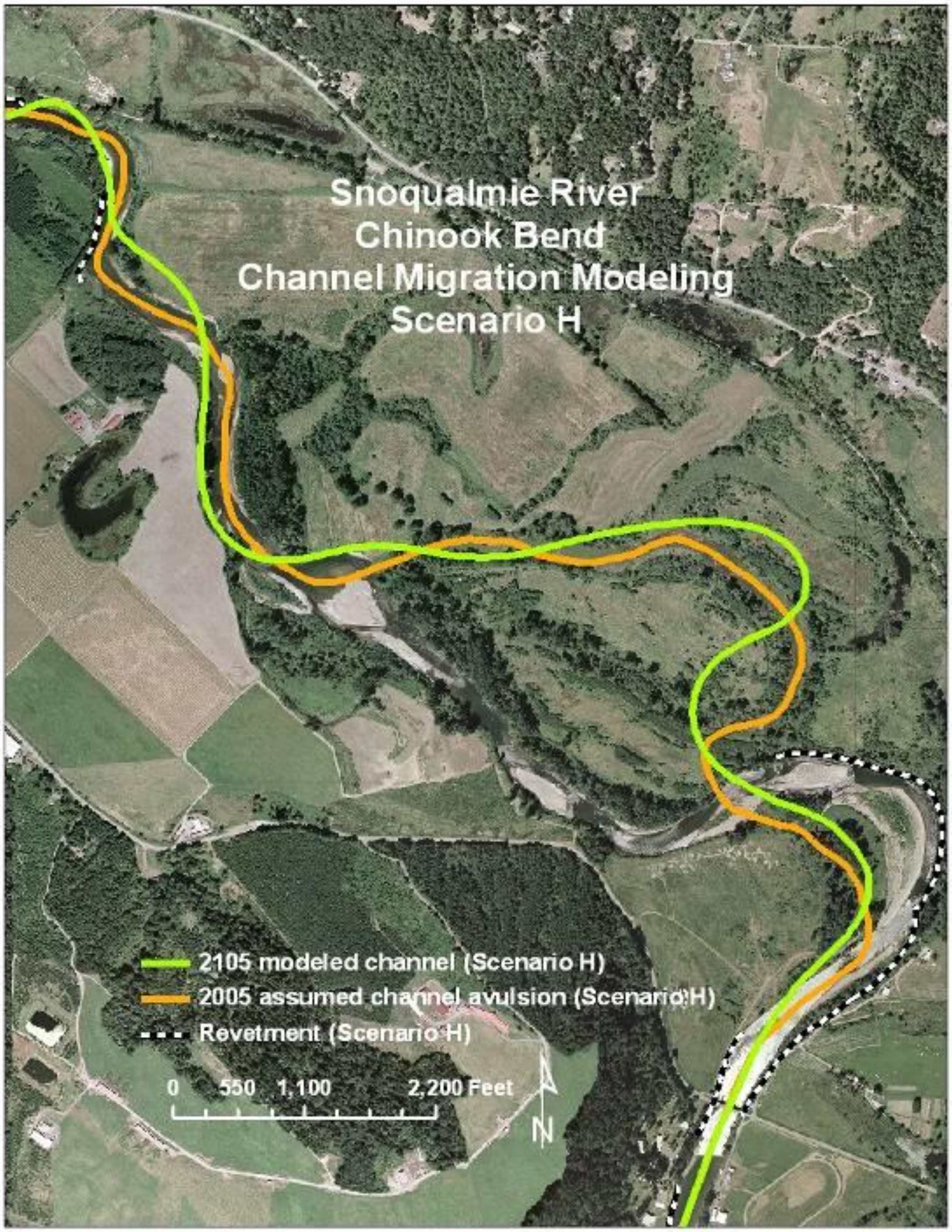

Figure 12 Chinook Bend migration Scenario H

3.3 Discussion of results and management implications

3.3.1 Migration patterns with different scenarios

Figures 5 through 12 show the migration patterns of each scenario when compared with the starting location for that channel. For another way of comparing different scenarios King County (Landau Pers. Com.2008) prepared images, which are included in Appendix 3, that compare each scenario prediction with the location of the channel as predicted to move without any revetment alterations (Figures 13-20). In other words, these images compare predicted movement with and without revetment.

In scenarios A and B the existing revetment on the right bank (outside) of Chinook Bend completely restricts the migration toward the right bank (outward) on the channel (Figures 5 and 6; 13 and 14). The left bank (inner) revetment on the upstream limb also restricts the movement of that limb (Figures 5 and 13). When the left bank (inner) revetment is removed in Scenario B, (Figures 6 and 14) the channel moves progressively into the floodplain in the interior of Chinook Bend. Downstream from the bend, in the area of concern, there is a moderate rate of migration of the existing bends in both scenarios. Figure 14 shows that downstream from the black dot on the image there is no difference in the channel movement between scenario A and B. This is reasonable, given that the change in revetment is upstream of this point, and the more downstream channel is restrained.

When an “upper cutoff” is assumed and the channel evolution post-cutoff is modeled (Scenario C, Figures 7 and 15), there is moderate channel change in the floodplain in the interior of Chinook Bend. More importantly for management concerns, the channel downstream does not move in a significantly different manner than it did in the cases with the existing revetment in place. Figure 15 shows that the movement downstream of the black dot remains identical to the “no cutoff” prediction. In order for the cutoff to occur, the upstream limb left bank (inner) revetment was assumed to be removed.

When a “lower cutoff” is modeled (Scenario D, Figures 8 and 16), the channel migrates a relatively large amount in the floodplain in the interior of Chinook Bend, but the bends immediately downstream, again, do not move in a significantly different manner than with the revetment in place. Figure 16 shows that the migration downstream of the black dot on the image remains identical to the “no cutoff” prediction. In order for the cutoff to occur, the entire left bank (inner) revetment was assumed to be removed.

Scenario E (Figures 9 and 17) evaluated how the channel would move without any revetment at all. The migration along the outside of Chinook Bend is reduced by the vegetation that exists there. Figure 21 shows the erosion potential field and shows that the area along the outside of Chinook Bend has an erosion potential that is less than non-vegetated areas. The channel at Chinook Bend moves toward the right bank (outward) where the right bank revetment is removed. Figure 17 shows the migration pattern downstream.

