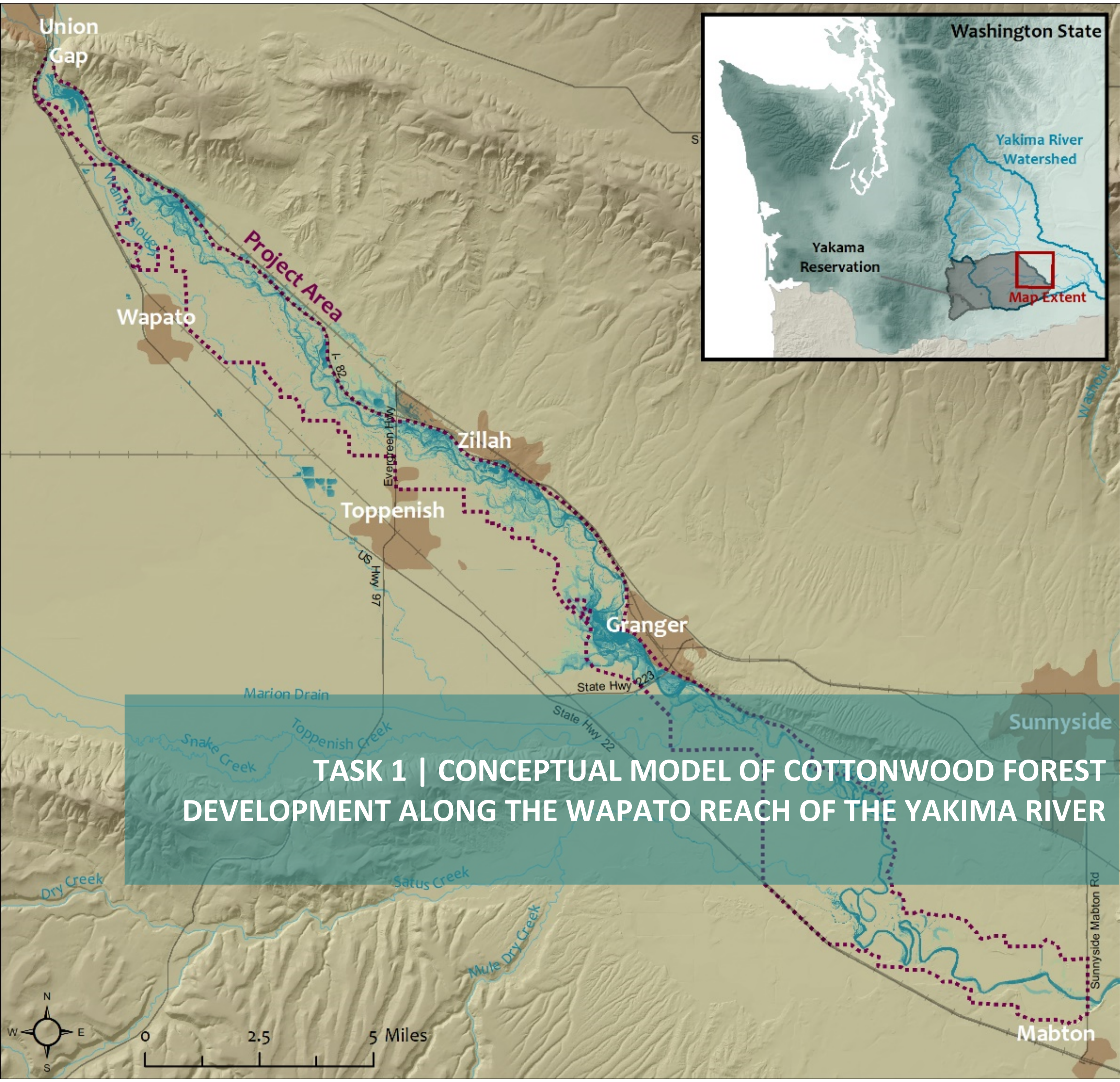

TASK 1 | CONCEPTUAL MODEL OF COTTONWOOD FOREST DEVELOPMENT ALONG THE WAPATO REACH OF THE YAKIMA RIVER

Prepared for: Yakama Nation Wildlife Program
DRAFT June 1, 2020

Prepared by: Natural Systems Design, Inc.

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DATE: April 16, 2024

TO: Tom Elliott & Bridger Cohan Yakama Nation Wildlife Program

FROM: Kevin Fetherston, PhD, PWS, Natural Systems Design
Scott Katz, MS, Natural Systems Design
Megan Whiteside, Natural Systems Design

RE: Task 1 Conceptual Model of Cottonwood Forest Development Along the Wapato Reach of the Yakima River

INTRODUCTION

The status of the health of the Yakima River Wapato Reach (Figure 1) black cottonwood (*Populus balsamifera* L. ssp. *trichocarpa* (Torr. & Gray ex Hook.) Brayshaw) forest was brought into question by Braatne et al., (2007) after they examined the relationship between hydro-regulated instream flows and cottonwood reproduction. The authors concluded that the regulated Yakima River flow regimes have not impacted the growth of established cottonwood, but have resulted in a reduction in the recruitment of cottonwood trees producing a skewed forest age structure such that the cottonwood are declining at a rate greater than forest reproduction (Braatne et al., 2007). Given black cottonwood (1) live typically for 100-150 years, and rarely beyond two centuries (Braatne et al., 1997; Paterson et al., 1996), (2) the Wapato reach was still experiencing cut and fill alluviation; the study concluded that an increased rate of cottonwood reproduction is essential to the future of these riparian forests (Braatne et al. 2007).

Cottonwood forest reproduction is dependent upon natural flow regimes where peak winter and spring flows create the open bare mineral substrate nursery conditions–resulting from either erosion or sediment deposition– necessary for cottonwood seedling germination (Figures 2 & 3). Concurrent with nursery substrate generation, a following spring hydrograph in synchrony with seed dispersal is necessary for seedling establishment (e.g., cottonwood box model) (Mahoney and Rood 1988; Braatne et al., 1996; Scott et al., 1997). Subsequent to seedling establishment in the first year, two to three years of non-seedling site scouring is necessary for recruitment of established seedlings to sapling and pole size cottonwood stands. Together, synchronous sequence of seedling establishment and stand recruitment are necessary for forest stand development into the common forest mosaic of even aged cottonwood forest stands found in unregulated rivers (Braatne et al., 1996; Stella et al., 2011). Hydroregulation, such as that found in the Yakima River, has changed the natural flow regime pattern impacting the rate of cottonwood forest reproduction (Braatne et al., 2007). Other researchers have grappled with the world wide observation that many *Salicaceae* (cottonwood) forests are being lost due to impacts of hydro-regulation.

> "Arguably, an important measure of success is whether or not the rate of creation of new forest stands is sufficient to compensate for losses by mortality at a minimum spatial scale that reflects the shifting steady state mosaic nature of riparian ecosystems (Johnson et al., 1976; Borman and Likens 1979). …Being able to recreate a new shifting steady state mosaic in degraded rivers, not only promoting regeneration, is a major challenge for long-term success of *Salicaceae* forest regeneration." (Gonzalez et al., 2018)

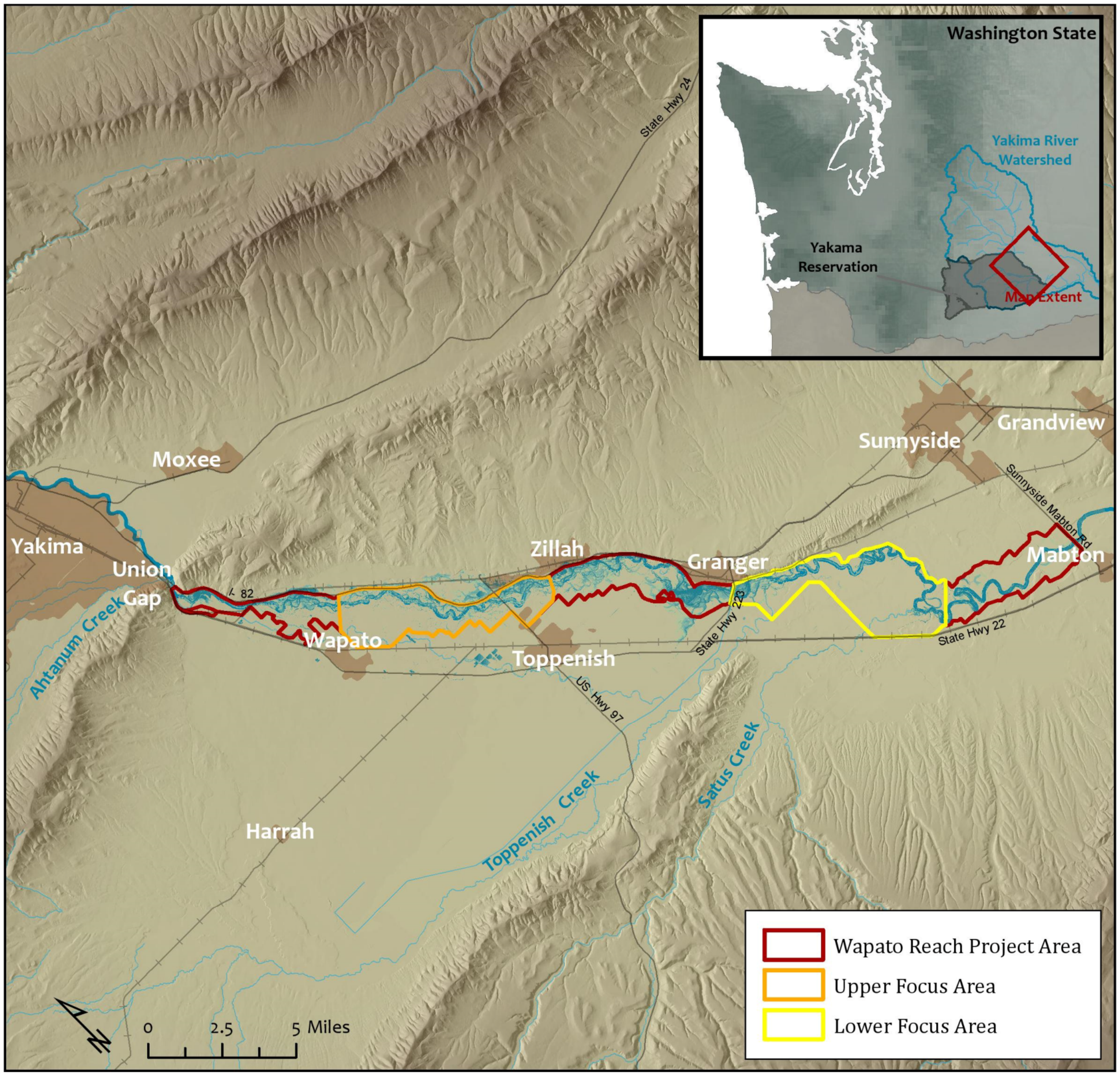

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Figure 1. Wapato Reach Project Area, Yakima River.

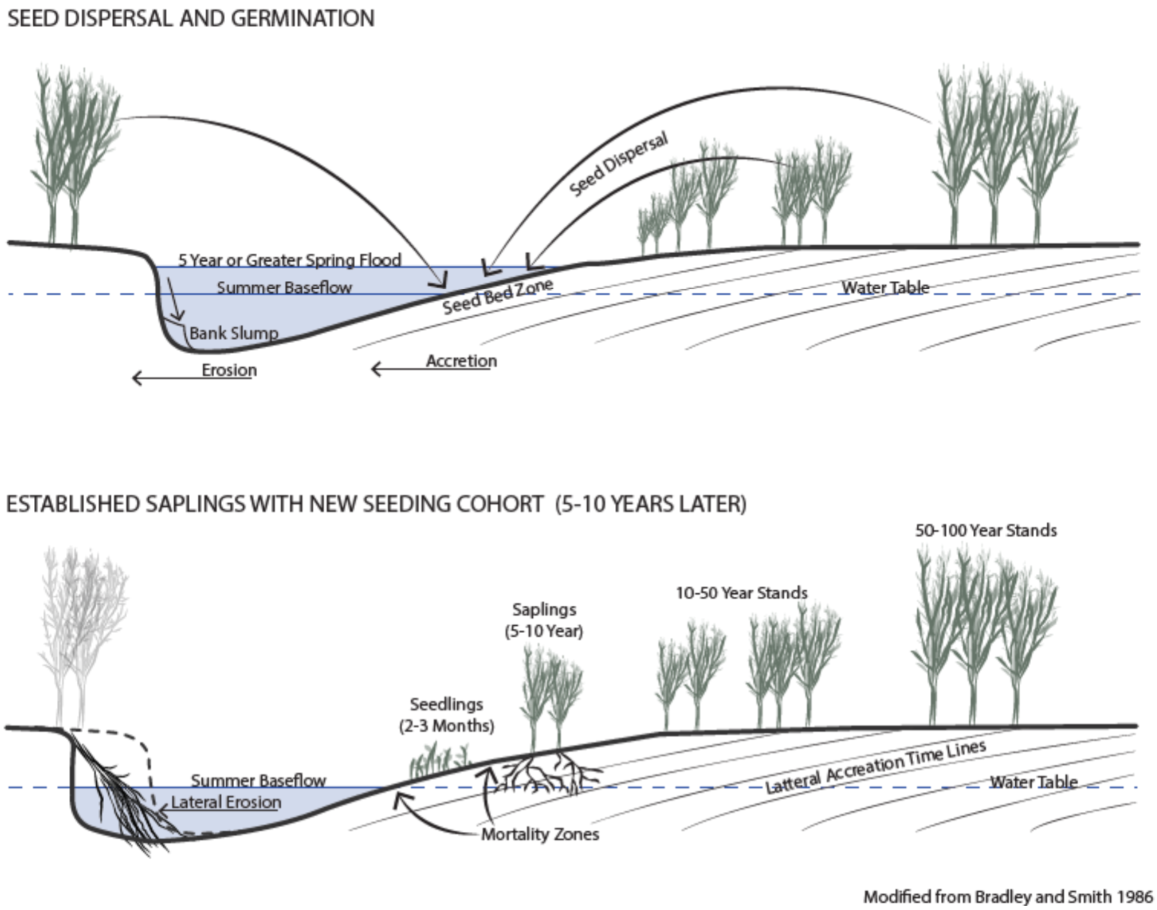


Figure 2. Cottonwood seed dispersal, seed germination and establishment, and cohort development (After Braatne et al 1997).

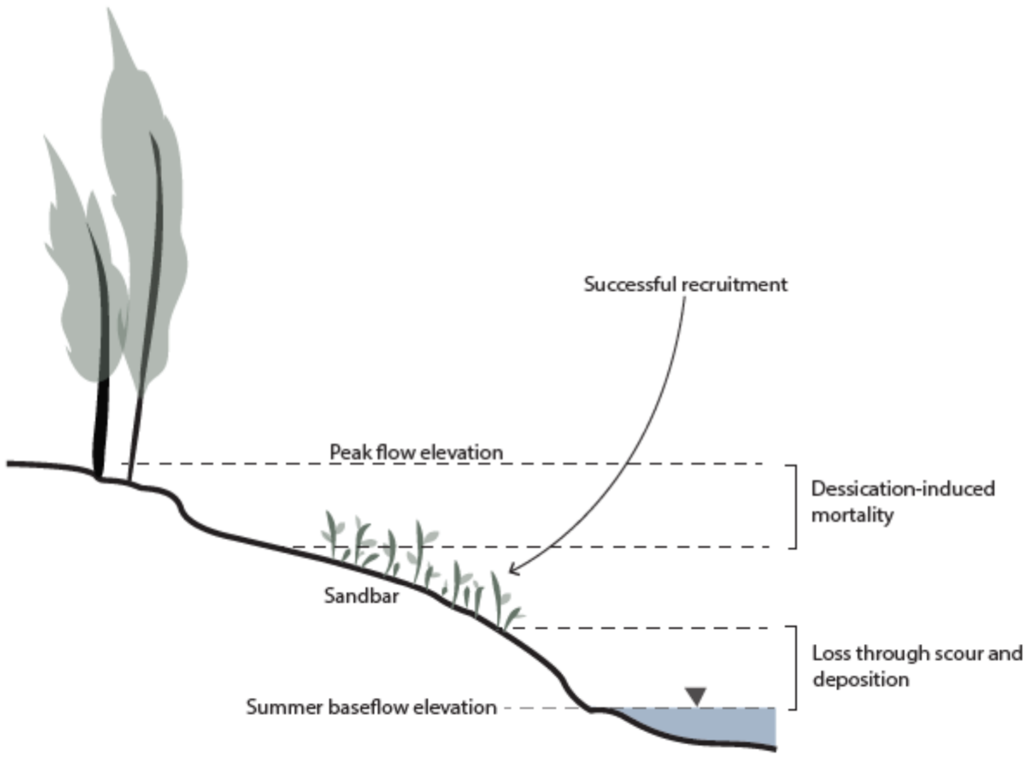


Figure 3. Cottonwood recruitment zone sites relative to peak flow channel scouring and summer baseflow water elevations.

Black cottonwood is the foundational species of the Wapato Reach riparian forest ecosystem (Braatne et al., 2007) providing stream shade, in-channel aquatic habitat structure as well as providing roosting and nesting habitat for a wide range of riparian dependent birds, especially during autumn and spring migration seasons. Given the importance of the Wapato Reach cottonwood forest to Yakama Nation cultural values, its critical role in supporting salmon populations and migratory bird habitat; a study was conducted to answer the following questions:

- What is the reproductive status of the Wapato Reach cottonwood forest?
- Is the forest reproducing at a rate sufficient to support forest replacement relative to forest loss?
- What are the major stressors impacting cottonwood forest reproduction?
- What are the mechanisms of forest reproduction (recruitment) and forest loss over the period of record (since 1949)?
- What are the hydrogeomorphic conditions under which the Wapato cottonwood forest is currently reproducing?
- What are the hydrogeomorphic conditions under which the Wapato cottonwood forest is currently maintained?
- Given the age structure, and rate of cottonwood riparian forest loss and gain, what is the predicted future of the Wapato Reach riparian cottonwood forest?

