Implications of land-cover change history for monitoring present and future ecological condition in nine basins on the urban fringe of Seattle, Washington

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Abstract:
Historic land use is a potentially significant factor determining present day watershed condition. Previous research has shown that historical land uses can have lasting effects on watershed condition that are manifest in present day hydrologic and water quality variables. However, the relative importance of past land uses such as the extent and intensity of forestry or agriculture within a basin, remains poorly understood. As part of a larger project to monitor the effectiveness of King County's Critical Areas Ordinance, we reconstructed land-cover conditions over approximately 100 years in nine small watersheds (80 – 1200 ha) in the Puget Sound region. We used these data to explore three questions: 1) how has forest cover changed overall within these watersheds; 2) how has forest cover changed within the riparian zone since 1936; and; 3) what land-cover changes are common to all watersheds and when and how do land-cover histories diverge?

We found that overall, the watersheds share a common history of forest-cover change, though the timing and extent of the change varied by watershed. The watersheds were primarily forested prior to 1900. All the watersheds lost between 50 and 100% of their forest cover between 1900 and 1948 and existing cleared lands either transitioned back to forest or were converted to agriculture during this time. Between 1936 and 1948, all the watersheds except Taylor and East Seidel retained 40% to 60% of their riparian forest cover even though the watersheds overall were only 20 to 40% forested. The retention of forested buffers within the riparian zone potentially reduced the impacts of early logging on overall watershed condition and contemporary water quality. Between 1948 and 1965, forest cover increased substantially in all watersheds, and by 1986, all watersheds were 60-100% forested. Since 1986, forest cover has declined slowly primarily due to conversion to rural residential land cover. In Cherry, Weiss and Tahlequah watersheds, development occurred primarily on previously forested lands without intervening agricultural land use. Comparatively, in Fisher, Judd and Taylor watersheds much of the early residential development occurred on previously agricultural lands. In addition, these latter watersheds developed to a greater extent than the other three treatment watersheds.

This analysis reveals potentially important variation in land-cover history among watersheds, which today have very similar land-cover characteristics. Identifying commonalities and variation in land use history is potentially critical for understanding both present day conditions and the overall trajectory of watershed change in the future.

Introduction
Numerous studies have demonstrated that watershed land use and land-cover composition correlates with water quality and ecological conditions in aquatic systems (Basnyat et al. 2001, and Pan et al. 2003, Groffman et al. 2004, Brett et al. 2005, Handler et al. 2006, Zampella et al. 1999). In particular, the amount and configuration of urban land cover within a watershed is significantly correlated with indicators of stream health (Walsh et al. 2005, Alberti et al. 2007).

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Understanding the relationship between urban land cover patterns and watershed condition is critical in order to protect and improve stream health in urbanizing regions. However, recent studies have found that the spatial complexities of watershed land use history can confound our understanding of the relationship between present day land cover and stream health (King 2005, Brown et al, 2009, and Harding et al. 1998). Watershed studies that include historical land use have found that prior land use and land cover conditions may have a lasting effect on stream ecology (Harding et al. 1998, Brown et al, 2009). As a result, historical land-cover conditions should be considered in stream monitoring studies. Ultimately, an improved understanding of the relationship between historical and present-day land cover and watershed condition is needed to adequately protect and manage urbanizing watersheds.

In 2005, King County (the County) updated its land use regulations as required by Washington State's Growth Management Act (GMA) to protect environmentally critical areas, including streams, lakes and wetlands. The regulations protect vegetative buffers surrounding critical areas, limit clearing and grading, and regulate the amount of stormwater runoff from developed surfaces (King County Code chapters 21A.24, Title 9, 16.82, and 21A.25). To assess the effectiveness of these regulations, the County initiated a multi-year (2008 to 2012) study of land-cover change and in stream conditions in nine sub-catchments (80 to 1,200 ha) located along the rapidly urbanizing fringe of Seattle. The study was conducted in six "treatment" catchments with relatively high future development potential indicated by parcels for which no known land-altering permits had been issued since 1989 and parcels whose value of improvements was ≤ 20 percent of the total parcel value based on the King County Assessor database. The resulting study watersheds selected to have relatively high similarity of land uses, regulations, and development potential over time and high sensitivity to development-based hydrologic alteration because of common geology, climate, drainage area, and gradients. The remaining three catchments were selected as controls as they are currently forested and protected from clearing and development. Over these five years, the County monitored flow flashiness, conductivity, temperature, benthic macro invertebrates, and channel hydraulic complexity as indicators of hydrology, water quality, biology and physical habitat quality, respectively. Simultaneously, the County quantified land use and land-cover change in each of the nine study watersheds. The County then compared in stream conditions and land-cover change in developing (treatment) and protected (control) catchments over time to identify any potential adverse effects of new development on watershed condition in these catchments. However, in order to truly isolate the effects of new development, it was necessary to understand historical conditions within these catchments that may still influence present day in stream dynamics.

Previous studies have found that land use history can have a lasting effect on in stream conditions (King 2005, Brown et al, 2009, and Harding et al. 1998). Specifically, watersheds with a history of logging may exhibit legacy effects such as a) reduced extent, size and diversity of riparian vegetation, b) little or no in-channel large wood and little or no new recruitment, c) reduced hydraulic complexity and quantity and quality of pools, d) channelization and bank hardening, and e) reduced soil perviousness from soil compaction, and f) altered flow paths roads and agricultural drainage ditches. In addition, the trajectory of land-cover change over time can have a significant influence on statistical relationships between present day urbanization and in stream condition. For example, Brown et al. (2009) found that the intensity of urban development in watersheds with an agricultural history had little to no effect on in stream conditions. In contrast, when forested watersheds are converted directly to urban development without an intervening period of agriculture, even small amounts of development had a measurable impact on stream macroinvertebrate communities.