Scenarios F (Figures 10 and 18) and G (Figures 11 and 19) simulate migration with the right bank (outer) revetment altered at the Chinook Bend site. First the right bank (outer) revetment is partially removed (called the Stillwater Scenario F) allowing the downstream limb of Chinook Bend to move laterally at a relatively rapid rate. When the revetment is further "shortened", and more revetment is removed, called the Gainsford scenario (Scenario G), the channel at Chinook Bend moves laterally on the downstream limb and also moves laterally near the apex of the bend. In both cases, the migration patterns downstream of Chinook Bend do not significantly differ from the previous scenarios. Figures 18 and 19 show that the patterns are identical downstream from the black dot. In both cases the inner revetment is assumed to stay in place.

The final modeling scenario (Scenario H, Figures 12 and 20) shows the meander migration subsequent to the channel occupying an abandoned meander loop that exists on the floodplain adjacent to Chinook Bend. In order to achieve this location, the "upper cutoff" at Chinook Bend is assumed, which also assumes that both the left bank (inner) revetments are not in place. The simulation shows that the channel evolves relatively quickly and migrates across the floodplain. Downstream from this evolution, the channel has more migration (than in the previous scenarios) as it joins the old channel.

The modeling scenarios predict that there are generally low predicted rates of lateral channel migration. This was also true for the observed migration in the calibration time period. There is some evidence that there is a difference between rivers that occupy post-glacially incised valleys and have relatively rapid channel movements compared with rivers (like the lower Snoqualmie) that occupy abandoned glacial troughs and move much more slowly (Bethel Pers. Com.2008). A thorough discussion of this would require a significant familiarity with Pacific Northwest geology which is outside the scope of this report. The relatively small slope of the Snoqualmie River near Chinook Bend causes it to have relatively slow rates of channel migration.

The migration patterns observed in all the scenarios show that there is very little change in migration pattern downstream from Chinook Bend when changes are made in Chinook Bend. This is a pattern of downstream propagation of effects that is well documented in meander migration literature (i.e. Ikeda and Parker, 1989). A brief mathematical discussion of this effect is discussed in the next section.

3.3.2 Theoretical distance of influence of upstream changes on downstream migration

Various researchers have developed analytical (mathematical) expressions that describe and predict meander migration over time (cf. Ikeda and Parker, 1989). Based on these equations as formulated specifically by Johannesson and Parker (1989), the effect of a disturbance or change upstream exponentially decreases as you go downstream. The exponential decay function is:

$$\left(e^{\frac{-2\phi}{r}}\right)$$

where Φ is a dimensionless downstream distance, and r is a scaled dimensionless wave number that describes some aspects of the average geometry of the reach (see Johannesson and Parker 1989 for details.)

The element of interest, the exponential decay term $e^{\frac{-2\phi}{r}}$, shows that as you go downstream from a given point, an effect is exponentially less as you proceed downstream. The practical implication of this is that the changes that occur near Chinook bend have less effect as you progress downstream. This can be seen on the figures in the results.

3.3.3 Conservative calibration assumption

The model is being used to assess the possible impacts of certain management actions near Chinook Bend on downstream land. For this reason the study team decided to use a migration model that would give us a "conservative" migration pattern. In essence, we chose to evaluate greater than average limits of the channel migration. Previous experience with the model showed that this could be done by adjusting a coefficient in the model, after a strict calibration. For management purposes, this is like using a "safety factor" in other engineering design applications. Because our main concern was to evaluate the downstream consequences of actions near Chinook Bend, this allows us to estimate what we feel is a greater than average extent of the migration that could occur. In addition, it is also conservative because it was assumed that the four revetments downstream of Chinook Bend are not present, when in fact they are likely functioning to some degree.

3.3.4 Summary

The main question that the modeling addressed was how much effect the changes in the vicinity of Chinook Bend would make in the downstream direction. From a general and theoretical understanding of the propagation of such planform changes (cf. Ikeda and Parker, 1989), one would expect for there to be little change, with the effect decreasing the farther one goes downstream (see section 3.3.2). The modeling, both with the strictly calibrated values and with the conservative assumption show that this theoretical pattern is confirmed by the modeling of this specific river reach – there is little change to the downstream areas when changes occur at Chinook Bend. This suggests that major cutoff or revetment removal could occur in the Chinook Bend area without major changes in migration patterns occurring downstream.

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5.0 APPENDICES

Appendix 1. Model run parameters for calibration run

Some of the model parameters are internal to the model and are recorded as metadata in the appendices. “Erosion coefficients” are used to establish the erodibility of the erosion surface and are described in other sources (e.g. Larsen and Greco 2002). “Centerline properties” record the projections for geographic data, the starting and ending channels for the modeled migration, the date and time of the run, and model version that was used.

“Flow parameters” are derived from acquired data. The discharge, width, depth, slope and particle size were described above. The “Upper threshold” and “bankfull” were not used in this modeling effort and can be ignored.

“Computational parameters”, “cutoff parameters” and “erosion algorithm parameters” are parameters that are internal to the model, and are recorded here as modeling metadata.

Table 3 Model parameters for calibration run

Snoqualmie River 1936
Larsen centerline
Gamma project
1936 Start Channel
1964 End Channel
file written 29-Apr-2008 11:39:28
Meander version: Meander 7.3.5: Finalized Code to EWL

FLOW PARAMETERS
Q = 814 cms
H (depth) = 8 m
B (width) = 64 m
S (slope) = 0.00013
Ds = 7 mm
FlowThresh = 0
Bankfull = 100000

COMPUTATIONAL PARAMETERS
dyr = 1
C_max = 0.6
Spacing = 0.5
Smoothing = 3, 10, 10
Eo_Spacing = 0.5
Cf_scale = 1
Calc_uf = 1
Check_curve = 1

CUTOFF PARAMETERS
Sinu Thresh = 1.1
Recur. Int. = 0
Cutoff Routine = 0

BEND PARAMETERS
bend length= 11
straightSin= 0.0005
bendSin = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo = 1
b--Depth = 0
d--Erosion = 1
E0 field: 1rrvgbcasc_1500_3500.asc