To answer these questions the following hydrogeomorphic and cottonwood forest analyses were conducted:

- Review of Braatne et al (2007) model of Yakima River riparian cottonwood decline.
- Hydrogeomorphic analysis of channel migration and floodplain forest turnover detailing cottonwood forest recruitment and loss over the period of record, 1949-2015.
- Analysis of cottonwood forest stand terrain position relative to mapped forest loss and forest gain.
  - Hydrogeomorphic analysis of alluvial terrain positions of cottonwood forest recruitment.
- Analysis of forest age structure using existing data sets.
- Analysis of cottonwood forest and soil type relationships.
- Relative elevation model (REM) analysis of cottonwood forest surface relative elevation above channel water surface.
  - Analysis of forest REM elevations as a proxy for depth to groundwater.

Wapato Reach Project Area

The Wapato Reach Project Area extends from the Sunnyside Diversion Dam at Parker, WA (RM 104) to Mabton (RM 60) including the active channel, floodplains and terraces, all riparian vegetation and black cottonwood forest, and adjacent agricultural areas as delineated by the Yakama Nation (Figure 1; Map-1 Appendix B). The Project Area includes tributary confluences with Ahtanum Creek at RM 110, Toppenish Creek at RM 81.3, and Satus Creek at RM 70 (Map 1; Appendix B). Over 47 miles the Wapato Reach trends from a multi-threaded braided/anabranching planform–with active channel migration, sediment deposition and transport, side channels, and a broad and well connected floodplain–to a single-threaded/meandering channel planform with slow channel migration, low sediment deposition, few side channels and a narrow active floodplain (Map-1; Appendix B). Two Focus Areas were selected to represent these two dominant, divergent Wapato Reach channel types to conduct detailed geomorphic and riparian forest characterizations, mapping, and analyses (Map 1; Appendix B) Focus Area).

The goal of Task 1 investigation was to develop a conceptual model of Wapato Reach cottonwood forest dynamics to inform the development of a strategic silvicultural restoration plan to conserve the Wapato Reach riparian cottonwood forests. The current investigation builds upon previous Yakima River cottonwood forest research conducted by Braatne et al., (2007) and Jamieson and Braatne (2000-2001). The findings of this investigation are presented in the following sections and appendices:

(1) Literature Review
(2) Methods:
    a. Relative Elevation Map (REM),
    b. Geomorphic Landform Mapping,
    c. 1949-2015 Historic Migration Zone (HMZ) Mapping,
    d. Riparian Forest Characterization and Mapping,
    e. Riparian Forest Age Structure Analysis–Dendrochronology,
    f. Cottonwood Forest Surface / REM Analysis,
    g. Cottonwood Forest Soil Type Analysis.
    h. Cottonwood Forest Stand Terrain Position Analysis,
(3) Results
(4) Discussion
(5) Conclusions
(6) Appendices
    a. Methods
    b. Maps
    c. Forest Type and Forest/Terrain Intersect Analysis

Synthesis of Past Work– Braatne et al., 2007; Jamieson and Braatne (2000-2001).

Braatne et al., (2007) developed a conceptual model of black cottonwood recruitment for the Yakima River (Figure 4). The model built on previous studies highlighting the hydrologic conditions under which cottonwood establishment and forest stand recruitment occur (Mahoney and Rood 1988; Scott et al., 1997; Braatne etal., 2007; Jamieson and Braatne (2000-2001).

Cottonwood seedling establishment begins with wind or water dispersal of cottonwood seed to moist barren mineral substrates. Seedling establishment then proceeds through seed germination and seedling growth and persistence through the first and second year of growth (Figures 2 & 3). Forest stand recruitment follows if established seedlings are not disturbed and cottonwood seedling cohort persists to pole size dimensions (dbh ~6-13 cm). The level of successful seedling establishment to forest stand recruitment size is a measure of the reproductive state of a cottonwood forest for pole size trees in general will grow into maturity if not disturbed by erosional processes. The rate of forest stand recruitment of a riparian landscape is a measure of not only of the current forest age structure but is also an indicator of future cottonwood forest persistence under existing conditions.

Seedling establishment is dependent upon winter and spring peak flows where new barren mineral nursery sites are generated through either erosional and/or depositional processes (Figures 2 & 3). These new barren mineral substrate sites occur along both primary and secondary active channel margins at an elevation such that they are exposed during seed dispersal. Concurrent with seed dispersal the river hydrograph must follow a narrow range of conditions such that the barren nursery sites are moist during seed dispersal and the following river water surface elevation must recede at a rate not greater than 2.54 cm/day, the rate identified by Mahoney and Rood (1988) in their classic cottonwood box model study. Following successful seedling germination during seedling's first summer, autumn through winter and spring flows must be moderate enough as to not mobilize and scour the newly established seedling nursery sites.

The Braatne et al., (2007) conceptual model identifies winter and spring freshet generation of barren nursery sites followed by cottonwood box model seed germination and establishment hydrology (Figure 4). The authors concluded that along the Wapato Reach (Braatne et al., 2007):

> "Downstream, irrigation withdrawls reduce the river stage, resulting in seedling establishment at low elevations that are lethally scoured by subsequent flows. These regulated flow regimes have not hindered growth of established trees, but have reduced the recruitment of cottonwoods, and particularly disfavoured females, thus altering sex ratios and producing skewed cottonwood population age and gender structures."

The current analysis is focused upon identifying and characterizing spatially explicit hydrogeomorphic terrain conditions under which black cottonwood forest stands are being recruited and maintained along the Wapato Reach. Additional analysis of geomorphic terrain positions and site elevations were targeted objectives of this study. Cottonwood pole size stands were individually mapped and their hydrogeomorphic site conditions characterized to provided data on cohort recruitment conditions in support of designing cottonwood silvicultural treatments. Once successful cottonwood pole size stand conditions are characterized, these data may be used for GIS based terrain analyses for selecting appropriate silvicultural sites and for strategic long term forest planning.

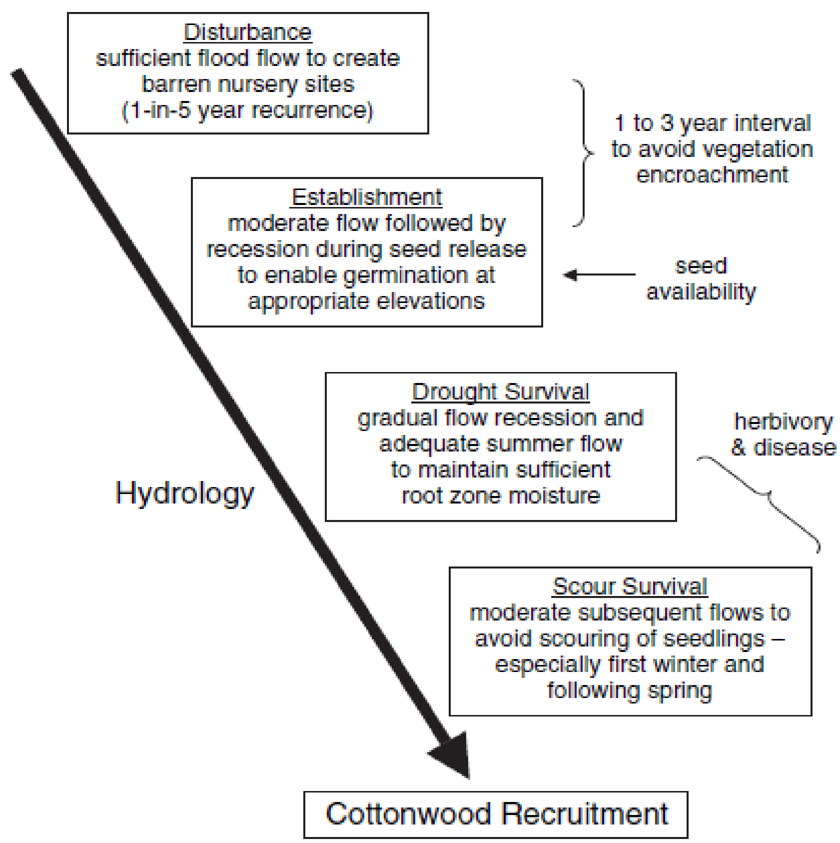


Figure 4. Braatne et al., (2007) conceptual model of fluvial geomorphology and cottonwood recruitment.

METHODS

The following sections present an overview of the methods used in mapping, characterizing and analyzing Wapato Reach geomorphic terrain and riparian vegetative cover. Complete technical methods and details are presented in Appendix A.

Hydrogeomorphic Terrain Characterization and Floodplain Turnover Analysis–Yakima River Wapato Reach 1949-2015

Geomorphic Landform Mapping and REM Analysis

The Wapato Reach alluvial terrain was typed and mapped relative to the channel water surface elevation using the 2015 Yakima-Benton county LiDAR digital elevation model (DEM). The alluvial terrain map is an important tool for analyzing the variety and pattern of surfaces and specific terrain positions that underly existing and developing cottonwood forest stands. Additionally, the REM water surface elevation may be used as a first order proxy in estimating the depth to adjacent floodplain shallow alluvial groundwater. Combined with soils map, and soil type hydraulic conductivity characterization, an approximate cottonwood root depth to groundwater capillary fringe may be estimated. From these data, a general estimate of cottonwood rooting depth may be generated for both existing conditions and as a terrain elevation target for silvicultural site selection.

REM

A REM was developed to evaluate the current geomorphic conditions present at the site. (Map 2; Appendix B). The methods used for this analysis were adapted from Jones (2006), and utilized 2015 Yakima-Benton county LiDAR DEM which was collected between 5/10/15-5/12/15 and 5/15/15-5/18/15 when flows were approximately 700 cfs at the Parker gage. A REM is a tool that depicts elevations of floodplain features relative to the water surface elevation of the channel at the time when the 2015 LiDAR was collected. Because the LiDAR flight only collected topographic information (as opposed to channel bathymetry), a topographic plane of the water's surface at the time of LiDAR collection was extracted directly from the DEM. The water surface plane was extended across the entire valley and subtracted from the bare earth DEM using raster calculator in ArcGIS to establish a relative elevation for each pixel of the bare earth DEM.

Geomorphic Landform Mapping

The complete range of geomorphic processes that have acted formatively on the Wapato Reach of the Yakima River Valley have produced a discrete set of geomorphic landforms in the valley bottom. By assessing the morphology and orientation of topographical features in the valley bottom, as rendered through the REM, the area within the valley was partitioned into categories based on these geomorphic landforms (Map 3; Appendix B). This analysis was conducted in ArcGIS 10.1 and informed by work done by the USGS in the Willamette Valley (J. Rose Wallick, 2013). In addition to the REM and LiDAR DEM, current and historical aerial imagery and 2-dimensional hydraulic model results (From Yakima County) were used to support the landform delineation. A geomorphic map was created by digitizing terrain features such as active channel, floodplain, terrace and valley margins. Our approach focused on determining the origin of the underlying surface (was the surface deposited and/or formed by the river) instead of solely one based on floodplain connectivity. Many of the areas included in the delineation include the "floodplain" and are mapped to distinguish the geomorphic processes that formed the underlying surface (was it deposited by a big flood or formed slowly by annual channel migration processes). The following geomorphic landforms were included in our analysis:

Low Flow Channel – The location of the primary low flow channel during May 2015

Secondary Channel – The location of secondary low flow channels during May 2015. These channels convey normal flow conditions but are generally smaller in width than the primary low flow channel

Perennial side channel – Channels that connect to the primary or secondary low flow channel and flow through the floodplain. These channels are generally wetted during most annual conditions.

Ephemeral side channel – Channels that connect to the primary or secondary low flow channel and flow through the floodplain. These channels generally convey flood flows and are not connected year-round

Tributary – Streams that have a confluence with the Yakima river within the project reach

Pond – Open waterbodies that contain still water within the project reach. Many of these features appear to have been created during gravel mining operations to build the adjacent highway.

Gravel Bar – Unvegetated surfaces within the active channel that contain mineral flood deposits (gravels, cobbles, sands, etc).

Vegetated Gravel bar – Gravel bars that are supporting riparian vegetation

Abandoned channel – active – Former low flow, secondary, or side channel locations that are still connected to the river network and convey flows during floods.

Abandoned channel – not active - Former low flow, secondary, or side channel locations that are not still connected to the river network and do not convey flows during floods.

Scroll bar – Floodplain surfaces on the inside of meander bends with elevated ridges that parallel the curvature of the channel. These deposits are formed by sediment that deposits on the inside of the meander bend during channel migration processes and become protected from hydraulic forces as the meander progresses away.

Generic Floodplain – Floodplain surfaces whose origin is indistinguishable by the underlying surface texture (i.e. not a scroll bar or channel). These surfaces are connected to the river during typical flood flows.

Generic Floodplain Terrace – Historical floodplain surfaces whose origin is indistinguishable by the underlying surface texture and that is not connected to the current river alignment during typical flood flows.

Terrace – A geologic formation that was not likely deposited by the river and is disconnected from the existing Yakima River.

Agriculture – Areas of existing agricultural activity. These areas may have previously been Yakima River floodplain.

Development – Areas where existing anthropogenic activity is occurring.

Road- Artificial hardened surfaces identified in the LiDAR DEM and aerial imagery.

Levee – Artificial flood defenses identified in the LiDAR DEM.

Irrigation Canal – Artificial flow conveyance features identified in the LiDAR DEM and hydraulic model.

Landform Typing and REM Analysis

The REM is useful in identifying side channels, wetlands, terraces, relict channel scars, and incised reaches of the channel. Active side channels (both perennial and intermittent) are shown in shades of blue, with darker blues and pink more frequently inundated (lower relative elevation) (Map 2; Appendix B,). Similarly, floodplains that are inundated more frequently are shades of blue, with darker blues and pink indicating more frequent inundation. Floodplains that are shades of green are inundated less frequently, with lighter greens to yellow only inundated during high flow events. Relict channel locations are also visible in the REM. The distribution of these features indicates areas where side channels are present and floodplains are relatively low (good floodplain connection), compared to areas where there are no side channels and floodplains are relatively high (disconnected floodplain) and the channel is inset within or incised into the floodplain surface.

1937/39-2019 Historic Migration Zone (HMZ) Mapping

An analysis of historic channel migration and floodplain forest turnover–floodplain forest loss and recruitment–for the period of aerial photographic record (1949-2015) was conducted to characterize the Wapato Reach floodplain forest status and trends. (Maps 4-5; Appendix B) Characterizing the rate of floodplain forest turnover within the HMZ allows for a projection of the fate of the HMZ floodplain forest over the next century under the current hydro-regulated flow regime. The HMZ is defined by the channel tracings during the period of record, in this case delineated using the aerial photographic record.

The HMZ was delineated by mapping the historic channel bank lines on the following aerial photographic imagery: 1937/39, 1949, 1973, 1981, 1992, 1995, 1996, 2000, 2004, 2009, 2019. The following is an overview of the methods used.

Methods

Channel tracings

Bank lines for the Wapato Reach of Yakima River were digitized from georeferenced aerial photographs viewed at 1:3000 scale (Google Earth eye elevation 6000' for 2018). The Wapato Reach included the entire mainstem Yakima River from the Sunnyside diversion dam to the Mabton Road bridge, as well as fully or partially connected side channels. Oxbows, disconnected sloughs, gravel pits, tributary streams, irrigation canals, and drains were not included in the delineation. Islands and gravel bars of any substantial size were delineated (i.e. removed from the channel delineation) but not logjams without any accompanying dry ground.
Bankline digitization was accomplished in ESRI ArcGIS by creating multiple draft polygons for each year, which varied in length based on the channel complexity.
Several years required extensive georeferencing of aerial photos, which was also accomplished in ESRI ArcGIS, generally using 1992 imagery for reference.

HMZ floodplain forest turnover analysis

Channel bank line tracings were used with the 1949 and 2015 forest maps to measure 1949 floodplain forest maintained and lost to channel erosion over the period of record. Additionally, forest recruitment between 1949 and 2015 was mapped. Using the mapped 1949 cottonwood forest area as baseline forest area maintained, forest lost and forest recruitment were measured in ArcGIS. From these 1949-2015 results, forest maintained, and rates of forest lost and forest recruitment were measured for the HMZ.

Riparian Forest Characterization and Mapping

Forest Type Mapping

Methods

For each Focus Area, aerial photography for the years 1949 and 2015 were used to map continuous polygons of the following cover types based upon observed percent canopy cover

1. Closed broadleaf (60-100% closed canopy cover / unit mapped area
2. Open broadleaf (25-59% canopy cover) / unit mapped area
3. Broadleaf woodland (10-24% canopy cover) / unit mapped area
4. Scrub (≥ 25% scrub cover) / unit mapped area
5. Russian olive (based upon field verified aerial photo color and texture signature)

Forest type polygons were digitized in ESRI ArcGIS from georeferenced aerial photographs viewed at the 1: 6000 scale (Maps 6-9; Appendix B). Minimum mapped polygon size was 1 acre.

Forest Change Analysis Summary

In the ArcGIS environment each pixel of mapped forest type polygons was assigned a numeric code corresponding to forest type and year. For example, 2015 closed canopy pixels were assigned the value 2, and closed canopy pixels in 1949 were assigned the value 1. 1949 pixel values were subtracted from 2015 mapped pixel values to create forest change polygons based on the subtracted values. Change polygons were then assigned into broader categories of forest recruitment, forest loss, and maintained forest (Maps 10-11; Appendix B).