Given the importance of historical land use in shaping present day in stream conditions, reconstructing the historical conditions within the nine study catchments is potentially central to understanding present day stream dynamics. Historical land cover within the study catchments could affect the outcomes of this study in several important ways. First, historical land use could influence the quality of the control catchments. These catchments are currently completely forested. However, present day in stream conditions may still be recovering from previous land uses such as logging or agriculture. Depending on the intensity and persistence of previous land use disturbances, the condition of reference streams may be more similar to treatment catchments than initially expected. Secondly, historical land use conditions may affect the starting conditions for the treatment watersheds, ultimately having an effect on the response of treatment catchments to new development. For example, if treatment watersheds experienced significant agricultural development prior to urbanizing, these watersheds may be starting from a degraded condition and show little to no change in response to new development.

In this study, we reconstructed land-cover conditions over a period of approximately 100 years in nine study catchments. The purpose of this study is to characterize the land use history of each catchment to establish the extent and trajectory of land-cover change in each catchment overall and the extent of forest loss within the riparian zone. Current theory suggests that protecting a buffer of vegetation adjacent to the stream channel can protect stream integrity despite forest loss in upland portions of a watershed (Sweeney 1993, Vuori and Joensuu 1996). Once this information is obtained, we can investigate the following questions:

1. Does land use history differ between the control and treatment catchments?
2. Does land use history differ among treatment catchments?
3. Did maintenance of forest riparian cover during periods of deforestation differ among catchments?
4. Do differences in land use history correlate with measures of present day watershed condition (i.e. the “starting conditions” of the nine catchments)?
5. Does the maintenance of riparian forest cover over time influence present day watershed condition?
6. To what extent have these streams recovered from previously degraded conditions?

Ultimately, understanding the historical land use conditions within these study catchments will contribute to the County’s ability to interpret observed starting conditions and change over time. Landscapes are constantly changing whether from management or natural processes– understanding historical land-cover helps us to understand trajectory of landscape conditions. Trajectory should affect the watershed’s resilience to further impacts or ability to ‘absorb’ development without significant changes in watershed health. A better understanding of the historical effects and legacies of land use change is necessary in order to understand the cause-and-effect relationships between development and stream health.

Methods

Study Sites

The selected study watersheds are located in the lowlands (predominantly < 500 feet in elevation) of the central eastern portion of Puget Sound. The study area covers the developing, low-lying western portion of King County, an area of common geologic history, flora, fauna, and human uses. Study watersheds contain small headwater alluvial streams originating on low-gradient upland plateaus, dropping across steep side-slopes to low-gradient base levels set by a major river, lake, or Puget Sound. Upland and riparian forests consist of second-growth conifers (mainly Douglas-fir, western hemlock, and western red cedar) and to a lesser extent deciduous trees (mainly big leaf and vine maple, red alder, and black cottonwood). Hydrology is rain-dominated, with naturally flashy flows during winter and low summer base flows. Aquatic productivity is typically limited by low nutrient availability, low summer flows, high winter flows, and, during winter, light.

Relatively small headwater watersheds (Strahler 1^{st} to small 3^{rd} order) with perennial, fish-bearing streams were chosen because prior studies demonstrate that they are sensitive to development-driven change in hydrology-mediated responses. A pool of candidate treatment watersheds was identified in an unbiased but nonrandom manner by screening for areas with relatively high future development potential indicated by parcels for which no known land-altering permits had been issued since 1989 and parcels whose value of improvements was ≤ 20 percent of the total parcel value based on the King County Assessor database. Subsequent selection of the study's six treatment watersheds was based on the following selection criteria:

- the presence of a past or existing flow, water quality or benthic invertebrate monitoring site;
- predominance of underlying glacial till-based geology, chosen because of its greater sensitivity to hydrologic change relative to glacial outwash, the other dominant surface geology in King County lowlands;
- absence of lakes, ponds and relatively large areas of wetlands, because these features may mask or reduce the magnitude of land-use driven hydrologic effects. Although effort was made to avoid wetlands it was not possible to select study watersheds with no wetlands as they are present throughout King County because of the relatively flat topography, moist climate, and prevalence of hydric soils in lowland Puget Sound; and
- lack or presence of only minor areas of urban zoning or areas under the regulatory control of other local jurisdictions to avoid confounding effects associated with the application of multiple land use regulations.

From the above criteria, the resulting study watersheds were assumed to have relatively high similarity of land uses, regulations, and development potential over time and high sensitivity to development-based hydrologic alteration because of common geology, climate, drainage area, and gradients. Reference watersheds were situated in municipal watersheds or nature reserves with no recent, existing or anticipated future development.