Appendix 2. Model run parameters for prediction runs

Table 4 Model parameters for prediction runs

Snoqualmie River 2005
Larsen centerline
Gamma project
2005 Start Year
2105 Prediction
file written 10-May-2008 12:42:50
Meander version: Meander 7.3.5: Finalized Code to EWL

FLOW PARAMETERS
Q = 814 cms
H (depth) = 5.5 m
B (width) = 72 m
S (slope) = 0.0004
Ds = 35 mm
FlowThresh = 0
Bankfull = 100000

COMPUTATIONAL PARAMETERS
dyr = 1
C_max = 0.6
Spacing = 0.5
Smoothing = 3
Eo_Spacing = 0.5
Cf_scale = 4
Calc_uf = 0
Check_curve = 1

CUTOFF PARAMETERS
Sinu Thresh = 1.1
Recur. Int. = 0
Cutoff Routine = 0

BEND PARAMETERS
bend length= 11
straightSin= 0.0005
bendSin = 0.0005

EROSION ALGORITHM PARAMETERS
a--Eo = 1
b--Depth = 0
d--Erosion = 1

Appendix 3. Model runs compared with Scenario A (base run)

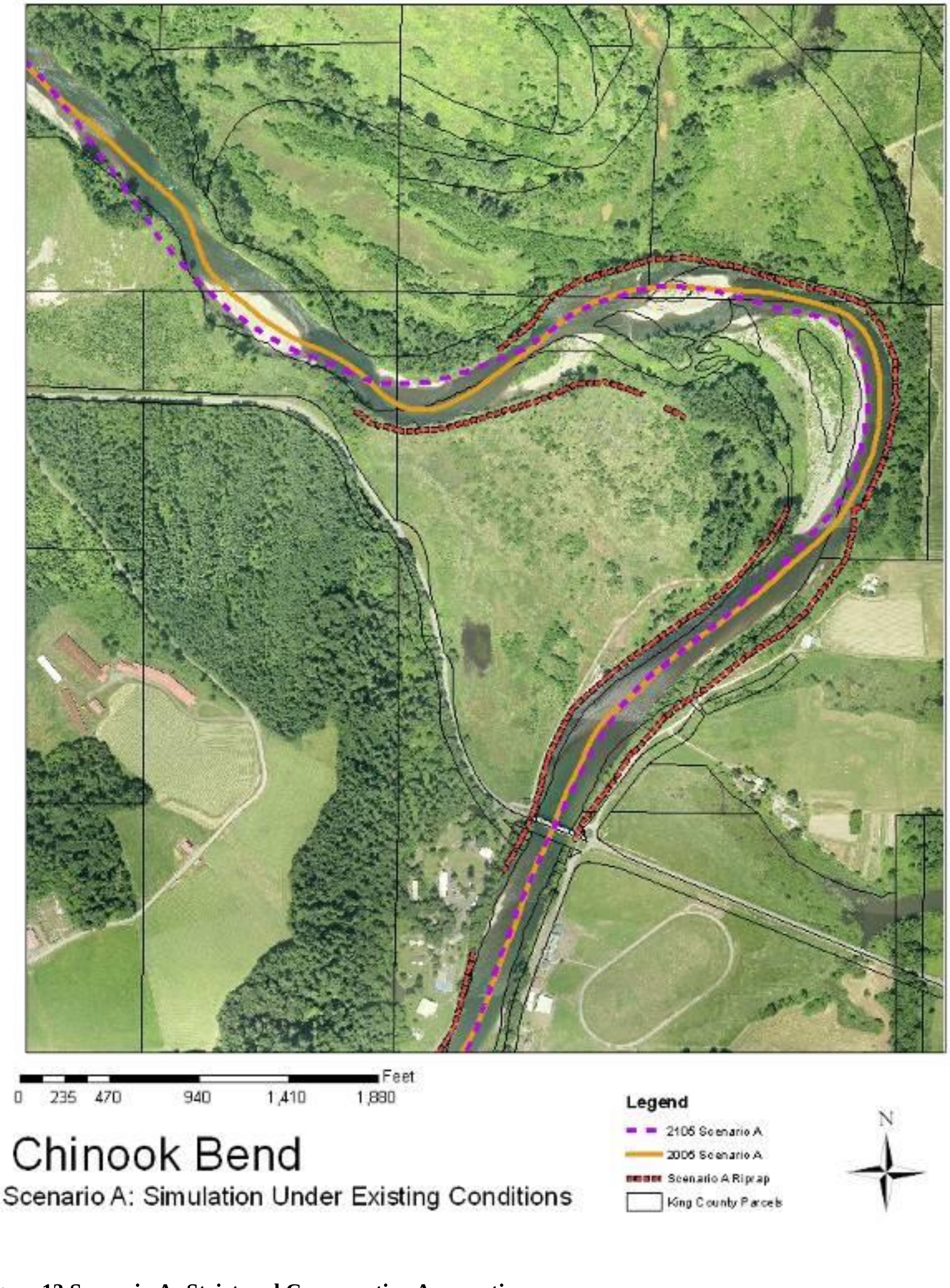

Figure 13 Scenario A: Strict and Conservative Assumptions

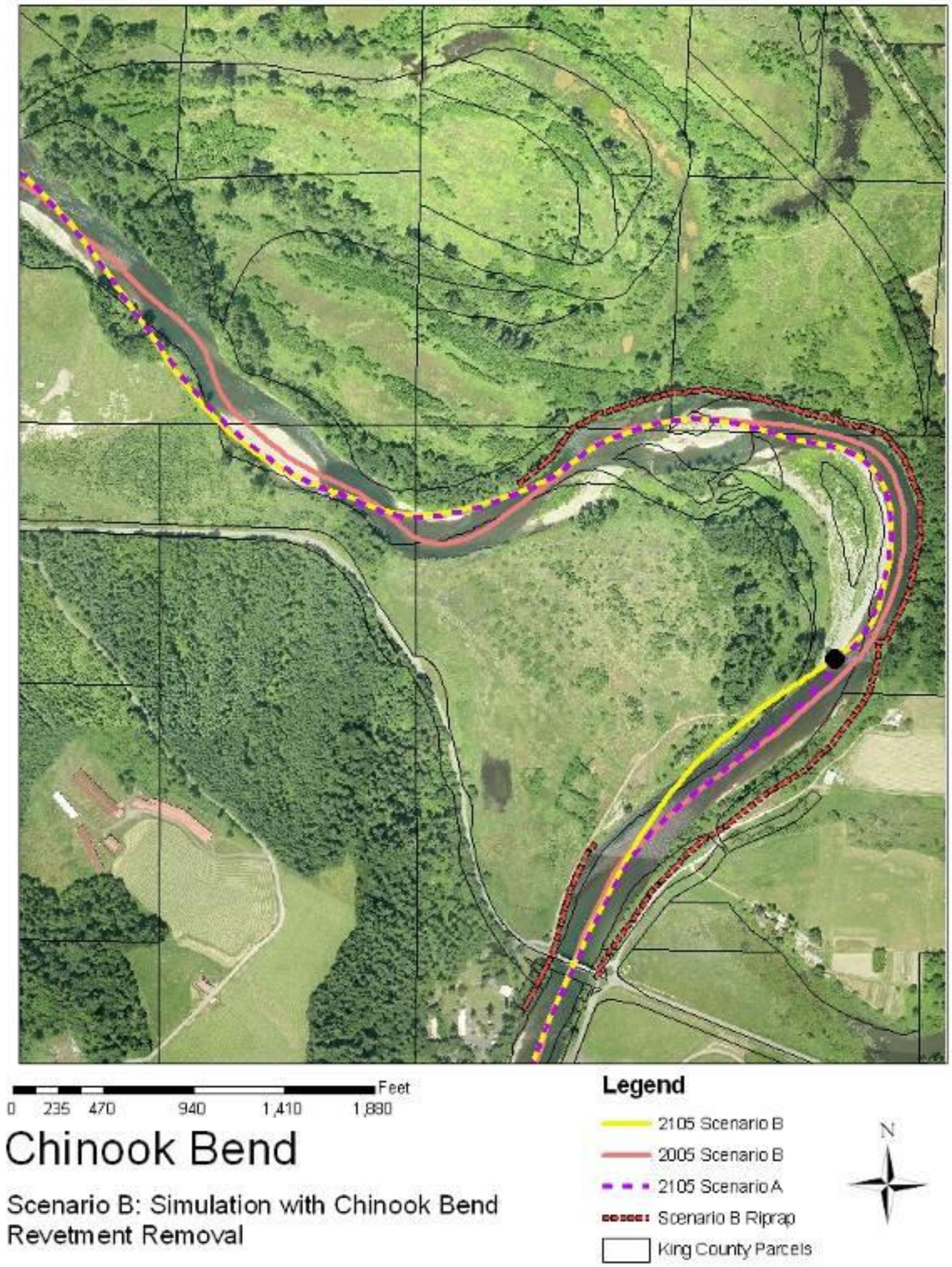

Figure 14 Scenario B: Simulation with Chinook Bend Revetment Removed

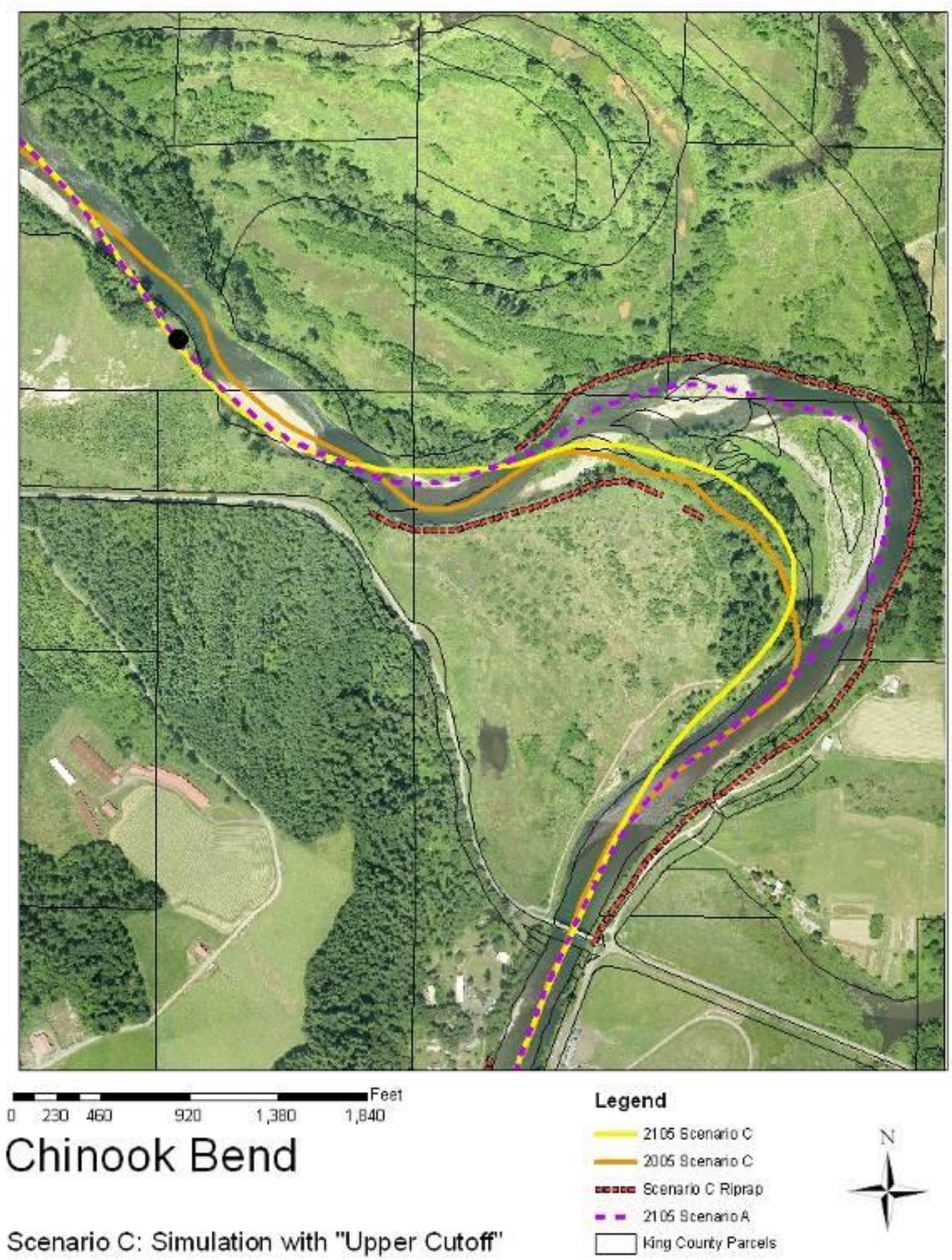

Figure 15 Scenario C: Simulation with "Upper Cutoff"