Vegetation Canopy Heights

Methods

Digitization of Forest Patches:

Methods used for the analysis and mapping of vegetation canopy cover were adapted from Jones (2006), and utilized 2015 Yakima-Benton county LiDAR digital elevation model (DEM) collected between 5/10/15-5/12/15 and 5/15/15-5/18/15. First return LiDAR measurements were used to create a canopy cover of heights above the bare earth LiDAR return surface. The raster calculator in ArcGIS was used to subtract the LiDAR bare earth return surface from the LiDAR first return surface to generate a complete cover type height map for the study area.

Forest patch polygons of similar canopy height were digitized for each focus area in ESRI Arcgis from 2015 Lidar canopy cover map (Maps 12-13; Appendix B). Vegetation height bins were as follows: 5-25 feet, 25-50 feet, 50-75 feet, 75-125. A minimum mapped patch size was one acre.

Canopy Height Area Calculation

Vegetation canopy height polygons were overlaid with forest type polygons using the Intersect tool in ESRI ArcGIS. The resulting canopy height/forest type polygons were multiplied by the average percent cover for each forest type class (Shrub= 75 percent Woodland= 17 percent Open=42 percent Closed=80 percent), then summed by height bin.

Riparian Forest Age Structure Analysis–Dendrochronology

The objective of the Wapato Reach riparian forest age structural analysis was to characterize the status and trends of the cottonwood forest over the period of mappable photographic record (1949-2015). 2015 imagery was chosen rather than available 2017 NAIP imagery, due to the fact that the LiDAR data set upon which the REM was generated, was captured in 2015.

Methods

Cottonwood forest maintained, forest loss and forest recruitment were measured by comparing mapped forest cover for 1949 and 2015. Additionally, two Wapato Reach cottonwood dendrochronologic data sets were evaluated (Elliott 2012; Braatne et al. 2007) giving a field based approximation of the dominant floodplain forest minimal age of origin. The minimal age of the cottonwood forest over the period of aerial photographic record (1949-2015) allows an estimate to be made of forest stand dynamics–forest cover maintained, lost and recruited since 1949. Forest height measurement and mapping provides a forest height structural analysis of the Wapato Reach forest cover. Using standard Height-age/site index curves minimal age and range of forest stand age may be estimated (Peterson et al., 1996; J.S. Thrower & Associates Ltd. 1992).

A LiDAR DEM first return model was used to measure the height of existing vegetation throughout the Wapato Reach Focus Areas (Maps 12-13; Appendix B). Using tree height, approximate forest age structure was back calculated from tree height /dbh /age relationship to give a first order estimate of forest stand age from the mapped tree height polygons. The aim of this analysis was to estimate a minimal age for the entire mapped forest. The minimal age of forest stands was then used to approximate the time to forest stand senescence based upon the fact that black cottonwood trees generally live 100-150 years with a few legacy tree outliers reaching ages over two centuries (Braatne et al 1997; Peterson et al., 1996).

The forest age structure estimate was made using multiple lines of evidence: (1) Braatne et al., (2007) and Elliott (2012) dendrochronologic data sets, (2) LiDAR DEM first return model measurement of the height of existing vegetation throughout the Wapato Reach Focus Areas (Maps 12-13; Appendix B), (3) the tree height/dbh rating curves,(4) diameter age regression analysis developed by Braatne et al., (2007) and (5) diameter (DBH) height relationships developed from sampling Wapato forest stands in 2019.

The objective of this analysis was to provide a first order approximation of the age structure of the Wapato forest to serve as a proxy in characterizing the Wapato forest status and trends since 1949, as well as to characterize the fate of the forest over the next 100-years under existing conditions. The minimal age of forest stands is a conservative estimate. Based upon field observations it is evident there exists patches of legacy cottonwood forest over 100 years in age.

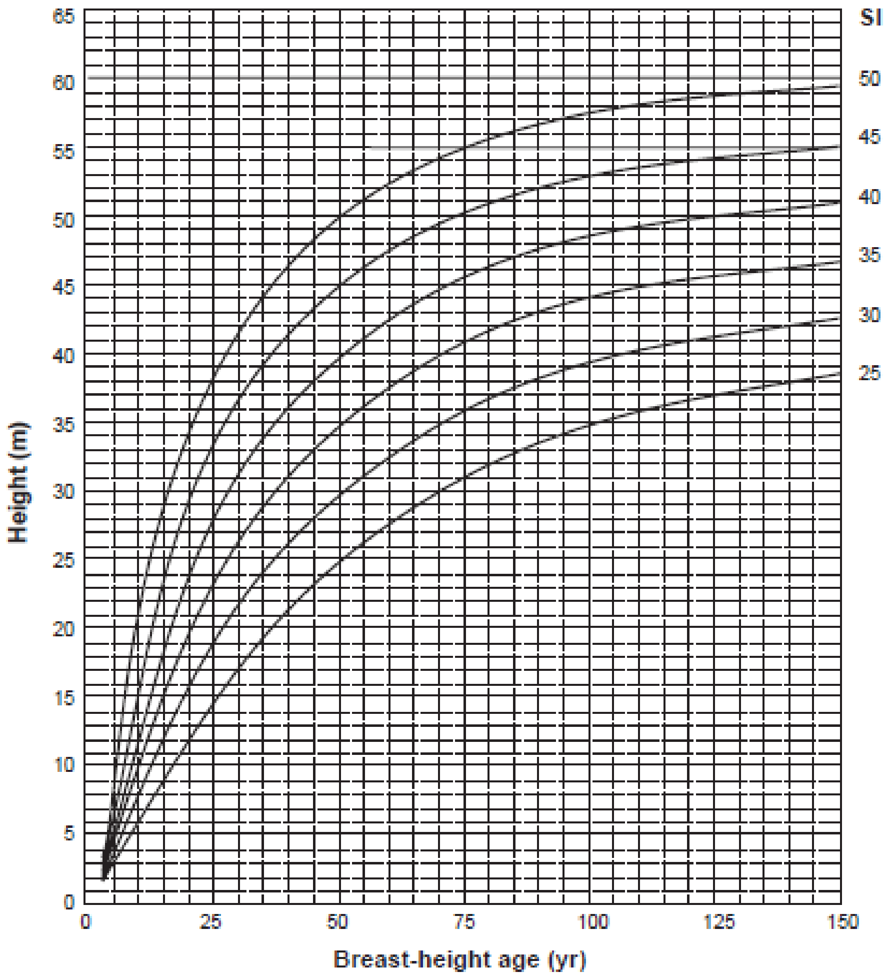


Figure 5. Height-age/site index curves for British Columbia black cottonwood for 0–150 years, with site index based on breast-height age of 50 years (Peterson et al., 1996 after J.S. Thrower & Associates Ltd. 1992).

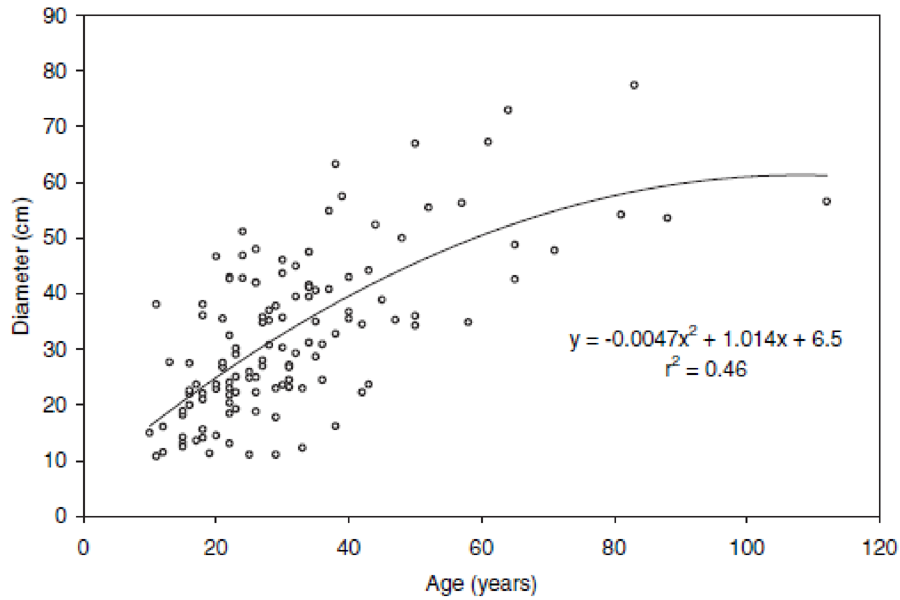


Figure 6. Relationship between basal diameter and the age of black cottonwoods along the Yakima River (Braatne et al., 2007).

Cottonwood Forest Elevations–REM Analysis

Methods

Summary statistics for the elevational ranges of existing cottonwood forest, cottonwood forest that was recruited between 1949 and 2015, and existing pole size stands were generated in ESRI ArcGIS based on the REM. Using the data generated in ESRI ArcGIS, Box whisker plots were created as a standardized way of displaying data sets based on a five-number (Holmes, A. et al., 2020) summary: the minimum, the maximum, the sample median, and the first and third quartiles.

Minimum: the lowest data point excluding any outliers.

Maximum: the largest data point excluding any outliers.

Median (Q2 / 50th Percentile): the middle value of the dataset.

First quartile (Q1 / 25th Percentile): also known as the *lower quartile* $q_n(0.25)$, is the median of the lower half of the dataset.

Third quartile (Q3 / 75th Percentile): also known as the *upper quartile* $q_n(0.75)$, is the median of the upper half of the dataset.

Analysis of Cottonwood Forest Change Relative to Associated Geomorphic Landforms

An analysis of cottonwood forest loss, recruitment and persistence of existing stands between 1949-2015 relative to mapped 2015 geomorphic landforms (primary channel, secondary channel, gravel bar, vegetated gravel bar, abandoned channel, scroll bar, generic floodplain, generic floodplain terrace, and terrace) was performed in ESRI ArcGis. Mapped polygons representing cottonwood forest that was maintained, lost or recruited between 1949 and 2015 were overlaid with mapped 2015 geomorphic landform polygons using the Intersect tool in ESRI ArcGis. The total acres of cottonwood forest for each change category (maintained forest, forest loss, forest recruitment) were then summed by associated geomorphic landform types. This analysis was intended to identify mechanisms driving forest loss and physical conditions supporting forest recruitment and forest persistence over time.

Cottonwood Forest Soil Type Analysis

An analysis of cottonwood stand soil types was performed in ESRI ArcGIS using NRCS soil data (Soil Survey of Yakama Indian Reservation Irrigated Area, Washington, Part of Yakima County J.J. Rasmussen, Soil Conservation Service 1976) and mapped forest polygons for the Upper and Lower Focus Areas. Dominant soils associated with cottonwood forest was mapped for the entire Wapato Reach Project Area (Map 14; Appendix B)

Cottonwood Recruitment Terrain Positions

An analysis of cottonwood forest stand recruitment was conducted using both forest soil type relationships, elevation ranges of existing forest in 2015, and elevation ranges of forest recruited between 1949 and 2015.Together with the forest stand terrain position analysis a hydrogeomorphic characterization of physical conditions under which forest recruitment is occurring along the Wapato Reach was developed.

RESULTS

Relative Elevation Maps (REM)

Wapato Reach REM map may be found in Map 2; Appendix B

Geomorphic Landform Mapping

Wapato Reach Landform Type maps may be found in Map 3; Appendix B.

1949-2015 Historic Migration Zone Mapping

The 1937/39-2015 HMZ throughout the entire Wapato Reach is depicted in Maps 4-5; Appendix B

Riparian Forest Characterization and Mapping

Wapato Reach riparian forest maps may be found in Maps 6-14; Appendix B. Summary statistics and figures may be found in Appendix C.

Wapato Reach Riparian Forest Age Structure

Wapato Reach Cottonwood Riparian Forest–Status & Trends 1949-2100

Multiple lines of evidence were used to make a first order estimate of the overall age structure of the Wapato Reach cottonwood forest. Wapato Reach Dendrochronologic data (Elliot 2012; Braatne et al., 2007; Table 1), 2019 Wapato Reach sample plot data from this study, and Interior British Columbia cottonwood stand survey height / growth curves (Figure 5; Peterson et al., 1996) were used together to estimate a minimal age of the Wapato Reach cottonwood forest.

The mapped generic floodplain forest age structure was sampled by Elliott (2012) and generic floodplain and scroll bars sampled by Braatne et al., (Figure 6; 2007) together consistently show generic floodplain cottonwood forest stands ranging from 30-60 years of age (age corrected to 2015). Given the challenges of aging cottonwood trees greater than 40 cm dbh due to heart rot, the 30-60 year forest age serves as a very conservative minimal estimate of the general age structure of the Wapato Reach cottonwood forest. The 30-60 year forest age estimate was used as a proxy for projecting the future generic floodplain forest life span extending to the end of the 21st century, 2100.

Table 1. Generic floodplain and scroll bar forest tree ages.

SOURCE	YEAR SAMPLED	MEAN (YRS)	MEDIAN	STANDARD DEVIATION	N
Braatne et al. 2007	2000	31	28	15	50
Elliott 2012	2008/2009	36	33	15	53

Using the results of Elliot (2012), Braatne et al., (2007) and Peterson et al., (1996) the following minimum proxy forest ages were assigned to the canopy height classes for the Upper and Lower Focus Areas (Figures 7 and 8; Tables 2 and 3). These results show a Wapato Reach cottonwood forest that in 2015 is dominated by forest stands 75-125 feet in height (53%) with an estimated age of 58 years in 2015.

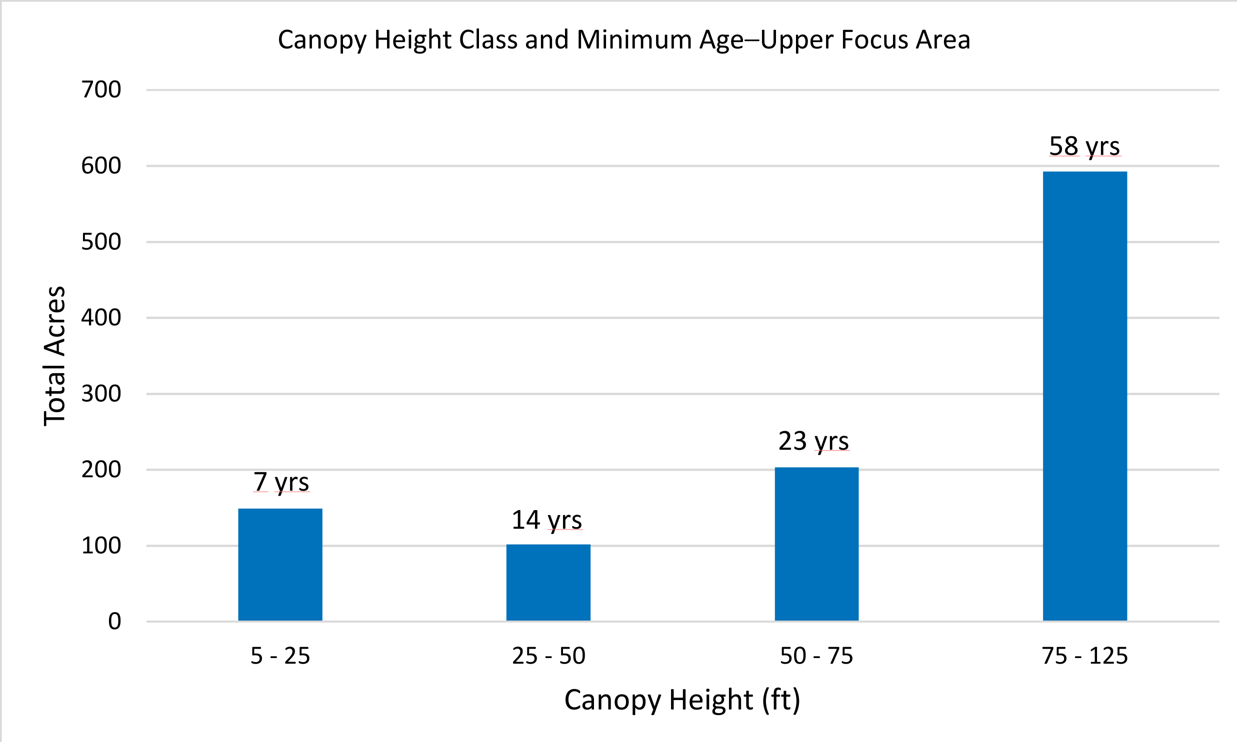


Figure 7. Cottonwood forest Upper Focus Area total area by height class and minimum age estimate as of 2015.

Table 2. Upper Focus Area Upper Focus Area cottonwood forest types area by 2015 height class.