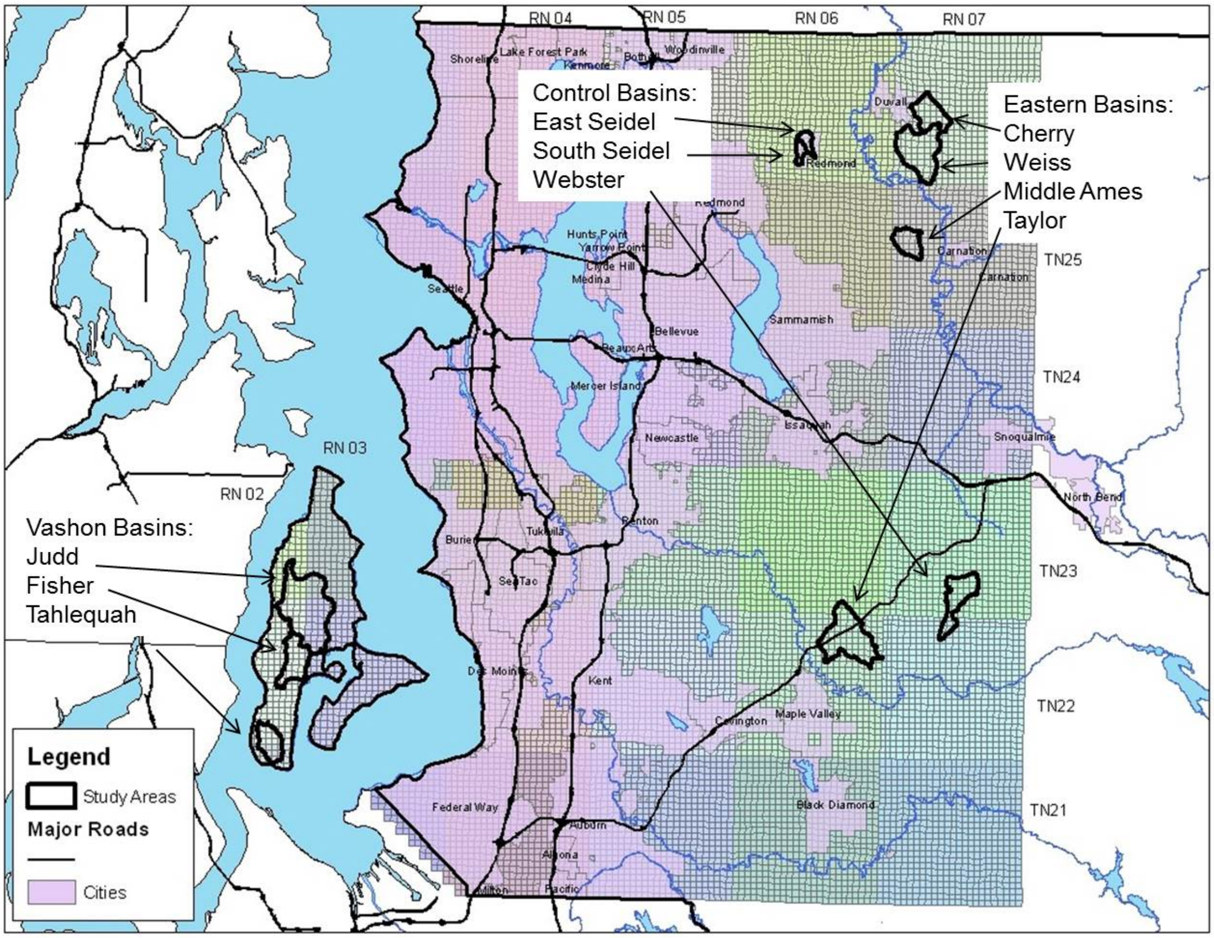

Figure 1 shows the location of the study catchments in King County. For presentation purposes, the catchments are categorized into three geographical and treatment groups: Vashon island catchments, eastern treatment catchments, and the three control catchments.

Data Collection

We used historical maps, aerial photographs, and classified Landsat TM land-cover data to reconstruct land-cover composition and configuration over six time periods within the nine watersheds. We searched the archives of the following organizations and agencies in order to identify all maps, records, and aerial photos that could provide information about land cover (forest cover, clearing, agriculture etc.) and land use (housing development, ranching, farming, road development etc.): the University of Washington map and special map collections (UW), the University of Washington Urban Ecology Research Lab (UW UERL), King County Department of Development and Environmental Services (KC DDES), King County Natural Resources Conservation Service (KC NRCS), King County Road Services Division (KC RSD), and the King County Archives.

We identified seven datasets that provided the most detailed and comparable land cover information and encompassed the majority of the study region (see Table 1). During the earlier time periods, not all datasets were available for all basins. It is also important to note that the scale and resolution of the datasets vary. In particular, the USGS Land Classification map was created at a very coarse scale, and thus may not show smaller patches of forest that may have been present.

Table 1 Final datasets included in the analysis. Not all datasets were available for all basins

Data set	GLO (1857-1892)	Timber Cruise (1907)	USGS Land Classification Map (1911)	Aerial photos - 1936	Aerial photos - 1948	Aerial photos - 1965	Land-cover data 1986-2007
Data Source	KC RSD, UW	King County Archives	UW	UW, KC RSD, KC DDES, KC Archives	KC NRCS	UW	UW UERL
Scale/ resolution	Twnship 10 miles: 1 in	40 acre tract	1:125,000	1:800	1:20,000	1:60,000	30 meter pixels
Cherry	Yes	Yes	-	-	Yes	Yes	Yes
East Seidel	Yes	Yes	-	Yes	Yes	Yes	Yes
Fisher	Yes	-	Yes	Yes	Yes	Yes	Yes
Judd	Yes	-	Yes	Yes	Yes	Yes	Yes
South Seidel	Yes	Yes	-	Yes	Yes	Yes	Yes
Tahlequah	Yes	-	Yes	Yes	Yes	Yes	Yes
Taylor	Yes	Yes	-	-	Yes	Yes	Yes
Webster	Yes	Yes	-	-	Yes	Yes	Yes
Weiss	Yes	Yes	-	-	Yes	Yes	Yes

Classification of past land-cover

We used visual interpretation of maps and photos to reconstruct long-term (1900 – 1965) historical land cover. The Timber Cruise and USGS maps were georeferenced in ArcGIS 9.3 based on the Public Land Survey System section grid boundaries. Aerial photographs were scanned to a pixel resolution of 1 meter and orthorectified using ERDAS software. Once maps and aerial photos were georeferenced, land-cover polygons were digitized in ArcGIS. For the maps, we classified land cover based on polygons delineated by the map's creators. For the aerial photographs, we developed a common classification system based on visually distinctive patch types. A patch was considered a relatively homogeneous land-cover type that could be reasonably distinguished from its surrounding land cover (Robinson et al. 2005). For consistency, digitization was performed by one analyst at a scale of 1:10,000 for all time periods. Given the resolution of the aerial photos, one hectare was considered the smallest, consistently classifiable unit. Classification was reviewed by an independent GIS analyst at King County.