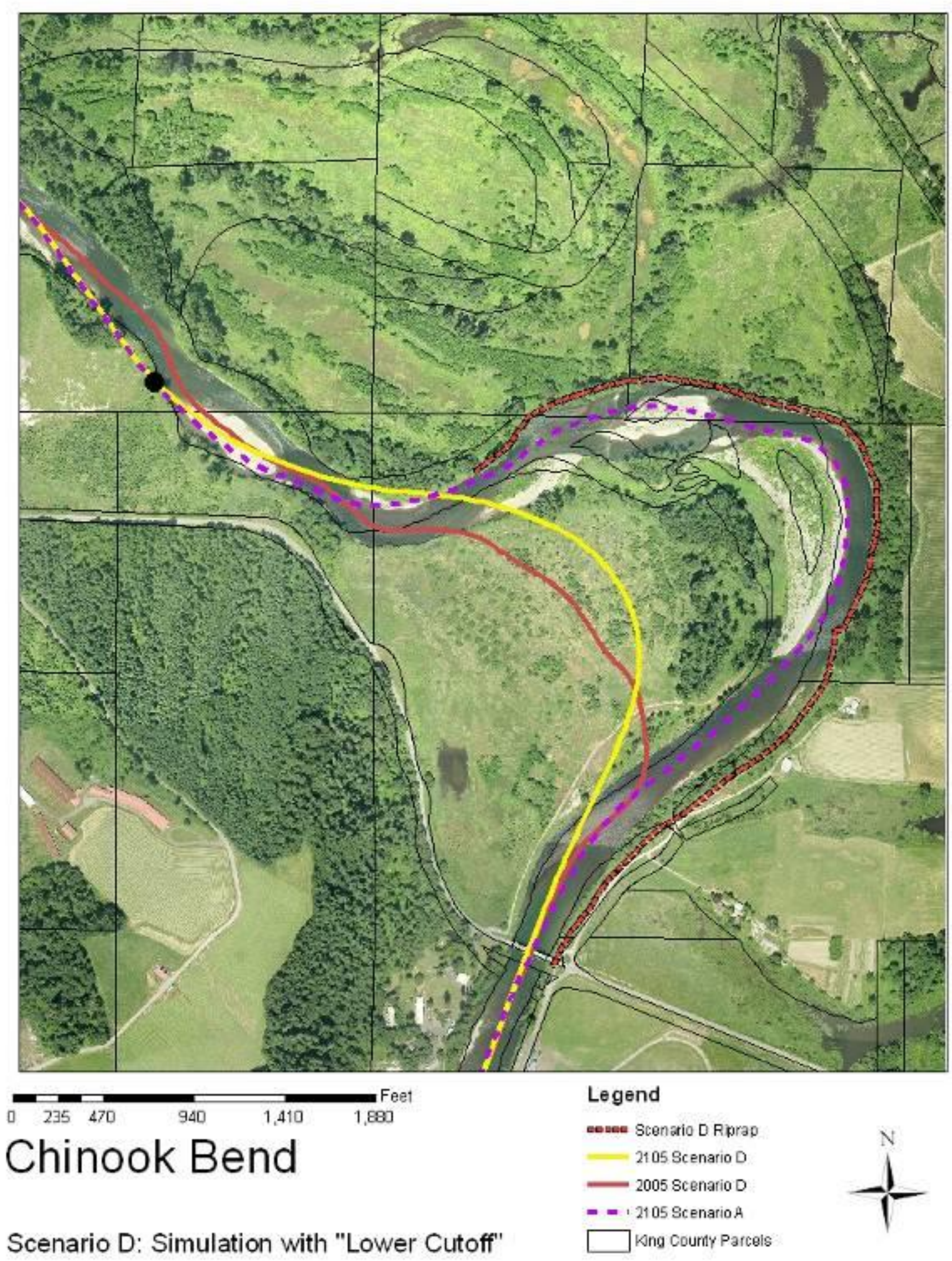

Figure 16 Scenario D: Simulation with "Lower Cutoff"