HEIGHT (FEET)	TOTAL ACRES SCRUB	TOTAL ACRES WOODLAND FOREST	TOTAL ACRES OPEN CANOPY FOREST	TOTAL ACRES CLOSED CANOPY FOREST	SUB-TOTAL ACRES
5 - 25	102	6	7	34	149
25 - 50	36	20	42	3	102
50 - 75	17	23	85	78	203
75 - 125	29	10	147	408	593
				Total Area	1,047

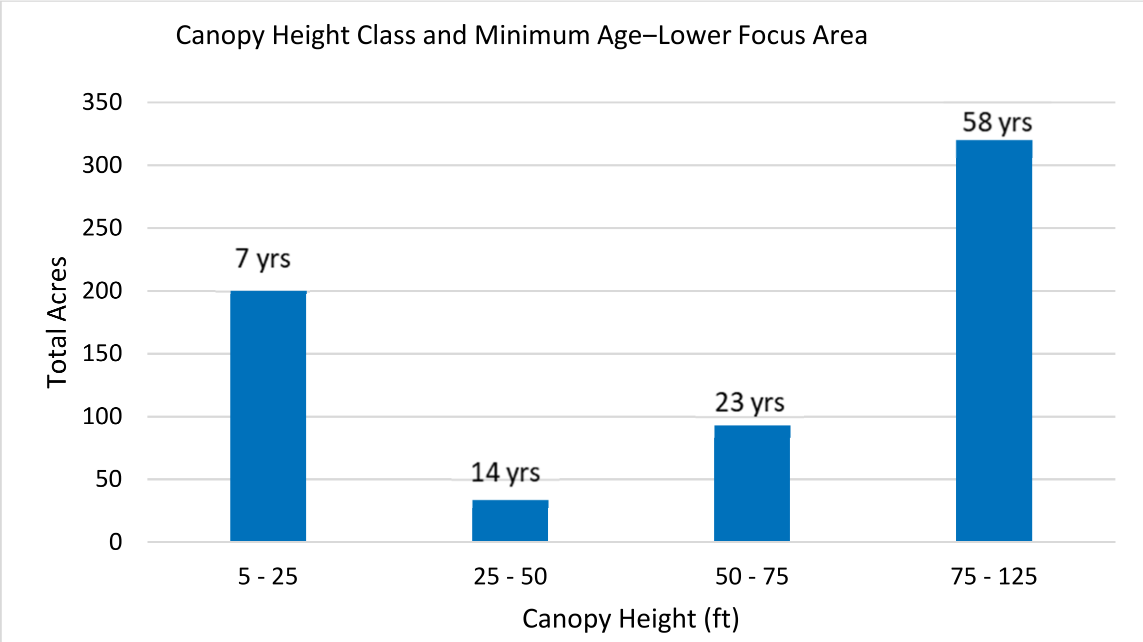


Figure 8. Cottonwood forest Lower Focus Area total area by height class and minimum age estimate as of 2015.

Table 3. Lower Focus Area cottonwood forest cover types area by height class.

HEIGHT (FT)	TOTAL ACRES WOODLAND FOREST	TOTAL ACRES OPEN CANOPY FOREST	TOTAL ACRES CLOSED CANOPY FOREST	TOTAL ACRES SCRUB	SUB-TOTAL ACRES
5 - 25	14	14	6	167	**201**
25 - 50	8	11	2	13	**34**
50 - 75	16	41	30	6	**93**
75 - 125	10	90	209	11	**320**
				Total Area	**648**

1949-2015 Forest Maintained, lost and recruited

Using the mapped 1949 cottonwood forest cover as baseline, 1949-2015 forest maintained, lost and recruited were mapped and areas measured. From these measurements, rates of forest lost and forest recruitment were calculated (Table 4; Appendix C). The rate of forest loss versus forest recruitment for both the Upper and Lower HMZ's show loss rates twice as high as forest recruitment within the HMZ. HMZ forest loss is the result of channel migration and floodplain erosion. Upper Focus Area Non-HMZ forest loss is 1.4 times that of forest recruitment, while the Lower Focus Area Non-HMZ forest loss and gain are nearly equal. Forest loss in the non-HMZ's is due primarily to conversion of forest to agriculture as well as to land clearing. Complete cover type change analyses may be found in Appendix C.

Table 4. Upper and Lower Cottonwood Forest Status and Trends 1949-2015

FOCUS AREA	1949 (ACRES)	MAINTAINED 2015 (ACRES)	LOSS 1949-2015 (ACRES)	RECRUITMENT 1949-2015 (ACRES)	TOTAL 2015 FOREST COVER (ACRES)	RATE LOSS PER DECADE (ACRES)	RATE RECRUITMENT PER DECADE (ACRES)
Upper							
HMZ	472	112	360	135	247	55	21
Non-HMZ	1,822	1,141	681	496	1,637	103	75
Lower							
HMZ	185	22	163	83	105	25	13
Non-HMZ	1,116	738	378	355	1,093	57	54

Cottonwood Forest Floodplain–REM Surface Elevation Analysis

Wapato Reach black cottonwood grow within a narrow range of elevations above the growing season low flows reflecting both floodplain history of sediment aggradation and maximum cottonwood rooting depths to groundwater. The cottonwood forest REM surface elevation analysis is presented in box whisker plot format, and tables, to allow for descriptive statistical display of the elevation data, and to provide target elevation ranges for selection of future cottonwood planting and seeding surfaces throughout the Wapato Reach (Figures 9-11; Tables 5-7).

Trends in the data show lower average elevations in the active HMZ floodplain surfaces as compared to the older higher elevation non-HMZ generic floodplains for both Upper and Lower Focus Areas (Figures 9-11; Tables 5-7). Pole size cottonwood stands, recruited since 2000, were characterized to identify surface elevations of recent successful stand recruitment and for identifying elevations for floodplain silvicultural designs (Figure 11; Table 7). The more dynamic Upper Focus Area floodplain forest elevations were significantly lower, average 1.5 compared to Lower Focus Area average 2.0 meters.

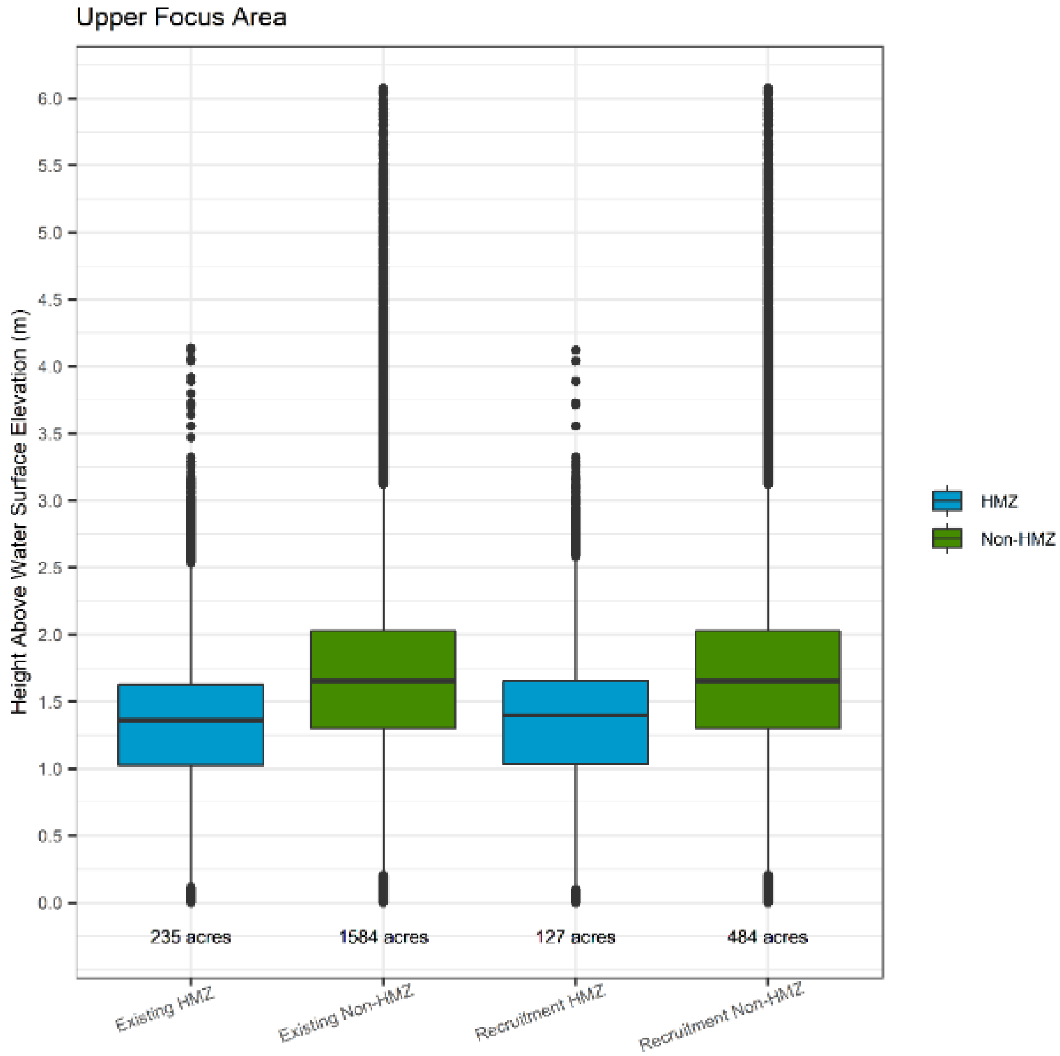


Figure 9. Upper Focus Area cottonwood forest surface elevation above REM water surface elevation (WSE). Existing 2015 cottonwood forest and new recruited forest. Historic channel migration zone (HMZ) and Non-Historic Migration Zone (Non-HMZ).

Table 5. Upper Focus Area cottonwood forest surface elevations above REM WSE.

DESCRIPTION	AREA (ACRES)	MEAN (M)	MEDIAN (M)	STANDARD DEVIATION	Q25	Q75	MINIMUM	MAXIMUM
Existing HMZ	235	1.31	1.36	0.45	1.02	1.63	0.00	4.14
Existing Non-HMZ	1584	1.66	1.66	0.62	1.30	2.03	0.00	6.07
Existing Upper	1819	1.59	1.61	0.56	1.25	1.93	0.00	6.07
Recruitment HMZ	127	1.32	1.40	0.46	1.03	1.65	0.00	4.12
Recruitment Non-HMZ	484	1.66	1.66	0.62	1.30	2.03	0.00	6.07
Recruitment Upper	611	1.59	1.59	0.61	1.23	1.94	0.00	6.07

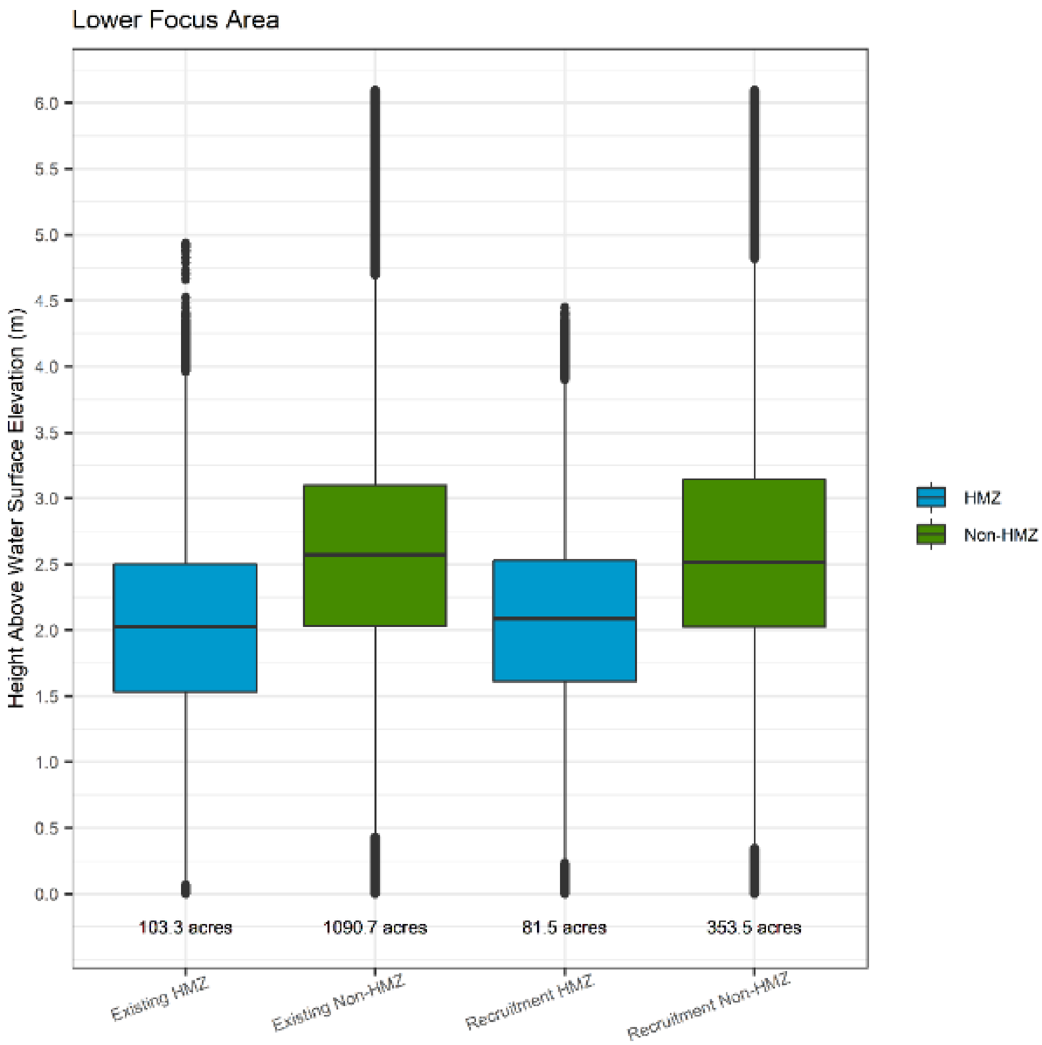


Figure 10. Lower Focus Area cottonwood forest surface elevation above REM WSE. Existing 2015 cottonwood forest and new recruited forest. Historic channel migration zone (HMZ) and Non-Historic Migration Zone (Non-HMZ).

Table 6. Lower Focus Area cottonwood forest surface elevations above REM WSE.

DESCRIPTION	AREA (ACRES)	MEAN (M)	MEDIAN (M)	STANDARD DEVIATION	Q25	Q75	MINIMUM	MAXIMUM
Existing HMZ	103	1.97	2.03	0.74	1.53	2.50	0.00	4.93
Existing	1194	2.52	2.52	0.81	1.98	3.06	0.00	6.10
Existing Non-HMZ	1091	2.57	2.57	0.80	2.03	3.10	0.00	6.10
Recruitment HMZ	82	2.03	2.09	0.69	1.61	2.53	0.00	4.45
Recruitment	435	2.52	2.43	0.93	1.93	3.00	0.00	6.10
Recruitment Non-HMZ	354	2.63	2.51	0.94	2.02	3.14	0.00	6.10

Forest Stand Recruitment–Pole Size Stands

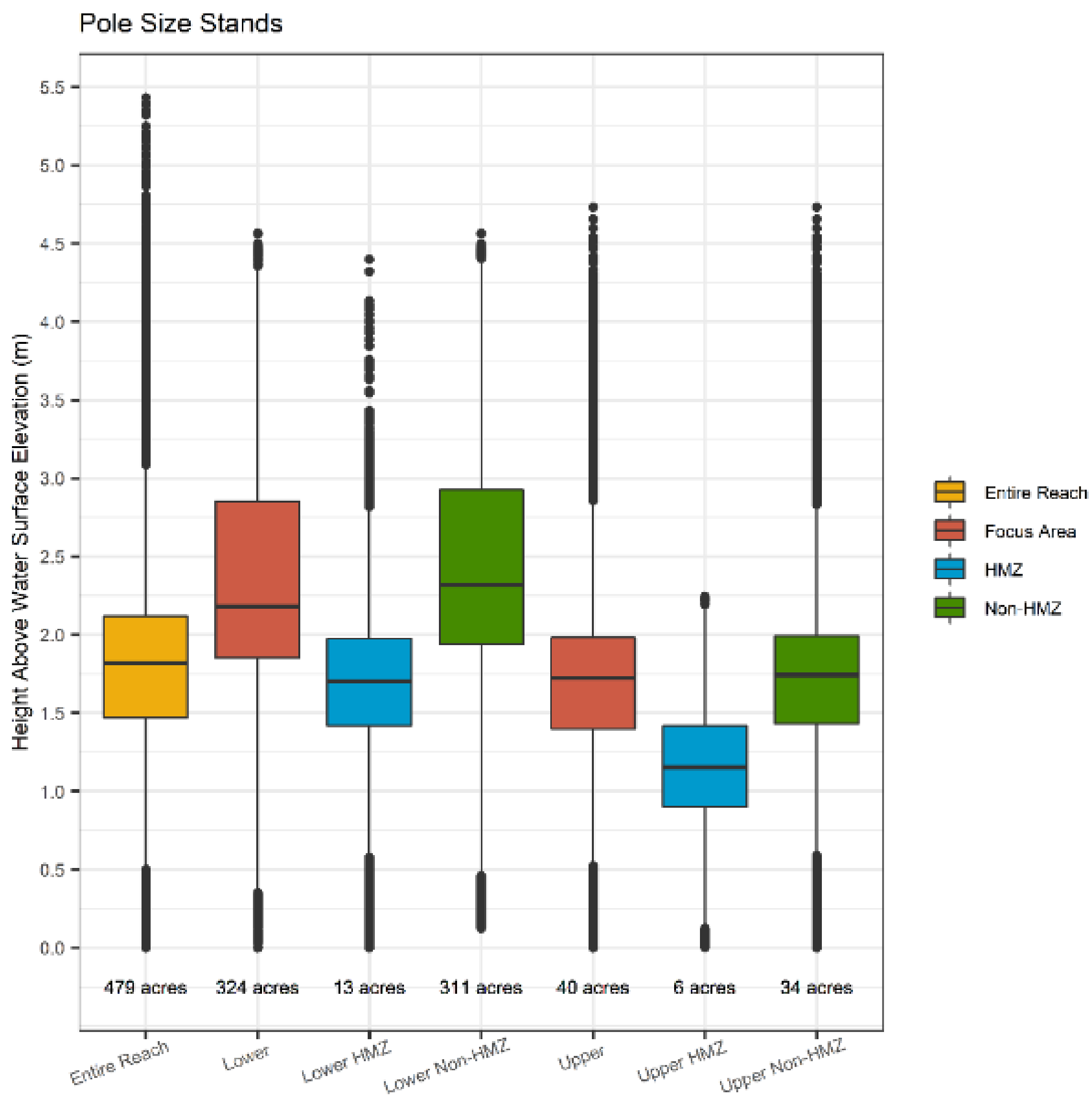


Figure 11. Lower and Upper Pole Size cottonwood forest surface elevation above REM WSE. Pole size stands are recently recruited in past 20 years, since 2000. Historic channel migration zone (HMZ) and Non-Historic Migration Zone (Non-HMZ).