To quantify more recent (1986 – 2007) land-cover changes, we used satellite-based land-cover data. These were generated by the University of Washington Urban Ecology Research Lab using Landsat Thematic Mapper (TM) imagery and supervised classification with spectral unmixing (for more details see Alberti et al. 2006). The same interpretation methods were used for all datasets resulting in a consistent classification into 12 land-cover classes with a spatial resolution of 30 meters. We used ArcGIS software to quantify land-cover composition for each basin for all time periods. We decided not to use aerial photos for this time period because digitizing polygons is time consuming and satellite data were available. Also in more recent history, classifying land cover in urban regions is more complex due to the diversity and complexity of urban forms. As a result, differentiating between patch types based on visual assessments is more challenging and satellite-based analysis provides a consistent method for quantifying land cover. To assess the comparability of aerial photo interpretation compared with the satellite-based land-cover data, the County independently digitized land-cover polygons using high resolution (15 cm pixels) orthorectified aerial photos for 2007. Land-cover statistics calculated using this polygon layer correlated will with results from the satellite-generated land-cover data for 2007.

Data Limitations

There are several important limitations and sources of error to consider when interpreting historical datasets. The earliest records of land cover, i.e. the GLO and Timber Cruise surveys, are from hand-drawn maps created in the field by potentially different individual authors. The Timber Cruise maps include a wide variety of land-cover types. However, associated records do not provide any description or definitions of these land-cover types. It is possible, perhaps likely, that these land-cover categories were created in the field without any consistent classification criteria.

The 1911 Land Classification map is a small scale map (1:125,000). This coarse resolution means that detailed pockets of forest cover would not be mapped. For example, this map shows the entire Island of Vashon as converted to agriculture. While it is likely that the Island was dominated by agriculture at that time, perhaps even close to 100% converted, it seems unlikely that all forest cover was completely cleared.

The more modern datasets including the aerial photos and satellite imagery are more reliable and consistent. While the aerial photos vary in their resolution, the limited number of land-cover types present in these areas during this time period (1936-1965) further increases the reliability of these data. Some error is introduced when aerial photos are georeferenced. However, comparisons between digitized land-cover layers from two independent georeferencing efforts demonstrated that this error is small (< 5%).

Finally, some error is introduced in the satellite data classification process. An error assessment is conducted in which randomly selected pixels are compared to aerial photos to assess validity. The overall accuracy for each of the land-cover layers used in this analysis was as follows: 1986 – 62%, 1991 - 85%, 1995 - 86%, 1999 - 88%, 2002 - 72%, 2007 - 98%. For more details on accuracy assessment methods see Alberti et al. 2006.

Land-cover Change Analysis

We estimated land-cover change over time to characterize the history of each basin. We used the six datasets that provided the most comprehensive, comparable, and reliable coverage for the study basins: aerial photos from 1936, 1948, and 1965 and land-cover raster data layers from 1986, 1995, and 2007. To facilitate comparison across years, polygons digitized using aerial photos were converted to raster grids. Because our smallest mapped polygon was 1 hectare, we converted polygon data into 90 meter raster grids by converting polygon data directly to a 90 meter raster and resampled the 30 meter raster grids to 90 meters. Our second approach to increase consistency was to aggregate our land-cover classes into six general categories: forest, agriculture, cleared, built, wetland, and water (see Tables 2 and 3). Both of these data manipulations reduced the precision of our data, but increased comparability across years. We used cross tabulation in IDRISI Taiga (Clark Labs 2009), to calculate land cover transitions over time for each basin.

Table 2 Original satellite based land-cover classification and reclassificiation categories

Final reclassified land-cover class	Original land-cover class	Description
Built	Heavy Urban	>80% Impervious area
	Medium Urban	50-80% Impervious area
	Light Urban	20-50% Impervious area
Cleared	Cleared for development	Land currently being developed
	Grass	Developed grass and grasslands
	Clear cut forest	Clearcut forest
	Snow/bare	Snow/bare
Forest	Deciduous/mixed forest	10-80% Deciduous or mixed forest
	Conifer forest	>80% Coniferous forest
	Regenerating forest	Re-growing forest
Agriculture	Agriculture	Row crops, pastures
Wetland	Non-forested wetland	Non-forested Wetlands

Table 3 Original aerial photograph classification and reclassification categories

Final reclassified land-cover class	Original aerial photo land cover type	Description
Built	Buildings	Buildings not associated with agricultural fields
Built	Developed	Impervious Surface dominant (parking lots, rooftops), high(er) density regularly spaced housing not associated with agriculture.
Cleared	Forest – Sparse	Sparse (individual trees distinguishable across more than 50% of the polygon) individual trees covering 10-50% of polygon
		Extremely Sparse – individual trees cover <10% of polygon
	Shrub/ Regenerating forest	Medium darkness between grass and forest – covering at least 70% of the polygon – smooth, dense texture
	Grass	Medium Light – cleared of forest, but not as dark as regenerating forest
	Cleared - unknown	Open treeless areas often in regular (straight line) shapes or with sharp edges, near roads or buildings, not clearly attributable to a particular purpose.
Cleared	Cleared – Eroded/bare	Star-like shapes associated with logging roads
	Cleared for Timber	Visible downed timber, in forestry area with little development or agriculture. Logging roads visible.
Forest	Forest-Clumped	Clumped (Individual trees form clumps and blocks but overall the polygon is > 10% and less than 60% forested)
	Forest-Contiguous w/ gaps	Gaps occasionally visible but otherwise contiguous (>60% forested)
	Forest – Contiguous	Spaces are not visible between trees

Agriculture	Orchard	Regularly spaced trees
	Cleared for Agriculture	Cleared area surrounding one or more building structures
	Row Crops	Regular rows (lines) in cleared land
	Mixed Ag	Multiple small patches of ag (orchard, row crop, buildings, unknown purpose)
Water	Open Water	Lakes, large rivers, wetlands

Forest Buffer Analysis

We estimated the percent of forest cover at increasing distances to the stream channel for 1936, 1948, 1965, 1986, 1995, and 2007 to determine whether the study basins retained forest within the stream buffer over time despite more widespread de-forestation. For this analysis, we converted a vector hydrography layer created by King County to a 90 meter grid and calculated both the Euclidean distance and the hydrologic distance from the stream channel. Regulatory stream buffer widths are often measured using Euclidean distance. However, topography alters the flow path of water over land and therefore measures that incorporate topographic variability are potentially more accurate. To measure hydrologic distance, we used a digital elevation model to measure the distance from each pixel to the stream channel via the most likely overland flow path. Distances for both methods were binned into six distance classes: 0-90, 90-180, 180-270, 270-360, 360-450, > 450 meters from the stream. Forest cover composition was summarized for each distance class.