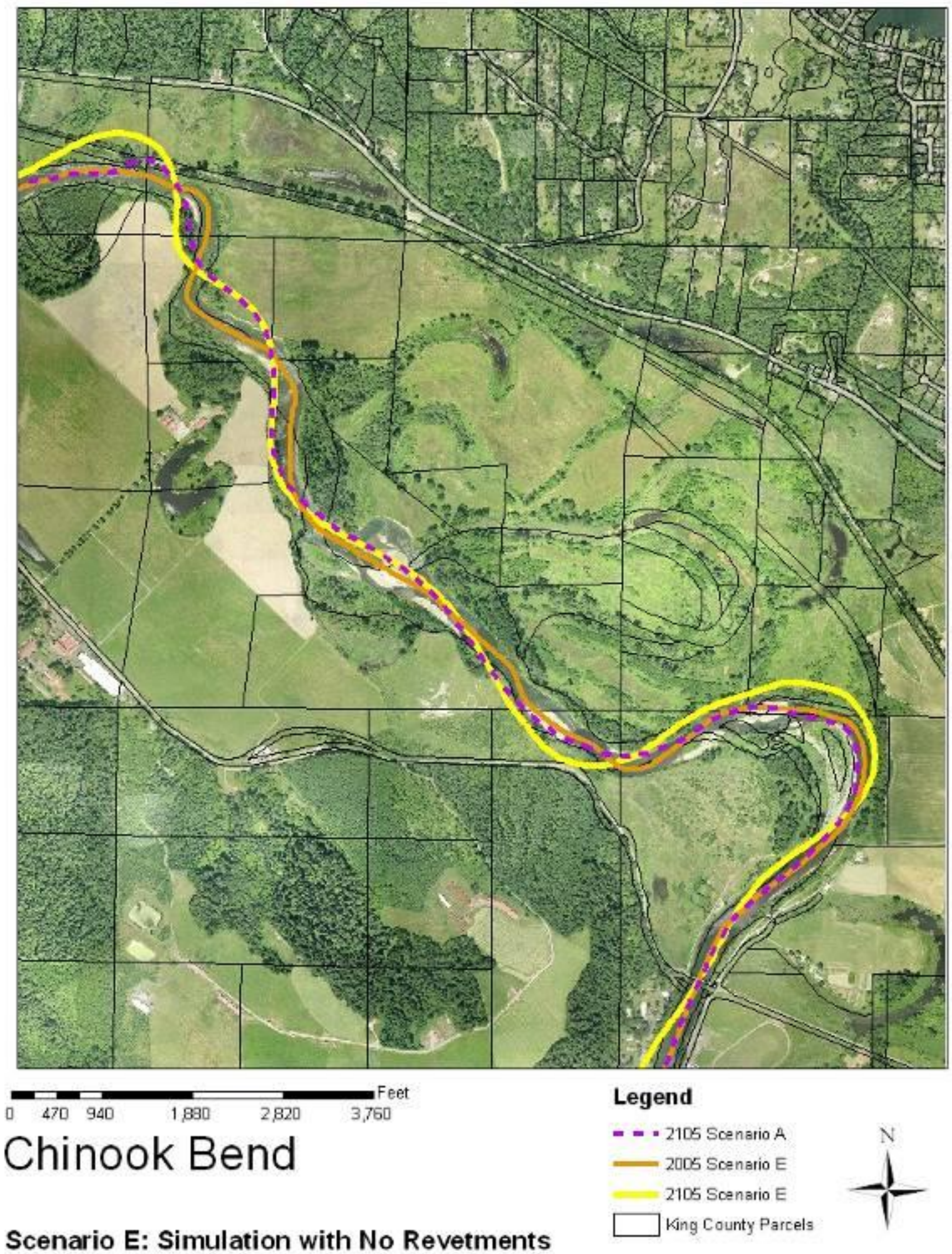

Figure 17 Scenario E: Simulation with No Revetments

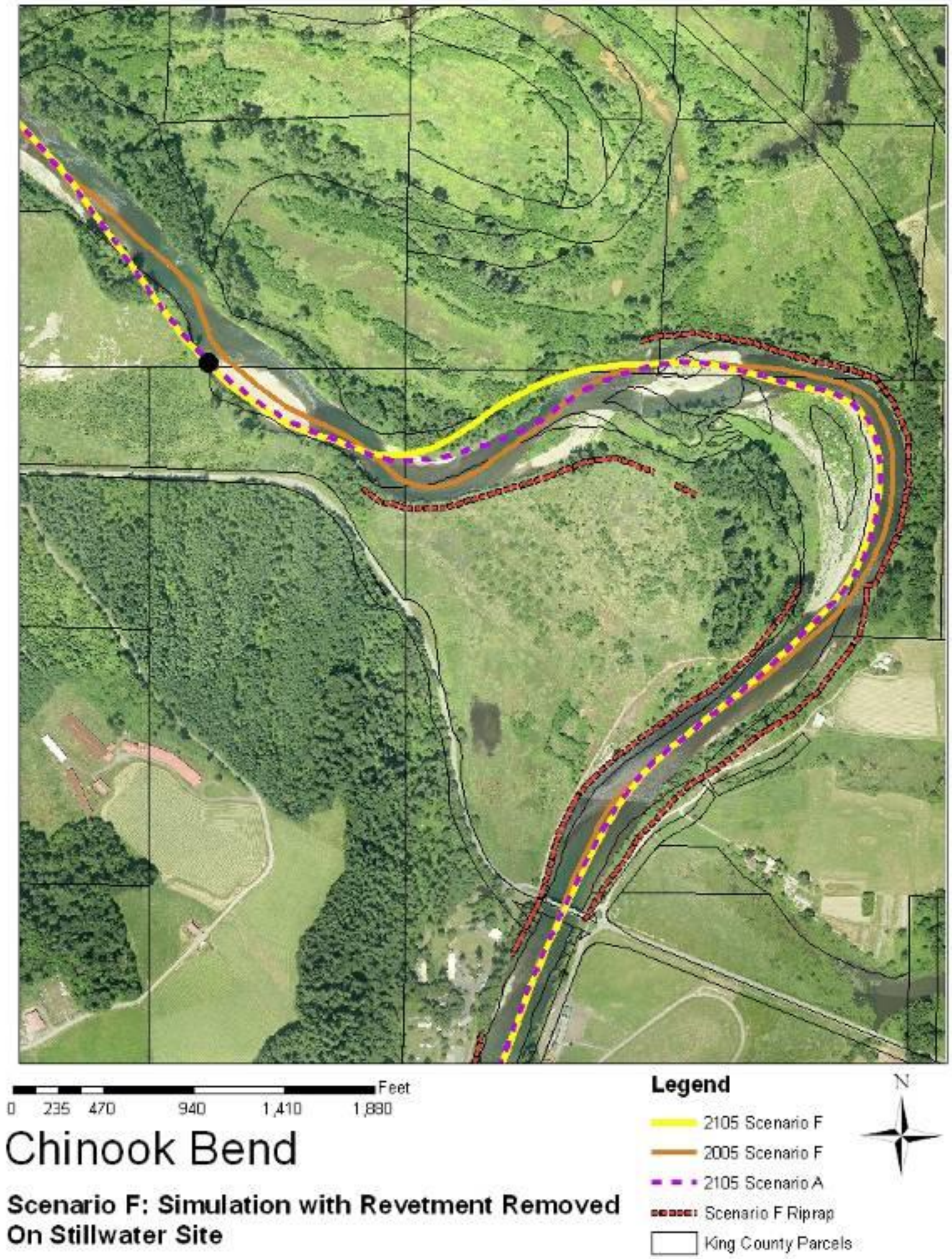

Figure 18 Scenario F: Simulation with Revetment Removed on Stillwater Site