Table 7. Lower and Upper Pole Size cottonwood forest surface elevations above REM WSE.

DESCRIPTION	AREA (ACRES)	MEAN (M)	MEDIAN (M)	STANDARD DEVIATION	Q25	Q75	MINIMUM	MAXIMUM
Entire Reach	479	1.80	1.82	0.57	1.47	2.12	0.00	5.43
Lower Focus Area	324	2.27	2.18	0.64	1.85	2.85	0.00	4.56
Lower HMZ	13	1.67	1.70	0.50	1.42	1.98	0.00	4.40
Lower Non-HMZ	311	2.38	2.32	0.60	1.94	2.92	0.12	4.56
Upper Focus Area	40	1.69	1.72	0.50	1.40	1.98	0.00	4.73
Upper HMZ	6	1.15	1.15	0.36	0.90	1.42	0.00	2.24
Upper Non-HMZ	34	1.71	1.74	0.49	1.43	1.99	0.00	4.73

Cottonwood Forest & Soil Type Relationship

Upper Focus Area

An analysis of the location of existing 2015 forest relative to NRCS soil types in the Upper Focus Area showed a strong correlation between two dominant soil types and cottonwood forest cove Weirman and Zillah soil series. Upper Focus Area cottonwood forest occurs 69% over Weirman sandy (channeled and unchanneled), fine sandy or gravelly sandy loam. Zillah silt loam (channeled and unchanneled) underlies 27% of the Upper Focus Area cottonwood forest area (Map 7; Appendix B).

Lower Focus Area

An analysis of the location of existing 2015 forest relative to NRCS soil types in the Lower Focus Area showed that Weirman fine sandy and gravelly sandy loam (unchanneled and channeled) cover 40% of the FA area. Zillah silt loam (unchanneled and channeled) cover 54% of the Lower Focus Area. The higher occurrence of Zillah series soils in the Lower Focus area is a result of a lower channel gradient, less dynamic single meandering channel planform and larger historic off-channel floodplain wetlands and water body complexes.

Cottonwood Establishment and Recruitment Terrain Positions

Based upon field reconnaissance, and aerial photographic vegetation and alluvial terrain mapping, a seedling establishment and stand recruitment terrain typology was developed (Figure 12). Alluvial terrain positions of pole size recruitment stands were mapped (Map 15) as noted in the field and the following terrain types characterized:

- Abandoned channels (chute/meander cut-offs)
- Behind log jams
- Scroll bars
- Point bar toes
- Coarse flood deposits

The following results first consider examples of the establishment and recruitment typology and then a statistical summary of the abundance and distribution of these types within the mapped Focus Areas.

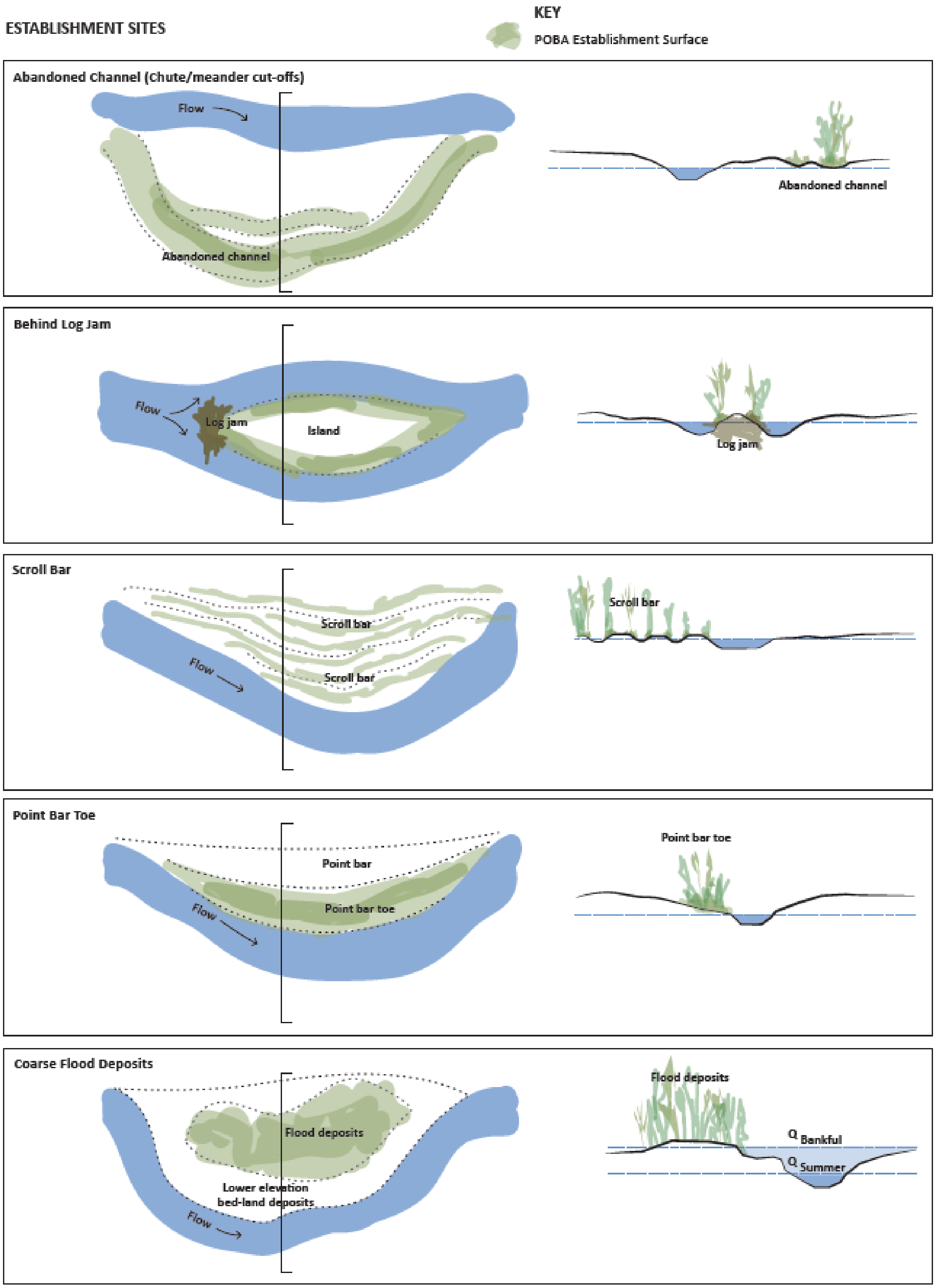


Figure 12. Seedling establishment and forest recruitment sites typology.

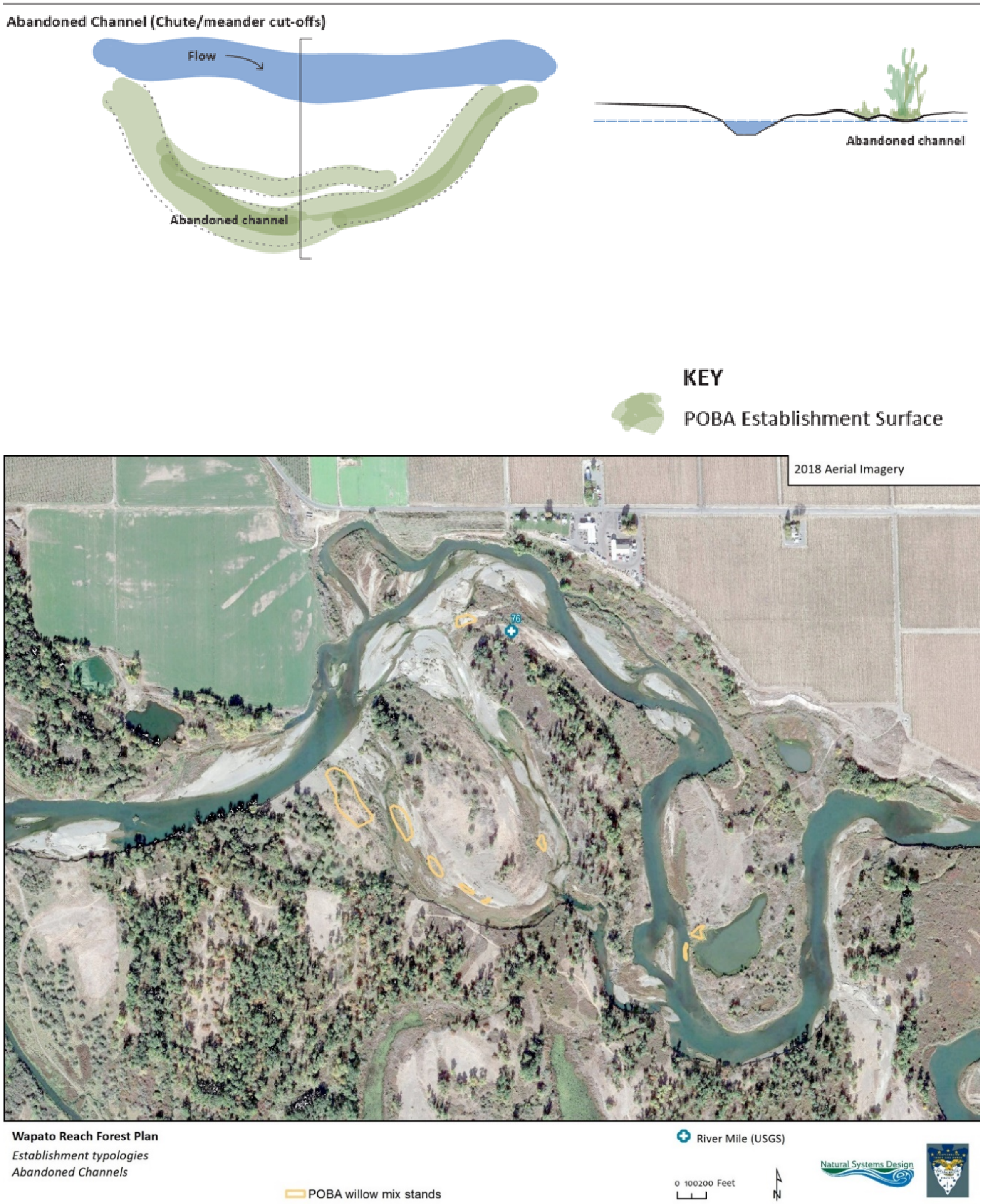


Figure 13. Abandoned Channel (Chute/meander cut-offs)

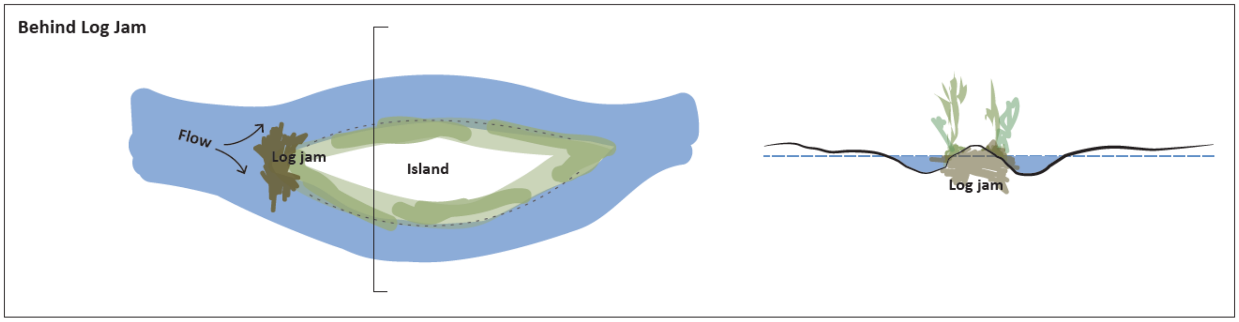
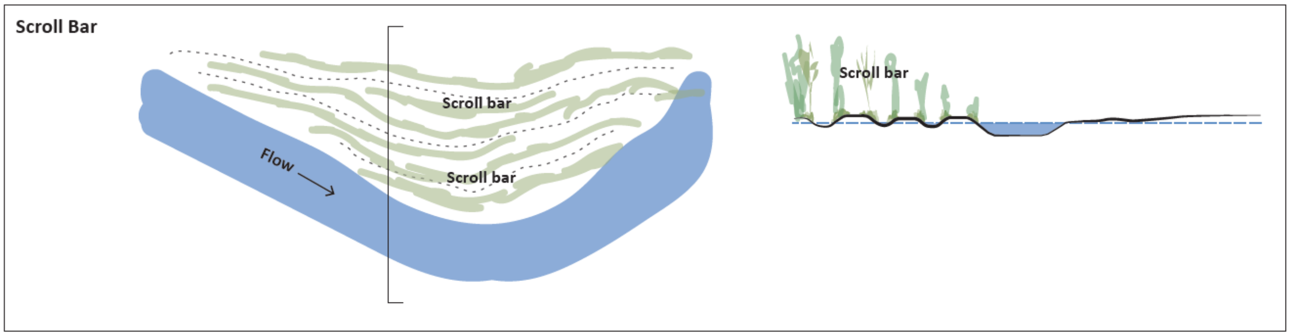


Figure 14. Behind log jam



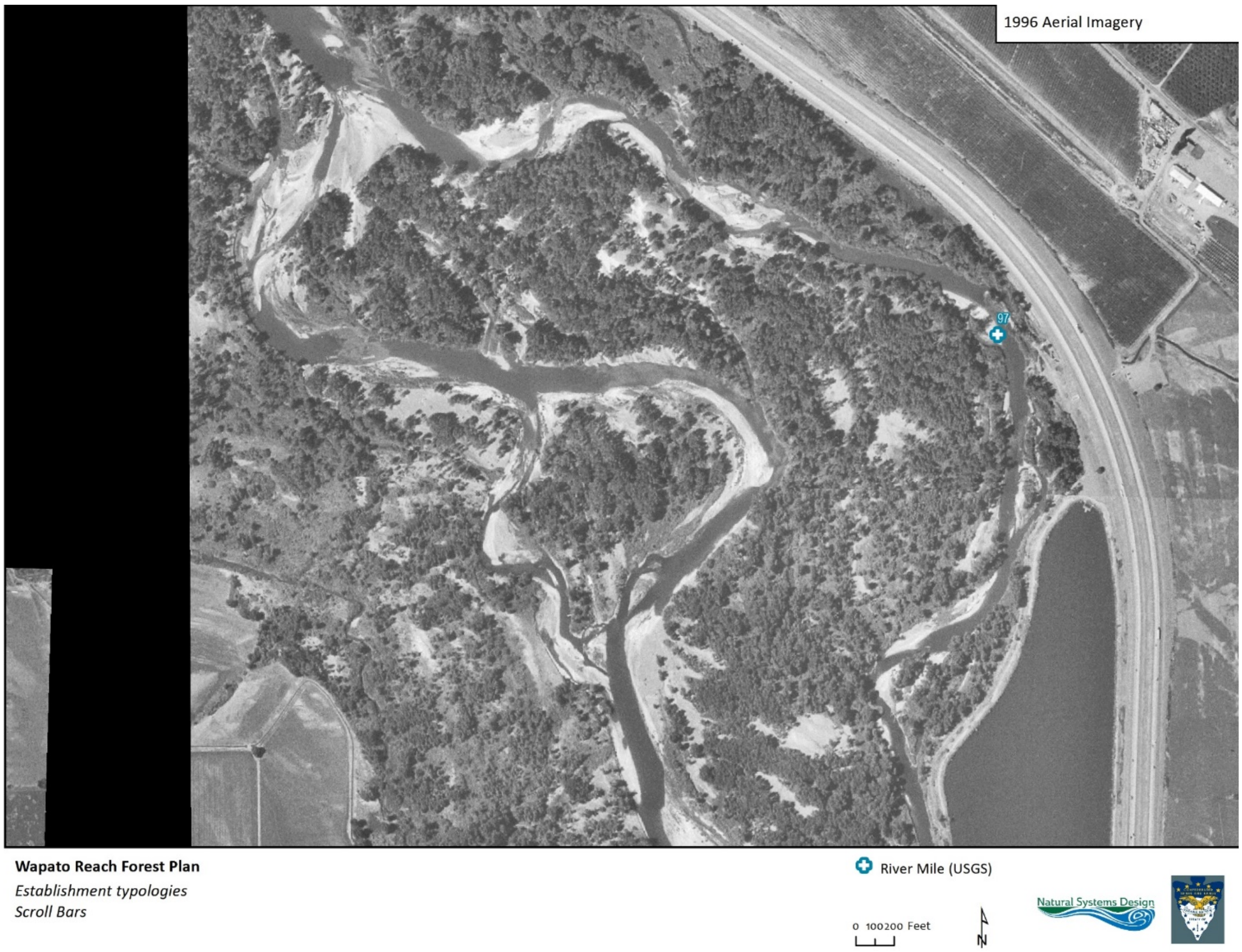


Figure 15. Scroll bars.

Figure 16.Point bar toe.