Results

Overall basin history

Overall, we found that the study watersheds share a common history of land-cover change, though the timing and extent of the change varied by watershed. Initially, all watersheds were presumed to be fully or near-fully forested then lost between 50% and 100% of their forest cover before 1948. Across all watersheds, forest cover increased substantially between 1948 to 1965. Since 1986, the treatment watersheds have been experiencing a slow but steady conversion of forest to residential and commercial development (see Figure 1). For presentation purposes, we have grouped the nine watersheds into three categories: 1) Vashon island catchments include Fisher, Judd, and Tahlequah basins; 2) eastern catchments include Taylor, Cherry and Weiss creeks; and 3) control catchments include Webster, East and West Seidels (Figure 1).

However, there are potentially important differences in the timing and progression of land-cover change among individual basins. Early records of forest cover including the USGS land classification map and the Timber Cruise report suggest that the three Vashon Island catchments (Fisher, Judd and Tahlequah) and Taylor catchment had all experienced significant forest clearing. According to the USGS land classification map, Vashon Island was primarily converted to agriculture by 1911. This may be an overestimate of clearing (see note on limitations for this dataset above) since aerial photos from 1936 show the three Vashon catchments retaining between 10 and 30% forest cover. The Timber Cruise records indicate that Taylor basin was significantly deforested (~70%) by 1907. In contrast, Timber Cruise maps recorded that the Webster catchment retained approximately 55% forest cover and the remaining catchments (Cherry, Weiss, East and South Seidel catchments) all retained 65-100% forest cover at this time.

In addition, three of the basins that were cleared earliest, Judd, Fisher, and Taylor, also recovered the least amount of forest between 1948 and 1965 relative to the other watersheds.

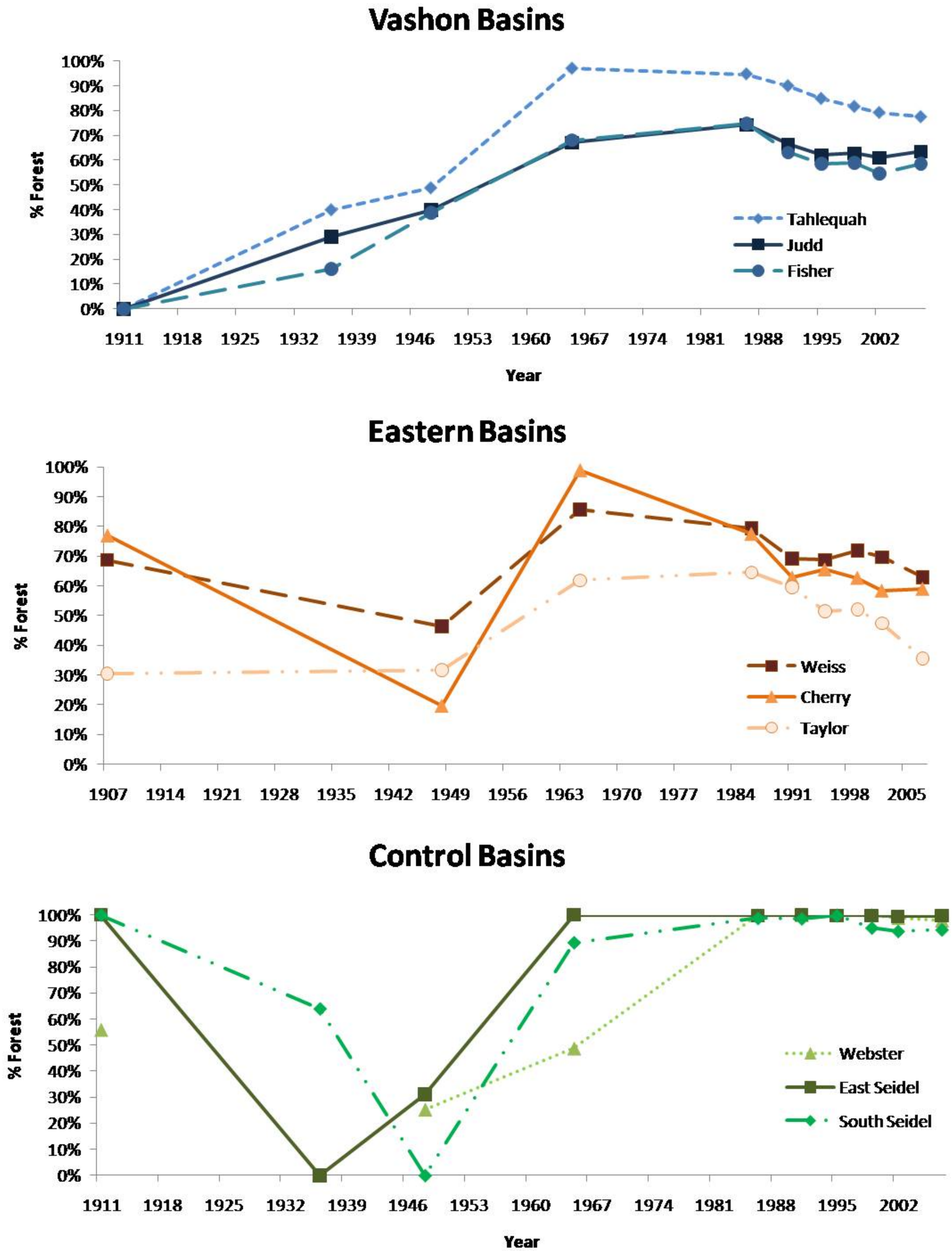

Figure 2 Forest cover change from 1907/1911 to 2007. Note that no data were available for Webster, Weiss, Cherry and Taylor basins from 1936.