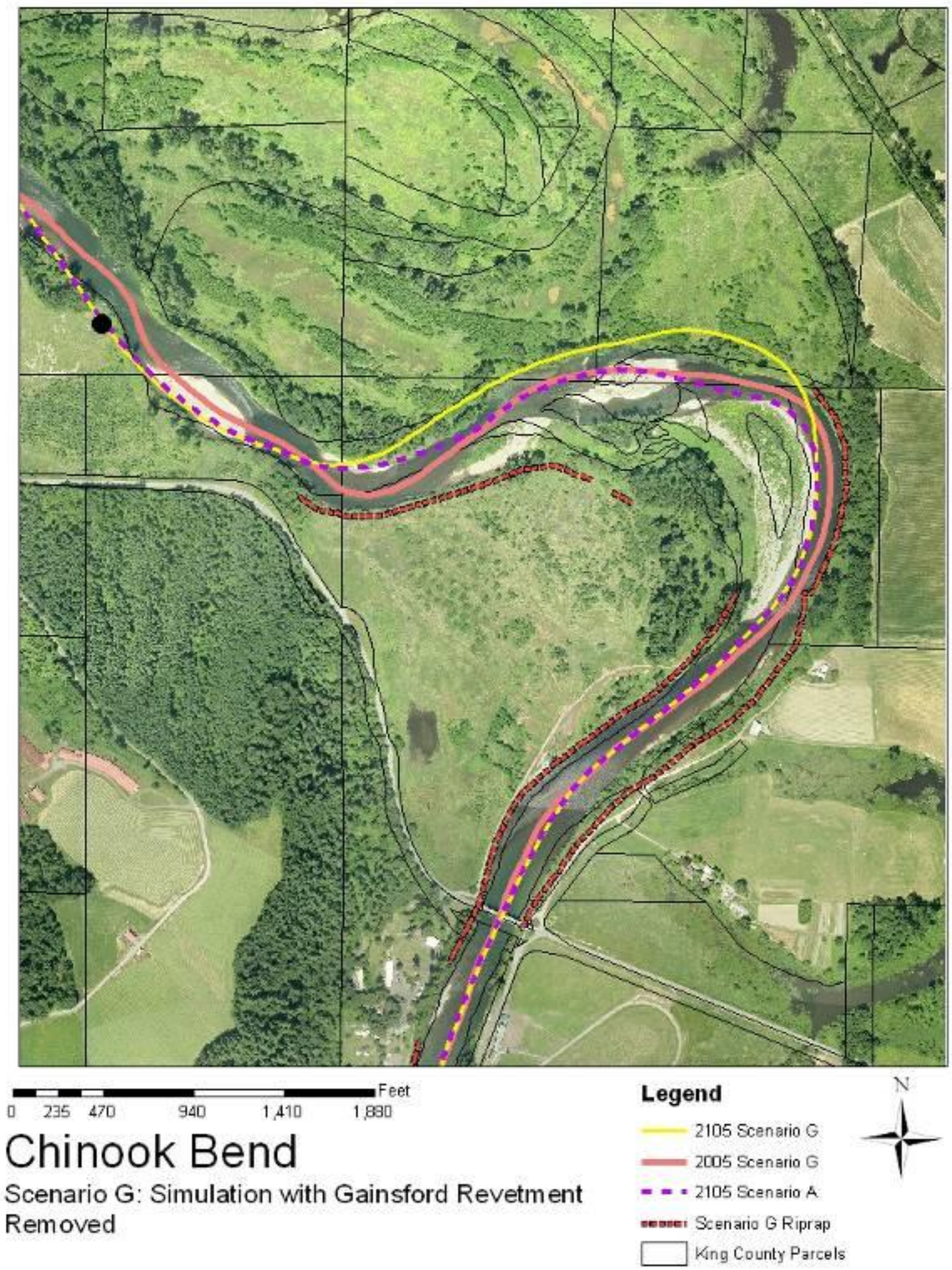

Figure 19 Scenario G: Simulation with Gainsford Revetment Removed

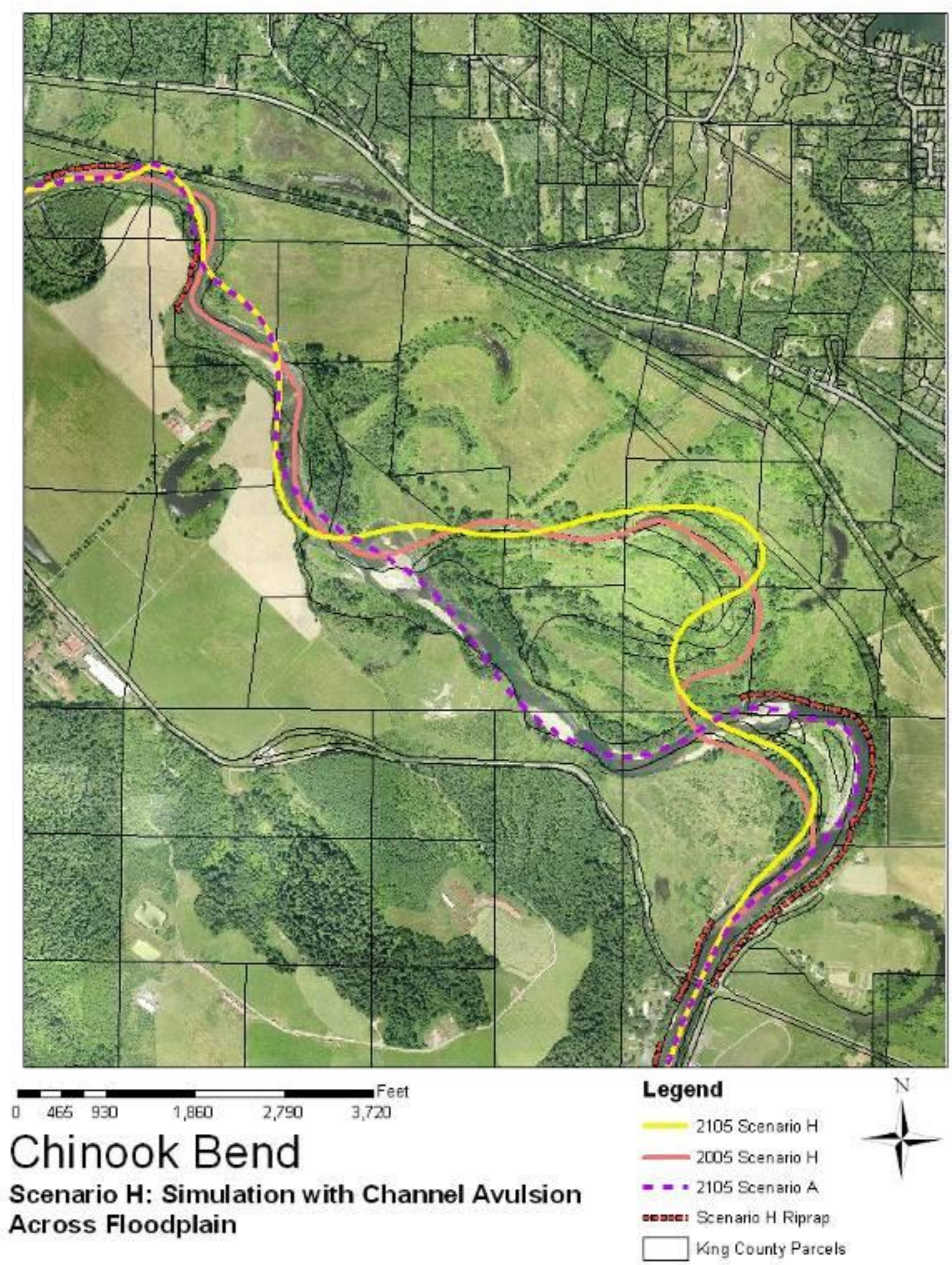