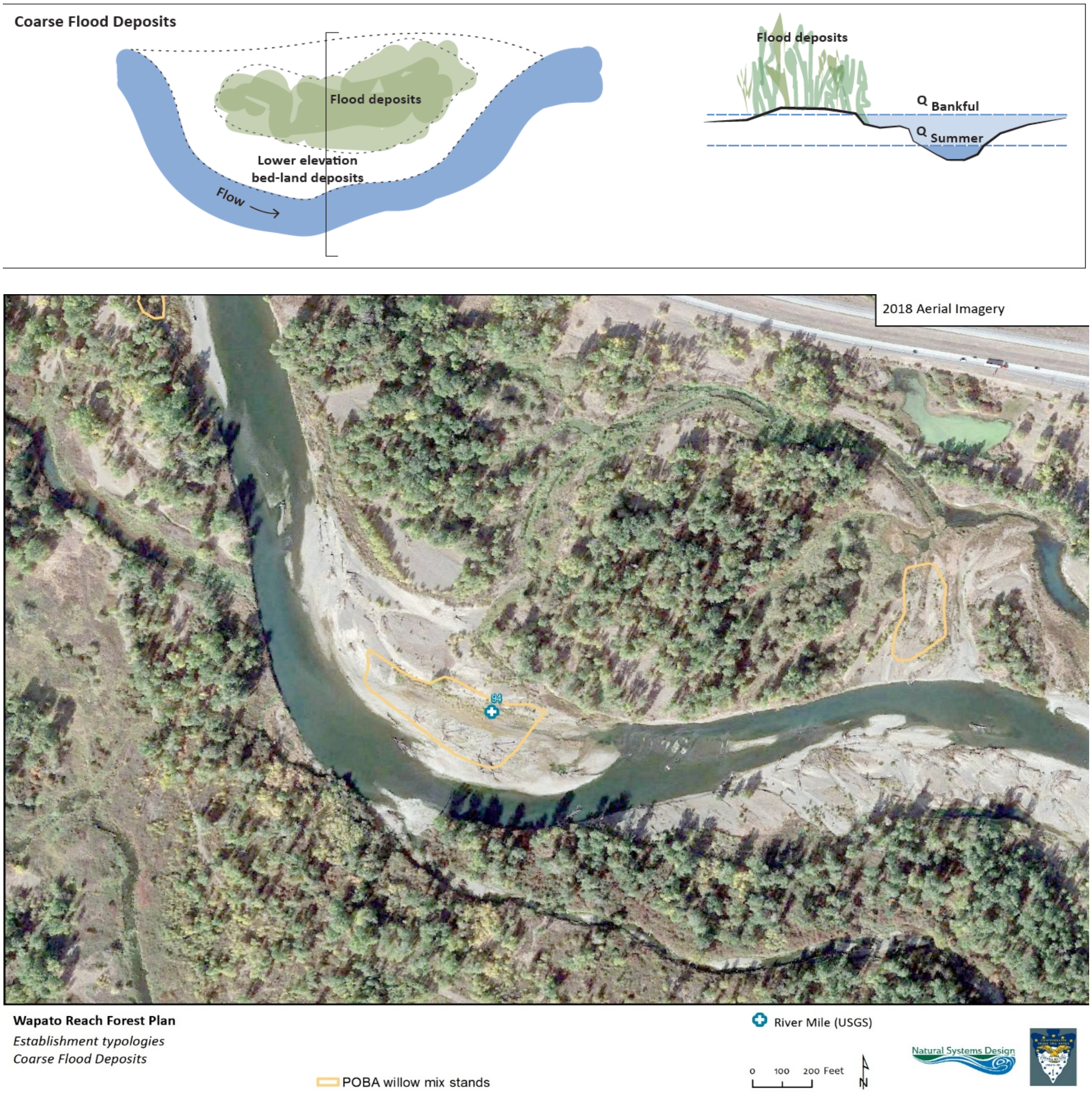


Figure 17. Coarse flood deposits.

Cottonwood seedling/sapling establishment and pole size recruitment Focus Area summary statistics are presented in Figures 18 - 19 and Tables 8-10. Flood deposits and flood deposits and point bars are the dominant sites of establishment and recruitment (Tables 11 & 12). The notable exception is the occurrence of pole size recruitment on generic floodplain surface that had been cleared (Figure 18; Table 11).

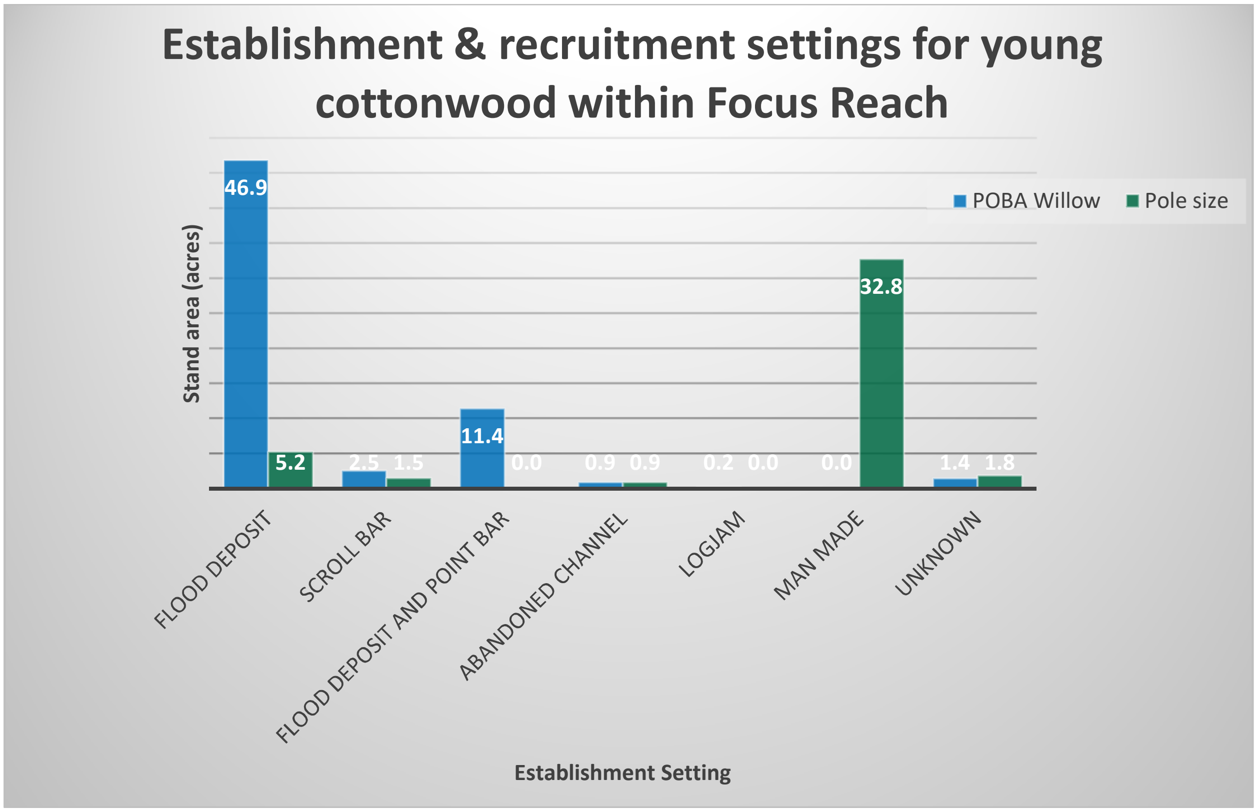


Figure 18. Cottonwood establishment setting type

Table 8. Cottonwood seedling establishment and stand recruitment sites

TYPOLOGY	POBA – WILLOW (ACRES)	POLE SIZE (ACRES)
Flood deposit	46.9	5.2
Scroll bar	2.5	1.5
Flood deposit and point bar	11.4	0.0
Abandoned channel	0.9	0.9
Logjam	0.2	0.0
Man made	0.0	32.8
Unknown	1.4	1.8
Total	**63.1**	**42.2**

Table 9. POBA (cottonwood)-Willow and Cottonwood Pole Size Focus Area establishment and recruitment sites.

2011 FLOOD DEPOSITS	POBA – WILLOW (ACRES)	POLE SIZE (ACRES)
Total area (acres)	56.1	2.9
% of total established area	89%	7%

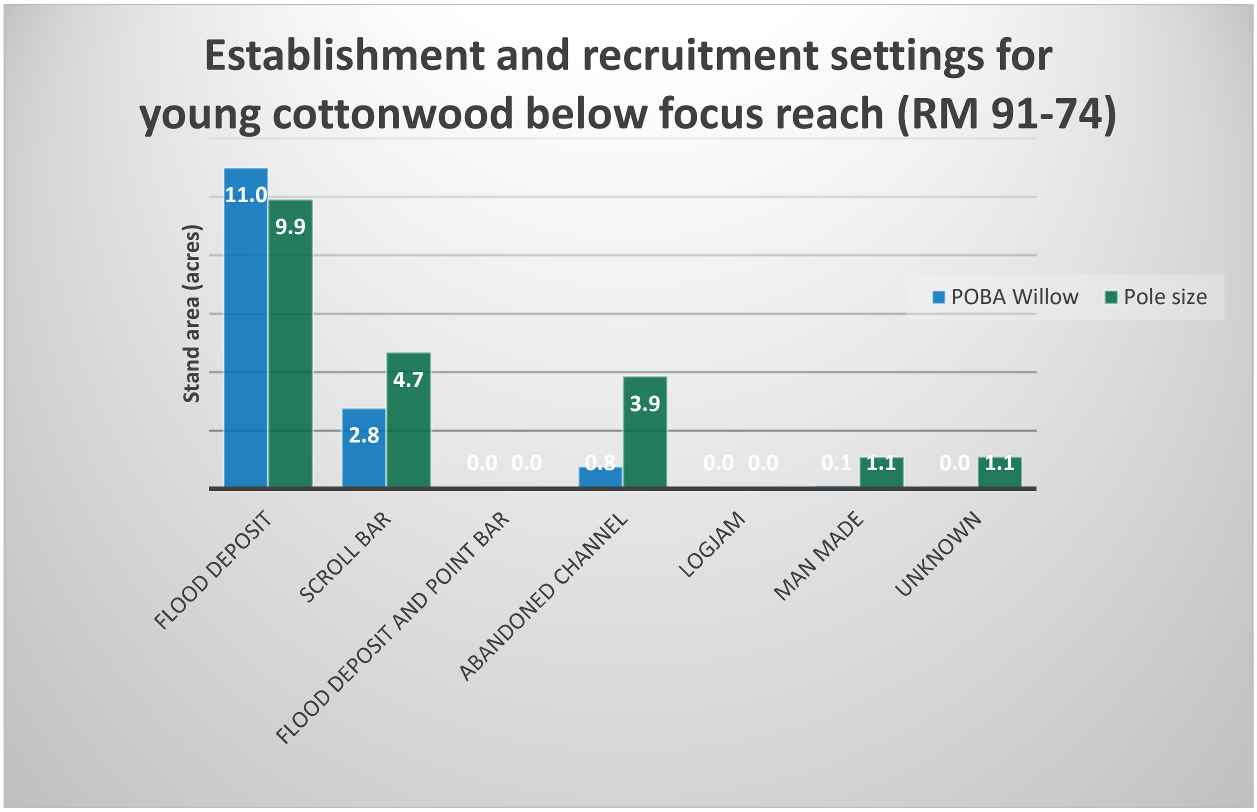


Figure 19. Cottonwood willow seedling establishment setting types – Below Focus Reach (RM 91-74)

Table 10. Seedling establishment and pole size recruitment setting type – Below Focus Reach (RM 91-74)

TYPOLOGY	POBA – WILLOW (ACRES)	POLE SIZE (ACRES)
Flood deposit	11.0	9.9
Scroll bar	2.8	4.7
Flood deposit and point bar	0.0	0.0
Abandoned channel	0.8	3.9
Logjam	0.0	0.0
Man made	0.1	1.1
Unknown	0.0	1.1
Total:	**14.2**	**20.7**

Table 11. Most effective at cottonwood seedling establishment and pole size recruitment – RM 105-RM 74

TYPOLOGY	POBA – WILLOW (ACRES)	% OF TOTAL POBA-WILLOW	POLE SIZE (ACRES)	% OF TOTAL POLE SIZE	% OF TOTAL COMBINED
Flood deposit	**57.9**	***73%***	**15.1**	***24%***	***52%***
Scroll bar	5.3	*7%*	6.1	*10%*	***8%***
Flood deposit and point bar	11.4	*14%*	0.0	*0%*	***8%***
Abandoned channel	2.5	*3%*	4.7	*8%*	***5%***
Logjam	0.2	*0%*	0.0	*0%*	***0%***
Man made	0.1	*0%*	33.9	*54%*	***24%***
Unknown	1.4	*2%*	2.9	*5%*	***3%***

Soil Types and Cottonwood Forests

The Wapato Reach cottonwood forest shows a strong association with both Weirman loam and Zillah silt loam soil types for both Upper and Lower Focus Areas (Maps XXX&XXX Appendix B). Black cottonwoods require aerated soil in their rooting zone, ~0.5-1.0 meter depth. Wierman soils are somewhat excessively to well drained. The Zillah series consists of somewhat poorly drained soils. However, the channeled Zillah silt loam is more coarsely stratified than unchanneled Zillah type and therefore has a higher hydraulic conductivity more suitable to cottonwood growth. This is reflected in the predominance of the channeled Zillah silt loam type seen in both Upper and Lower Focus Areas.

Weirman series soils are deep, somewhat excessively drained and well drained and medium textured to moderately coarse textured soils underlain by gravels, the former river channel bed. These soils are formed in recent alluvial deposits derived mostly from basalt. They are found on floodplains adjacent to the Yakima river (Rasmussen 1976). Yakima River Weirman floodplain soils are dissected in places by perennial secondary and tributary channels.

> "These soils are associated with Ashue, Naches, and Zillah soils. In a representative profile, the surface layer is grayish brown fine sandy loam about 9 inches thick. The substratum is brown loamy fine sand to a depth of about 20 inches and grayish-brown very gravelly loamy sand to a depth of 60 inches." (Rasmussen 1976)

Zillah Series consists of deep, somewhat poorly drained soils that formed in recent alluvium deposited in ponded areas. These soils are found on Yakima River low alluvial floodplains.

> "These soils are associated with Esquatzel, Naches, Onyx, and Weirman soils. In a representative profile, the surface layer is grayish brown silt loam about 19 inches thick. The substratum is light brownish-gray silt loam to a depth of 31 inches, gray silt loam that has thin lenses of loamy sand to a depth of 51 inches, and gray loamy sand to a depth of 60 inches." (Rasmussen 1976)

The Zillah silt loam channeled type is coarsely stratified and makes up the dominant Zillah type in both the Upper and Lower Focus areas. The hydraulic conductivity of these soils is greater than the unchanneled Zillah silt loam.

Process-based Case study–Upper Toppenish Bridge Reach

The Upper Toppenish Bridge reach was selected as a case example to present the hydrogeomorphic terrain and forest characterization approach used in this study (Figure 20). Channel migration between 1996 and 2018 resulted in 11 acres of generic floodplain forest loss and 11 acres of point bar development with seedling establishment between 2016 and 2019 and pole size forest stand recruitment between 1996 and 2015 (Figure 21). Geomorphic landform typing (Figure 22) provides context for both channel migration analysis and subsequent field sampling, mapping and characterization in 2019 (Figures 23-33; Tables 12-16). The REM provides surface elevations for pole size plots 5-7 that developed on elevated flood deposits (Figure 21). Tables 12-14 provide seedling establishment measurements while Table 15 provides relative elevation measurements of seedling, sapling and generic forest surfaces. Notable is the consistent elevation ranges of seedling to sapling to pole size plots. Together with sample plot measurements of sand/silt mantle depth to gravel/cobble refusal layer (historic underlying active channel bed) a seedling establishment elevation of 0.6-1.3 m above baseline water surface can be inferred (Table 15). These elevational ranges provide elevation targets for development of silvicultural planting designs.

Figures 23-30 and Tables 12-17 provide sequentially seedling to sapling to pole size stand site photographs and stand characteristics.

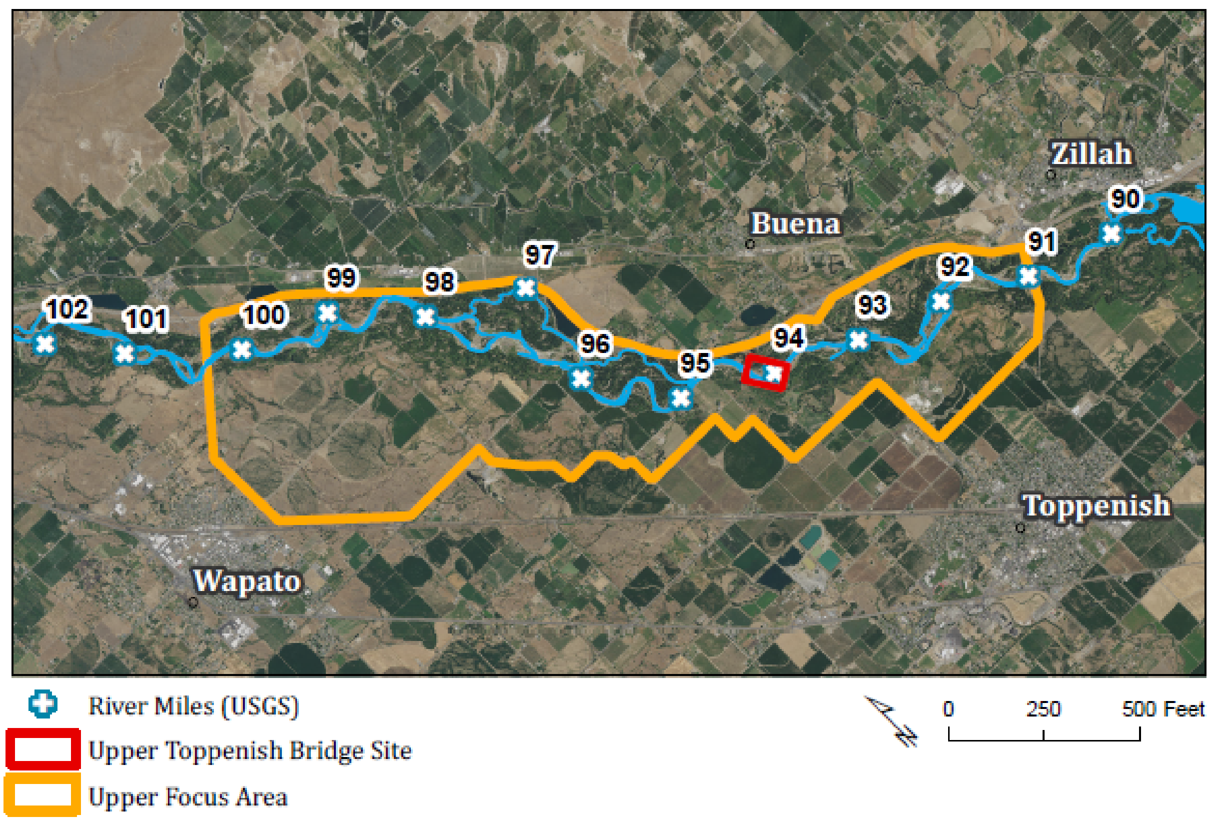


Figure 20. Upper Toppenish Bridge Reach location map.