Land-cover change analysis

In addition to finding a similar broad trajectory of forest-cover change across time, we also observed general trends in land-cover transitions over time across all watersheds (Table 4). All the study watersheds had been primarily cleared of forest at some point between 1936 and 1948. During the period from 1948 to 1965, the dominant land-cover trend was for cleared land to return to forest cover. Very little additional area was converted to agricultural areas after 1965. In contrast, some agricultural lands were converted into built lands during this time and some forested areas were directly converted into built areas. Beginning in 1986, a more significant conversion to built lands occurred. In contrast to the previous time period (1965 – 1986), development activities converted forested or cleared lands rather than agricultural lands. Also during this time, forest losses began to exceed forest gains.

Table 4 Land-cover transitions for each time period included in the analysis. Total forest loss and gain are also shown for each time period. By 1936, the Vashon catchments and East Siedel had all been cleared extensively. Consequently, the transition time period from 1936 to 1948 shows very little additional forest cover loss (which all occurred in South Seidel). Similarly, the remaining basins were at their least forested point in 1948, data were not available for Weiss, Cherry, Taylor, and Webster basins in 1936, leading to a smaller over all study area for that time period.

	1936-1948		1948-1965		1965-1986		1986-1995		1995-2007	
Transition	**Hectares**	**%**	**Hectares**	**%**	**Hectares**	**%**	**Hectares**	**%**	**Hectares**	**%**
Forest to Cleared	87	3%	67	1%	201	4%	302	6%	136	3%
Forest to Agriculture	4	0%	56	1%	1	0%	4	0%	2	0%
Forest to Built	0	0%	5	0%	17	0%	237	5%	323	7%
Forest Persistence	601	24%	1605	33%	3323	68%	3604	74%	3257	66%
Cleared to Forest	329	13%	1841	38%	455	9%	126	3%	180	4%
Cleared to Agriculture	40	2%	137	3%	0	0%	6	0%	53	1%
Cleared to Built	0	0%	7	0%	8	0%	198	4%	121	2%
Agriculture to Built	0	0%	0	0%	72	1%	2	0%	1	0%
Agriculture to Forest	4	0%	85	2%	365	7%	2	0%	2	0%
Agriculture to Cleared	28	1%	53	1%	338	7%	5	0%	2	0%
Total Forest Gain	**332**	**13%**	**1926**	**39%**	**831**	**17%**	**131**	**3%**	**202**	**4%**
Total Forest Loss	**90**	**4%**	**129**	**3%**	**226**	**5%**	**550**	**11%**	**478**	**10%**
Total Study Area	**2512***		**4900**		**4900**		**4900**		**4900**	

Individual basin narratives

1850 to 1907/1911 (Primary Forest and Clearing Phase)

According to the General Land Office Survey, the early history (1857 – 1892) of land-cover change within the study catchments is dominated by deforestation. According to a land classification map created by USGS, by 1911, the majority of forested land on Vashon Island forest had been cleared and converted to agriculture. By contrast, maps of land cover and land use created during a timber cruise in 1907 indicate that the extent of forest clearing was variable in the eastern basins. The Seidel watersheds had experienced no forest clearing while the Webster, Cherry and Weiss systems retained over 50% of their forest cover. The Taylor watershed experienced the most significant deforestation, retaining only 30% forest cover. Taylor was also the only eastern watershed with some agriculture in 1907.

Agricultural development occurred early and was extensive in the Vashon basins compared to the other basins. The Vashon watersheds had a significant and extensive period of agricultural cultivation during these early years. The Taylor catchment was the only eastern basin with even small amounts of agriculture (3% of basin area) during this time.

1936 to 1948 (Continued Clearing and Early Forest Regrowth Phase – data available for Vashon catchments and East and South Seidels only)

By 1936, Fisher, Judd, and Tahlequah and East Seidel basins had been extensively cleared and retained only 16%, 29%, 40%, and 0% of their forest cover respectively. South Seidel retained 64% of its original forest cover. Between 1936 and1948, forest cover increased between 14-24% in each of the Vashon and East Seidel catchments while the remaining forest in South Seidel had been cleared. Overall during this time, 333 hectares (13% of the study area with data for 1936) of previously cleared land had re-forested while 85 new hectares (3%) of forest land were cleared resulting in a *net increase of approximately 250 acres of forest in these five basins*. In addition, approximately 40 (2%) hectares of cleared land was converted to agriculture.

1948 to 1965 (Maturing Regrowth Phase)

During this time period, forest cover in all the study catchments increased substantially. By 1948, approximately 1800 hectares (35% of the study area) had returned to forest cover, while only 70 new hectares (1%) had been cleared, *resulting in a net increase of 1730 acres of forest (35%) between 1948 and 1965*. Afforestation did not occur evenly across all basins. By 1965, forest cover in the Webster, Taylor, Fisher, and Judd watersheds ranged from 49% and 67%. In contrast, forest cover in remaining catchments exceeded 80%.

Agricultural land cover peaks during this time period due to *a net increase of approximately 55 hectares of agricultural land cover* (approximately 130 hectares of cleared land converted to agriculture, and 85 hectares of agricultural land reverted to forest). In the Taylor, Fisher and Judd systems a small percentage of cleared land (4-7%) was converted to agriculture. By 1965, agriculture increased to 33%, 10%, and 25% of land in each of these three basins, respectively. In addition, 1965 is the first time (within the constraints of the data available) that housing and commercial (“built”) land cover is recorded in these catchments (approximately 10 hectares).