Figure 20 Scenario H: Simulation with Channel Avulsion Across the Floodplain

Appendix 4. Erosion potential coverage

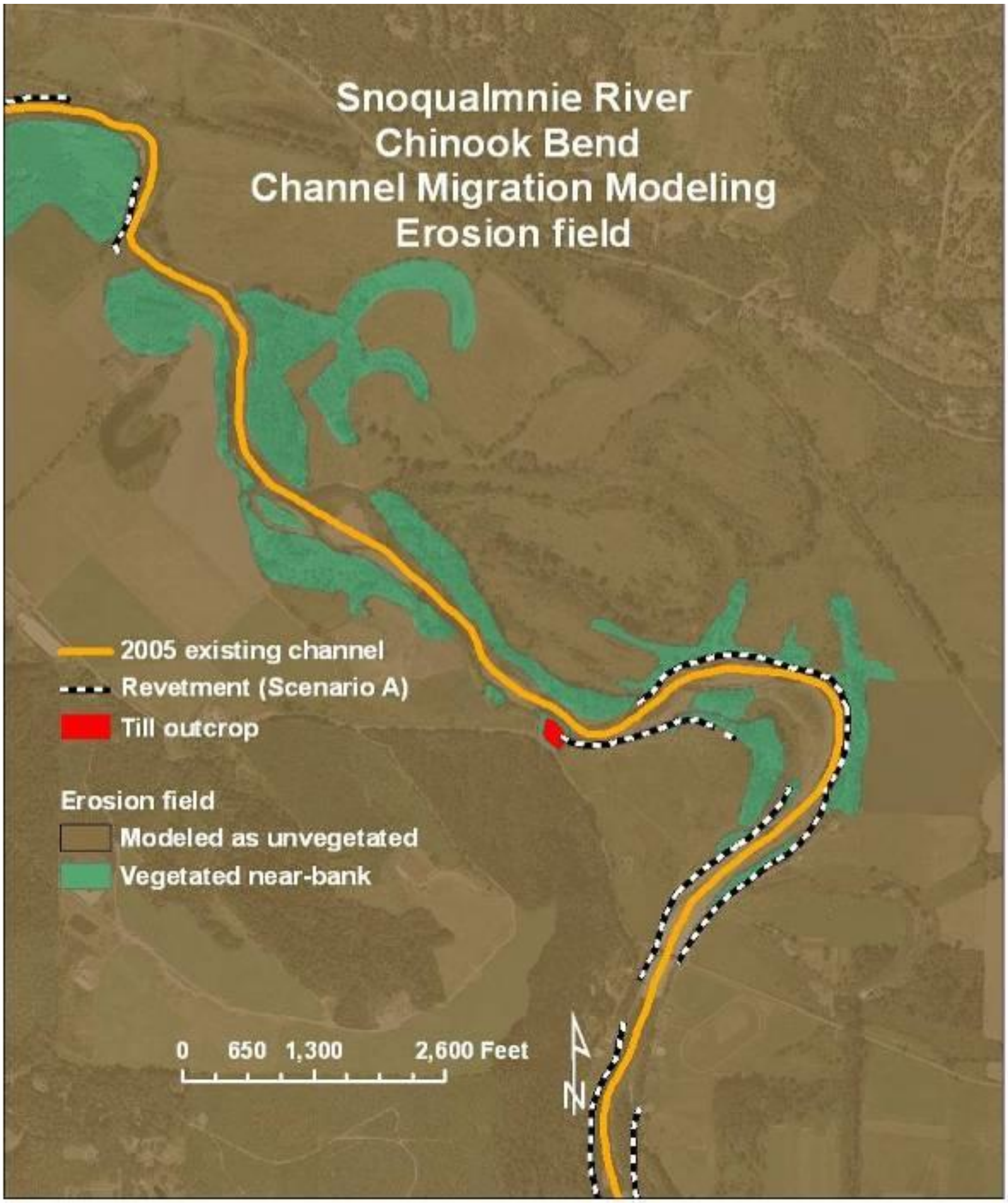

Figure 21 Erosion potential coverage