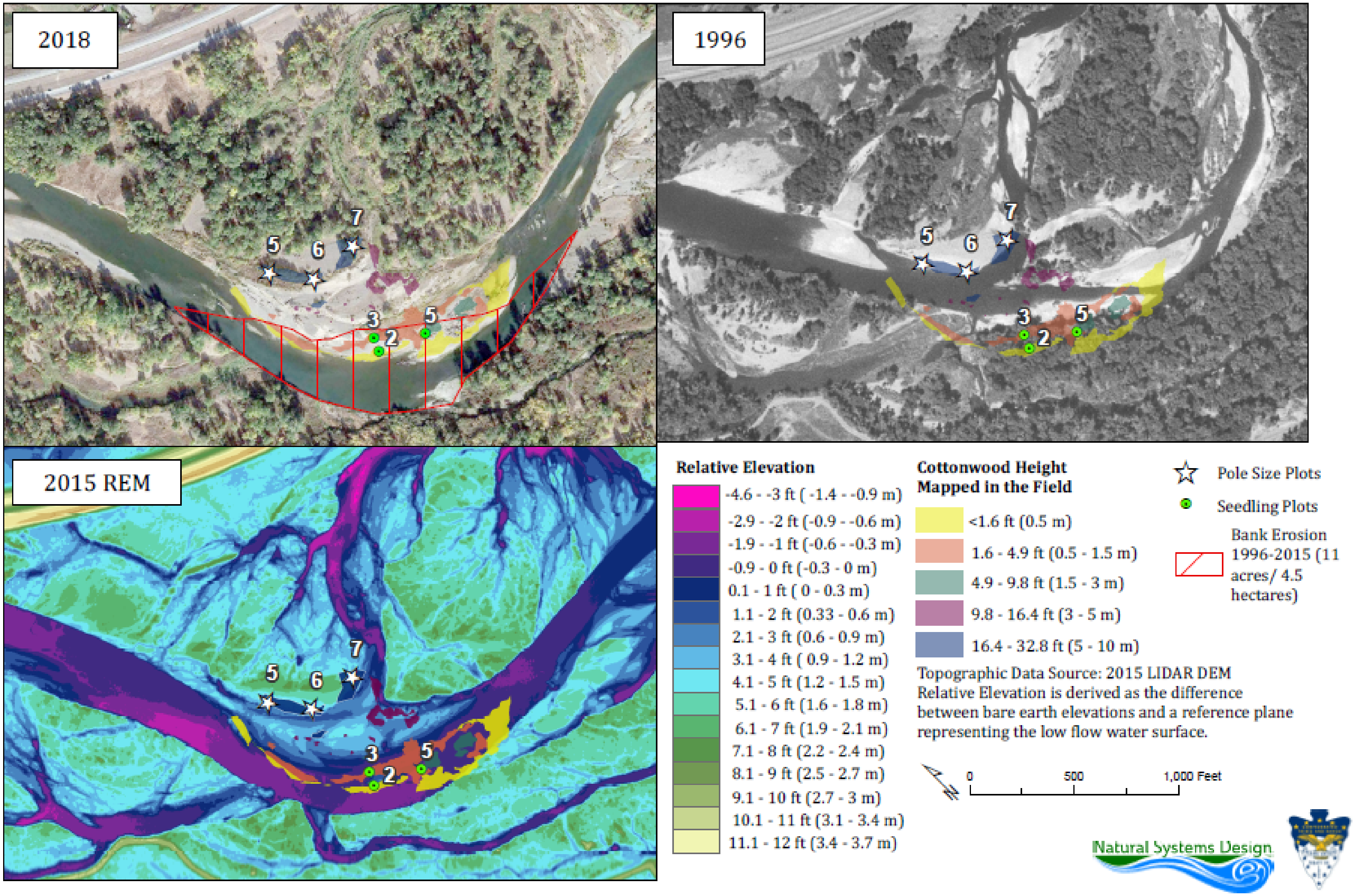


Figure 21. Upper Toppenish Bridge Reach 1996-2018.

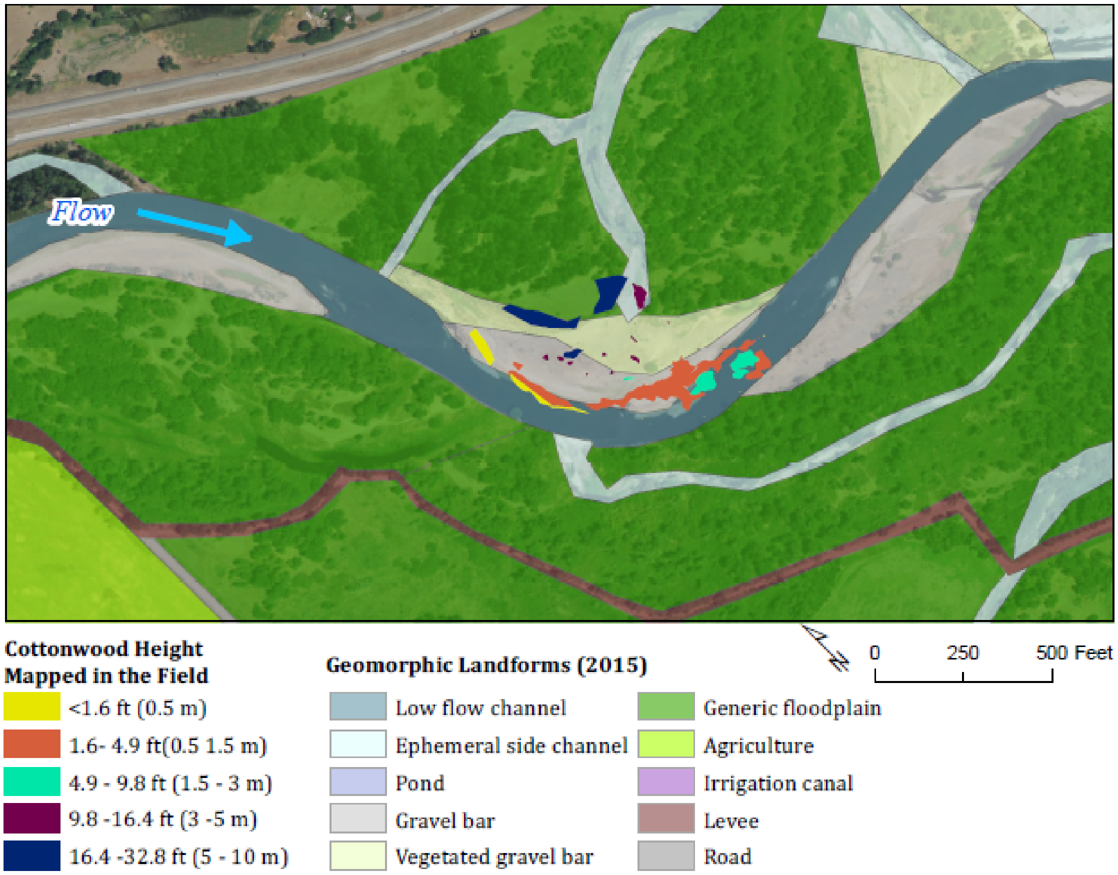


Figure 22. Upper Toppenish Bridge Reach landform types.

Figure 23. Upper Toppenish Bridge Reach. Cottonwood seedlings < 0.5 meters tall, < 0.5 meters above water surface DATE/Discharge. Photo pole in one-foot increments.

Table 12. UTB Cottonwood seedling plot height class <0.5 m, ~0.5 m above water surface

SEEDLING PLOT #2 (POBA HEIGHT CLASS <0.5 M)	
Mean Stem Height (cm)	6
Std. Dev. Stem Height (cm)	2
Number of Measurements	102
Seedling Density (m2)	204

Figure 24. Upper Toppenish Bridge Reach. Cottonwood seedlings 0.5-1.5 meters, ~1.0 meter above water surface DATE/Discharge. Photo pole in one-foot increments.

Table 13. UTB Cottonwood seedling plot height class 0.5-1.5 meters, ~0.5 m above water surface.

SEEDLING PLOT #3 (POBA HEIGHT CLASS 0.5-1.5 M)	
Mean Stem Height (cm)	92
Std. Dev. Stem Height (cm)	20
Number of Measurements	81
Seedling Density (m2)	40

Figure 25. Upper Toppenish Bridge Reach. Cottonwood saplings 1.5-3.0 meters tall, ~1.0 meter above water surface DATE/Discharge. Photo pole in one-foot increments.

Table 14. UTB Cottonwood seedling plot height class 1.5-3 m, ~0.5-1.0 above water surface.

SEEDLING PLOT #5 (POBA HEIGHT CLASS 1.5-3M)	
Mean Stem Height (cm)	142
Std. Dev. Stem Height (cm)	27.2
Number of Measurements	40
Seedling Density (m2)	20

Table 15. Pole size tree plot REM elevation above water surface (meters / feet), Upper Toppenish Reach.

UPPER TOPPENISH BRIDGE					
REM Height Data	Min (m/ft)	Max (m/ft)	Mean (m/ft)	Median (m/ft)	Std. Dev (m/ft)
Upland Forest	0 / 0	2.8 / 9.3	1.3 / 4.4	1.3 / 4.40	0.4 / 1.4
POBA 3-5 m	0.03 / 0.1	1.3 / 4.3	0.7 / 2.4	0.8 / 2.60	0.3 / 1.0
POBA 5-10 m	0.52 / 1.7	1.8 / 6	1.3 / 4.3	1.3 / 4.10	0.2 / 0.7

Figure 26. UTB Cottonwood saplings 1.5-3.0 meters tall, ~1.0 meter above water surface.

Figure 27. UTB Cottonwood saplings 3.0-5.0 meters tall, 0.7 ±0.1 m above water surface.

Figure 28. UTB Plot #5 cottonwood pole size trees 5.0-10.0 meters tall, 1.3 ±0.2 m above water surface.

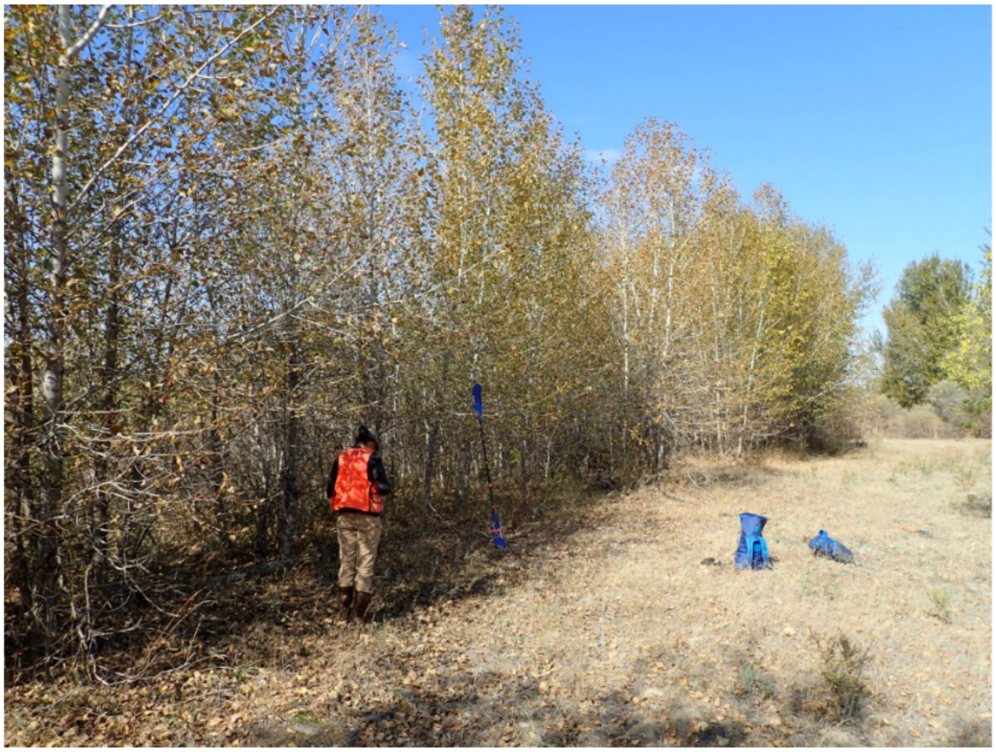


Figure 29. UTB Plot #6 pole size stand 1.3 ±0.2 m above water surface

Figure 30. UTB Plot#7 pole size stand 1.3 ±0.2 m above water surface.

Table 16. Pole size tree plot summary data, Upper Toppenish Reach.

POLE SIZE PLOTS SUMMARY TABLE	PLOT 5	PLOT 6	PLOT 7
Plot Dimensions (m)	9.5 X 30	30 X 10	30 X 13
Plot Area (m2)	285	300	390
Mean DBH (cm) of Pole Sized Trees	10.9	7.4	9.6
Number of Pole Sized Trees	87	84	171
Pole Size Tree Density (Trees/ha)	3,000	3,000	4,000
Mean Tree Height (m)	12.5	7.1	10.1
REM surface height (m)	1.3 ±0.2 m	1.3 ±0.2 m	1.3 ±0.2 m
Average of tile probe depth to refusal (cm)	41.2	27.2	70.3
Soil Type	Weirman Sandy Loam	Weirman Sandy Loam	Weirman Sandy Loam

DISCUSSION

The goal of Task 1 investigation was to develop a conceptual model of Wapato Reach cottonwood forest dynamics to inform the development of a strategic silvicultural restoration plan to conserve the Wapato Reach riparian cottonwood forests. The current analysis focused upon identifying and characterizing spatially explicit hydrogeomorphic terrain conditions under which black cottonwood forest stands are being lost, recruited and maintained along the Wapato Reach. In this study the Yakima River Wapato Reach cottonwood forest was: (1) typed and mapped, (2) height-structure measured and mapped, (3) age-structure approximated, (4) 1949-2015 forest cover status and trends measured, and (5) the underlying alluvial terrain positions of forest loss and recruitment characterized and mapped. The following discussion addresses each of the six questions addressed in the introduction.

What are the hydrogeomorphic conditions under which the Wapato cottonwood forest is currently maintained

The Wapato cottonwood forest existing in 1949, and forest recruited within the past 70 years is growing nearly exclusively on Weirman and Zillah Series soil types. The Upper Focus Area–more dynamic anabranching channel– cottonwood forest is growing within a narrow mean elevation range of 1.59±0.56 meters above river baseflow, with a slightly lower mean elevation range of 1.40±0.46 meters above baseflow for recently recruited cottonwood stands. This slight variation in floodplain elevation reflects the nature of a developing, aggrading floodplain surface compared to an older developed floodplain no longer increasing in elevation. The Lower Focus Area cottonwood forest–single meandering channel–is growing at a higher mean surface elevation of 2.52±0.81 meters above baseflow, with recently recruited forest stands at a similar elevation. Given the arid precipitation conditions of the Wapato Reach, cottonwood can be expected to be accessing groundwater as their primary source of water. The consistently narrow range of cottonwood forest surface elevations are a reflective of the rooting depth of the forest above the shallow alluvial aquifer water table. These data are critically important for planning and selecting future cottonwood silvicultural restoration efforts.

What are the hydrogeomorphic conditions under which the Wapato cottonwood forest is reproducing?

Field observations show that cottonwood seedlings are establishing at low elevation sites <0.5 meters above base flow (e.g., Upper Toppenish Bridge Site), however, cottonwood stand recruitment is observed only at higher elevations, specifically on flood deposits and flood deposit point bars. Recruitment site elevations are lower at the Upper Focus Area site, than at the Lower FA, with a mean elevation of 1.32±0.46 meters above base flow within the HMZ and non-HMZ surfaces mean elevation of 1.66±0.62 meters. Whereas recruitment within the Lower Focus Area less dynamic meandering single channel have a mean elevation of 2.03±0.69 and 2.63±0.94, on HMZ and Non-HMZ surfaces respectively. Taking into account that floodplain sand/silt mantle depth ranges widely varying with the age of the floodplain surface, measured depths of Wapato floodplain mantle (depth to tile probe refusal) of 17-156 cms (n= 40) illustrate that cottonwood recruitment surfaces are occurring at higher elevations than observed seedling establishment sites.

In conducting the geomorphic terrain analysis, it was observed that pole size recruitment stands occur predominantly on higher elevation flood deposits. These terrain positions are less likely to be disturbed by bed mobilizing discharges found during higher peak flows. These results also confirm the Braatne et al., (2007) observations.