1965 to 1986 (Secondary Forest and Development Phase)

By 1986, the study watersheds were largely forested. The control watersheds (Webster, East Seidel and South Seidel) were protected from development and forest clearing, and retained 99% of their forest cover. They remain 99% forested to the present day. For all watersheds, there was a *net increase of 605 hectares of forest* cover during this time period as agricultural land and cleared lands reverted to forest cover. A new trend emerged during this time period as about 20 hectares of forest and 70 of agriculture were converted to residential and commercial development. All transitions to built land cover occurred in the Judd and Taylor basins (3% each). While forest and developed land covers increase, agriculture experienced the greatest net loss of cover (780 hectares). Of this loss, 365 hectares was due to reversion of agricultural lands to forest and 70 hectares were converted into built cover.

During this time period, the control and treatment catchment histories begin to diverge. By 1986, the three control catchments are fully forested and remain to until present day. For the treatment basins, forest cover peaks in 1986. The Tahlequah catchment reverts to a nearly fully (95%) forested state. The Weiss, Cherry, and Fisher catchments reach a peak of 75-77% forest cover. Taylor and Judd have the lowest amount of forest recovery (65% and 74% respectively). In addition, residential and commercial development begins in Taylor and Judd. Judd, Fisher and Taylor catchments lost a significant amount of agricultural land cover to abandonment (cleared; 13%, 11%, and 12%) and aforestation (10%, 10%, and 20%).

1986 to 1995 (Development Phase)
During the time period between 1986 and 1995, forest cover begins to slowly decline as it is replaced by residential and commercial development. Approximately 300 hectares of forest land were cleared and 240 hectares of forest were converted to development. *Overall, there was a net loss of approximately 420 hectares of forest cover*. Built land cover increased by almost 440 hectares. At this point, forest cover remained above 50% for all basins, and at 52%, the Taylor basin had the least forest cover. Otherwise, the basins were all near (59% for Fisher) or above 60% forested.

The increase in residential and commercial development was not evenly distributed across the basins (Table 6). The Cherry, Weiss, and Tahlequah basins showed less than 10% developed land cover while the Taylor, Fisher, and Judd basins all showed greater than 15% developed land cover. Virtually all the developed land cover was converted from land that was forest or cleared in 1986. Cherry and Weiss are the only basins that showed any increases in forest cover (12% and 7% respectively). The Fisher, Weiss, Taylor, and Judd basins all showed additional forest clearing (10%, 9%, 8% and 7% respectively). Otherwise, all changes were due to conversion of cleared and forested land to development

Table 5 Percent of each basin transitioning from cleared, forest or agriculture to built lands between 1986 and 1995.

	Cleared to Built	Forest to Built	Agriculture to Built
Cherry	2%	6%	0%
E. Seidel	0%	0%	0%
Fisher	6%	6%	0%
Judd	7%	4%	0%
S. Seidel	0%	0%	0%
Tahlequah	1%	5%	0%
Taylor	7%	10%	0%
Webster	0%	0%	0%
Weiss	1%	3%	0%

1995 to 2007 (Continued Development Phase and Just Prior to Start of Effectiveness Monitoring)
Between 1995 and 2007, built land cover increased by about 420 hectares. About 320 hectares of forest and 120 hectares of cleared land were converted into built. In turn, approximately 180 hectares of cleared land reverted to forest, while 140 hectares of forest were cleared. Around 50

hectares of cleared land were reclassified as agriculture. This reclassification may be at least partially due to classification error, as distinguishing between cleared and agricultural land can be difficult.

Within all treatment catchments, significant land-cover change is primarily from forest into built. Taylor experienced the most significant increase in development (20%) with the majority of this conversion occurring on forested land (Table 5). The Weiss basin underwent the next most significant increase in development, also primarily on forested lands. Cherry and Tahlequah both experience small amounts of development of forested lands. Fisher and Judd both experience a small increase in development which occurs both on previously cleared and previously forested lands.

Table 6 Percent of each basin transitioning from cleared or forest to built lands between 1995 and 2007. No agricultural lands converted to built during this time period.

	Cleared to Built	Forest to Built
Cherry	1%	8%
E. Seidel	0%	0%
Fisher	5%	3%
Judd	3%	2%
S. Seidel	0%	0%
Tahlequah	0%	5%
Taylor	4%	16%
Webster	0%	0%
Weiss	2%	10%

Riparian forest-cover analysis results

Though the catchments were primarily deforested by 1936 (Vashon and East Seidel) and 1948 (Cherry, Weiss, Taylor, South Seidel, and Webster), riparian areas (defined here as areas within 90 meters of the stream channel) generally retained proportionally more forest cover than other distance classes and the study area as a whole (Figure 3). Indeed, 1965 is the only year during which riparian areas are not more forested than other distance classes, and this finding is only the case when Euclidean distance measures are used. This is likely because by 1965 several of the basins were nearly 100% forested. Since 1986, riparian areas again showed a greater proportion of forest cover than other distance classes or the study area as a whole. Excepting 1965, these patterns hold for both Euclidean and hydrologic distance measures. The 2007 land-cover data in particular reveal a steady decrease in proportional forest cover with increasing distance from stream channels.