Black cottonwood is known to reproduce clonally (Braatne et al., 1997) and anecdotal observations during field reconnaissance for this project point towards clonal reproduction occurring in some of the older legacy cottonwood stands and within known forest burn sites. Determining the level of clonality occurring as a stand replacement mechanism was outside of the scope of this project. However, measurement of the level of clonal reproduction would be useful in developing the Wapato forest restoration strategy.

What are the major stressors impacting cottonwood forest reproduction?

The major stressors currently impacting the reproduction of the Wapato Reach forest are twofold. First, loss of non-HMZ cottonwood forest resulted primarily from land clearing and land clearing for agriculture. Second, within the HMZ the hydro-regulated reversed hydrograph, identified by Braatne et al., (2007), impacts both seedling establishment and the survival of seedlings to pole sized stand recruitment. Seedlings established at low elevation sites are mostly disturbed by subsequent peak flows. Only seedlings that become established on higher elevation flood deposits survive to pole size stand recruitment. This is the primary limiting factor currently impacting Wapato Reach forest reproduction. Without a change in the current hydro-regulated flow regime of the Yakima River, cottonwood forest reproduction will not be sufficient to replace cottonwood loss to channel migration erosion.

What is the reproductive status of the Wapato Reach cottonwood forest? What are the mechanisms of forest reproduction (recruitment) and forest loss over the period of record (since 1949)?

The Wapato cottonwood forest is reproducing and recruiting nearly exclusively within the HMZ on flood deposits. Non-HMZ forest reproduction is occurring on land that has been cleared or agricultural lands allowed to go fallow. Forest loss is occurring by three primary mechanisms: (1) channel migration and floodplain erosion within the HMZ, (2) senescence of forest stands over 150 years in age throughout both the HMZ and Non-HMZ, and (3) forest loss to land clearing in the Non-HMZ. The reproductive status of the Wapato forest is that rates of forest loss are greater than rates of forest recruitment.
Significantly, the Wapato cottonwood forest is being lost at rates within the Upper and lower Focus Areas HMZ's twice as great as forest recruitment. The non-HMZ trends are that in the Upper Focus Area the rate of loss is 25% greater than recruitment. Whereas in the Lower Focus Area non-HMZ forest loss and forest recruitment are nearly equal.

Given the age structure, and rate of cottonwood riparian forest loss and gain, what is the predicted future of the Wapato Reach riparian cottonwood forest?

The conservative estimate of the maintained 1949 forest area of 58 years, and the average life span of black cottonwood being 100-150 years, together with the forest loss and forest recruitment rates all point to one conclusion–the loss of the majority of the Wapato cottonwood forest by the turn of the century, 2100. As Braatne et al., (2007) indicated the altered hydro-regime not only presents a significant risk to the viability of the Wapato cottonwood forest but creates conditions that support invasion of the Yakima River floodplains by non-native trees and shrubs such as Russian olive, silver maple and crack willow.

Cottonwood Forest Soil Types and Terrain Positions / Elevations

Under the current regulated Yakima River hydro-regime, the Wapato cottonwood forest occurs under a narrow range of alluvial soil types, and alluvial terrain positions / elevations above Yakima River. Characterization and mapping of these conditions allows not only a physical description of the current Wapato cottonwood forest but serves as the geomorphic template for future silvicultural restorative strategies.

The cottonwood forest shows a strong association with both Weirman soil series and channeled Zillah silt loam soil type for both Upper and Lower Focus Areas. The Wierman soil series and channeled Zillah silt loam are located at elevations where the capillary fringe of the shallow alluvial aquifer is at least 50-75 cms below the terrain surface. Wierman series soil types and channeled Zillah silt loam have a hydraulic conductivity sufficient to support aerated soil conditions within the upper 50-75 cms of the soil profile during the growing season, a requisite to support and maintain black cottonwood (Braatne et al., 1997; Rood et al., 2003).

The Wapato cottonwood forest has a narrow range of floodplain surface elevations consistent with the hypothesis that the Wapato Reach cottonwood are phreatophytes dependent upon the shallow alluvial aquifer as its primary source of water. Mature cottonwoods are growing at elevations 1-2 meters (Upper FA) and 1.5-3 meters (Lower FA) above the baseflow. The consistent elevation range of cottonwood and cottonwood soil type fidelity together define the narrow environmental conditions within which cottonwood grow in the arid Wapato Reach environment. These results are generally consistent with elevation range of cottonwoods relative to baseflow reported by Braatne et al., (2007; Figure 31).

The Focus Areas demonstrate that channel gradient and plan form–dynamic anabranching Upper FA vs. single channel meandering Lower FA–result in consistent floodplain forest surface elevational ranges. The LiDAR REM water surface elevation baseline, against which all REM surfaces are measured, occurred at the approximate discharge of 700 cfs (2-dimensional hydraulic model from Yakima County). The Upper FA HMZ mean floodplain forest elevation of 1.36±0.45 meters contrasts with the non-HMZ of 1.66±0.62 meters. The Lower FA HMZ mean floodplain forest elevation of 1.97±0.74 meters contrasts with the non-HMZ of 2.57±0.0.80 meters. The HMZ floodplain surfaces are younger, lower in elevation and still actively aggrading compared with the older non-HMZ floodplain and terrace surfaces. Throughout the study reaches Cottonwood floodplain soil probe depths to underlying gravel / cobble refusal layer (a measure of the floodplain sand and silt mantle overlying the channel bed) 2019 field measurements ranged from 32-156 cms (n=39). These results are consistent with other black cottonwood research findings demonstrating that in arid environments, such as the Wapato, cottonwood are acting primarily as phreatophytes (Jackson et al., 1996; Rood et al., 2011).

The Wapato cottonwood forest was found to establish and grow to recruitment pole size stands under specific terrain position elevations dominated by floodplain deposits and flood deposit point bars. Pole size stands were found at lower elevations than the established cottonwood forests of the generic floodplain and terraces. Upper FA HMZ mean pole size stand elevation of 1.15±0.36 meters contrasts with the non-HMZ of 1.71±0.49 meters. The Lower FA HMZ mean floodplain forest elevation of 1.67±0.0.5 meters contrasts with the non-HMZ of 2.38±0.60 meters. These elevation ranges demonstrate two points concerning current Wapato Reach cottonwood forest recruitment: (1) cottonwood is not recruiting at lower elevation sites adjacent to spring/summer low flow conditions where currently observed seedlings are establishing, and (2) pole size recruitment is occurring primarily on higher elevation flood deposits and flood deposit point bars. These elevated flood deposits surfaces are protected **safe sites** from subsequent channel margin scouring flows currently disturbing the lower elevation seedling establishment sites. Since the flood deposit sites are more limited in total area, compared with channel margin sites, **the safe site area available for cottonwood establishment and recruitment is currently the primary limiting factor to Wapato Reach cottonwood forest recruitment.** The results of this study both verify Braatne et al., (2007) conclusions concerning hydro-regulation impacting seedling establishment sites and further identify the higher elevation flood deposit terrain positions as the limited sites of stand recruitment under current conditions (Figure 31).

These results confirm the Braatne et al., (2007) model that Wapato Reach seedling establishment along spring/summer low flow channel margins has resulted in the loss of these seedlings due to subsequent high flows mobilizing the seedling establishment site channel surfaces. The limited recruitment of pole size stands found throughout the Wapato Reach occur on these slightly higher elevation flood deposits or flood deposit toe bar surfaces captured in these elevation ranges. Observed 2019 seedling establishment cohorts were approximately 0.5 meters or less above the water surface elevations.

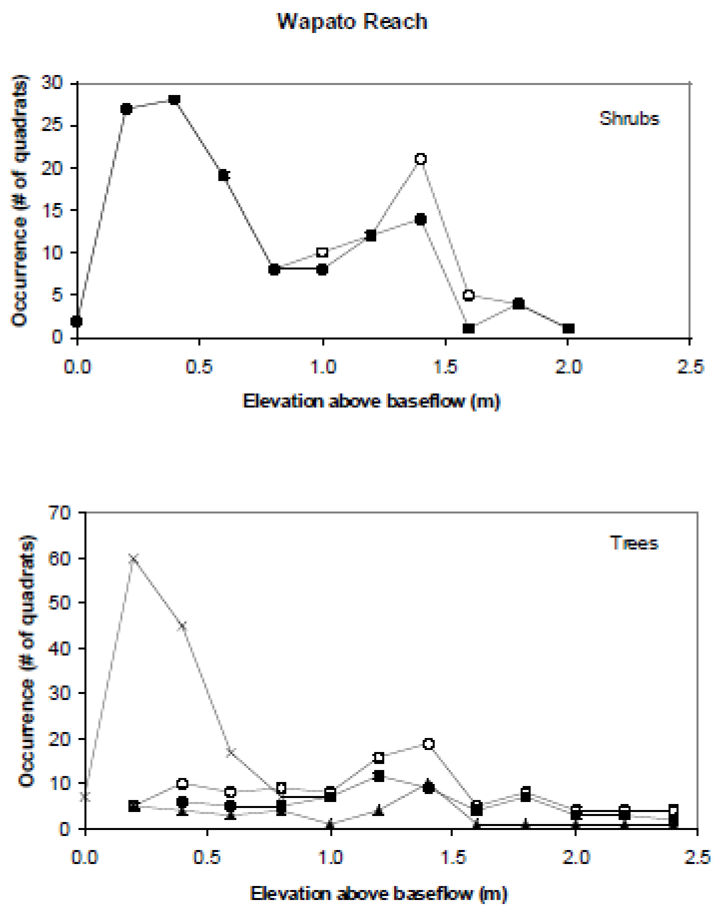


Figure 31. The distribution of shrubs and trees relative to seasonal baseflow conditions in the upper Wapato study reach. (Shrubs: open circles = all shrub species, closed circles = native willows; Trees: open circles = all trees, closed circles = mature cottonwoods, closed triangles = other deciduous species, x = 2000 cottonwood seedlings) (Braatne and Jamieson. 2001).

Wapato Reach Cottonwood Forest–Status and Trends

The results of this study expand upon observations and the model of cottonwood recruitment developed by Braatne et al., (2007).

> "During the same time period (May-July), low flows along the Wapato reach result in the germination of seedlings at low elevations near the base of riverbanks. After the irrigation season is over, higher flows

> along the Wapato reach scour and remove these young seedlings. As a result, there was no seedling recruitment observed in these study reaches. The extent of younger stands (<25-35 years old) was also extremely limited in all three reaches, and largely limited to clonal expansion. Riparian cottonwoods are thus dominated by an older age class that established prior to initiation of current flow regimes. If these altered flow patterns persist, cottonwood populations will become more fragmented and largely composed of decadent individuals with lower levels of genetic diversity." (Braatne et al., 2007)

Contrary to Braatne et al., (2007) findings, cottonwood seedling establishment was observed at a number of low elevation sites throughout the Wapato Reach. However, cottonwood recruitment to pole size stands was observed in only a few select alluvial terrain positions dominated by flood deposits and flood deposits associated with point bars.

The rates of Wapato cottonwood forest recruitment are half of the rates of forest loss due to channel erosion throughout the HMZ in both the Upper and Lower Focus Areas and therefore are representative of conditions throughout the entire reach. The remaining 2015 maintained HMZ forest is generally a minimal age of 58 years and therefore can be expected to senesce by the turn of the century if not disturbed through channel erosion. Under these conditions the 2015 HMZ forest can be expected to be mostly lost by the end of the century.

The non-HMZ forest in both the Upper and Lower Focus Areas is also being lost at a rate greater than replacement through stand recruitment. The majority of both Upper and Lower Focus Areas 2015 cottonwood forest is conservatively estimated to be an age class 50-60 years, a forest that will mostly senesce by the turn of the century, given the average life span of black cottonwood. Although 36% of the non-HMZ forest (235 acres) of the Lower Focus Area will be approaching 100 yrs by the turn of the century, the remaining forest will be well past the normal age of cottonwood senescence. All together these data present a bleak future for the Wapato Reach cottonwood forest by 2100. Given that Russian olive, silver maple have already become established throughout much of the reach these tree species can be expected to increase in abundance replacing the lost black cottonwood. Under current conditions, the only future scenario these data present is that of a cottonwood forest very similar to what Braatne et al., (2007) describe–a fragmented Wapato cottonwood forest composed of a few decadent individual cottonwoods invaded by non-native Russian olive, silver maple and crack willow.

Conceptual Model of Wapato Reach Cottonwood Forest Development

The results and findings of this study support and expand upon the Wapato Reach cottonwood forest conceptual model developed by Braatne et al., (2007). In contrast to the Braatne model, we focused upon developing a spatially explicit terrain model of cottonwood loss, maintenance and recruitment (Figure 31). The objective of this study was to develop a conceptual model that would serve to guide Wapato Reach cottonwood forest restoration. In characterizing and delineating where and how cottonwood forest is lost and recruited, specific hydrogeomorphic terrain was identified for future silvicultural restorative actions.

As discussed, existing Wapato Reach cottonwood forests are lost through channel migration and erosion, land clearing and stand senescence. Cottonwood forest recruitment is happening on a very limited array of flood deposit surfaces associated with peak flows. Together, these hydrogeomorphic terrain positions, and forest loss and recruitment mechanisms, point towards a cottonwood forest that is being replaced under a very narrow range of terrain positions and geomorphic processes. However, identification and characterization of the hydrogeomorphic conditions under which the Wapato cottonwood forest is maintained, lost and recruited serves as a template for developing a science-based silvicultural restoration strategy and design.

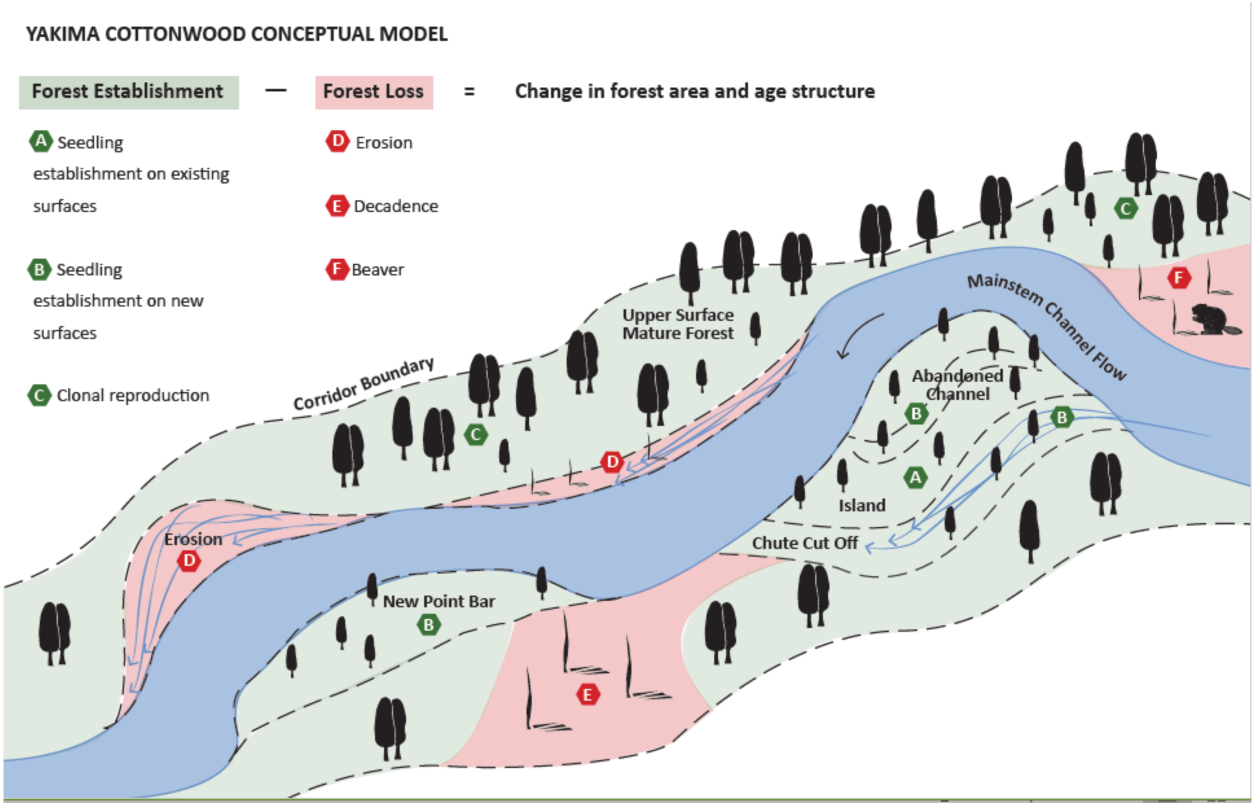


Figure 32. Wapato Reach Cottonwood Forest Conceptual Model.

CONCLUSIONS

1. The Wapato Reach cottonwood forest is maintained and replaced under a narrow range of hydrogeomorphic position and soil type conditions, predominantly on flood deposits.
2. Cottonwood seedling establishment to stand recruitment in the Upper dynamic anabranching channel reach occurs on flood deposits at elevations around 1-1.5 meters above baseflows. Seedling establishment to cottonwood stand recruitment in the Lower meandering single channel reach occurs on generic floodplains and flood deposits at elevations around 2.5 meters above baseflow. Cottonwood forests are growing almost exclusively on two alluvial soil series, Wierman and Zillah silt loam.
3. The Wapato reach forest is being lost at a rate greater than its replacement. The 1949 to 2015 maintained forest can be expected to largely senesce by 2100. Under current conditions, the entire Wapato Reach cottonwood forest may be expected to be generally lost by the end of the 21st century, 2100. By 2100 the Wapato forest will be composed of fragmented patches of legacy cottonwood, exotic non-native Russian olive, crack willow and silver maple.

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