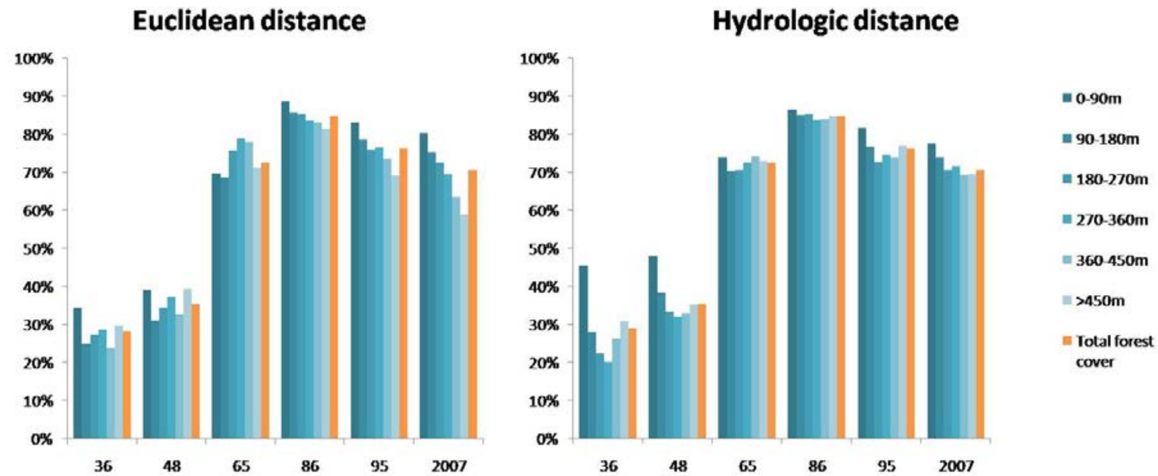

Figure 3 shows the percent of each distance class in forest cover for the entire study area. Total forest cover refers to the total forest cover across all basins for that year. Distance class is measured by Euclidean distance from the stream channel and hydrologic distance measures the distance of the water flow path to the stream channel based on basin topography.

The relatively high proportion of forest cover retained in riparian areas can be seen in most, but not all of the individual basins. In addition, results from individual basins reveal potentially important differences between Euclidean and hydrologic measures of distance. In 1936 and 1948 all the basins except Taylor and South Seidel showed higher proportion of riparian forest cover. In addition, the Judd and Webster basins do not show this pattern for Euclidean distance measures, but do show higher percentages of forest cover in the riparian zone using hydrologic distance measures (Figure 4). Webster in particular has a very steep topographic profile, which likely explains the significant difference in forest cover measures between the two distance measures.

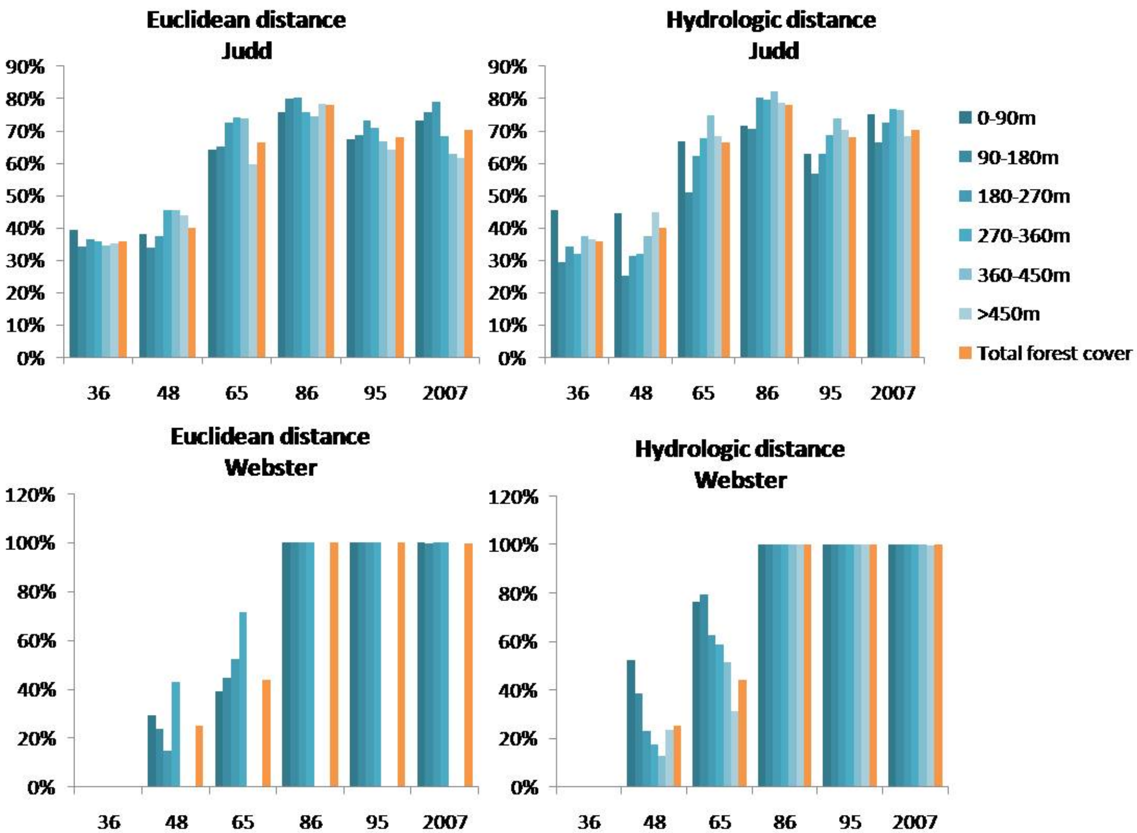

Figure 4 compares forest cover results measured using Euclidean and hydrologic distance for Judd and Webster. These two basins show the greatest qualitative difference for forest cover results using the two distance measures. Total forest cover refers to the total % forest cover for the basin overall.

From 1986 to 2007, most of the basins again showed a pattern of declining forest cover as distance from the stream channel increases (Figure 5). This is the case for the Fisher, Taylor, Weiss, and Cherry basins (using hydrologic distance measures). The Webster, East Seidel and South Seidel catchments are all virtually 100% forested, and so logically show no patterns of forest cover by distance from stream. Tahlequah was also primarily forested during these years, and shows no relationship between distance from the stream and forest land cover. The Judd basin also retained a moderately high level of forest cover compared to other distance classes during these years, but this pattern was not as pronounced as those seen in many of the other basins.

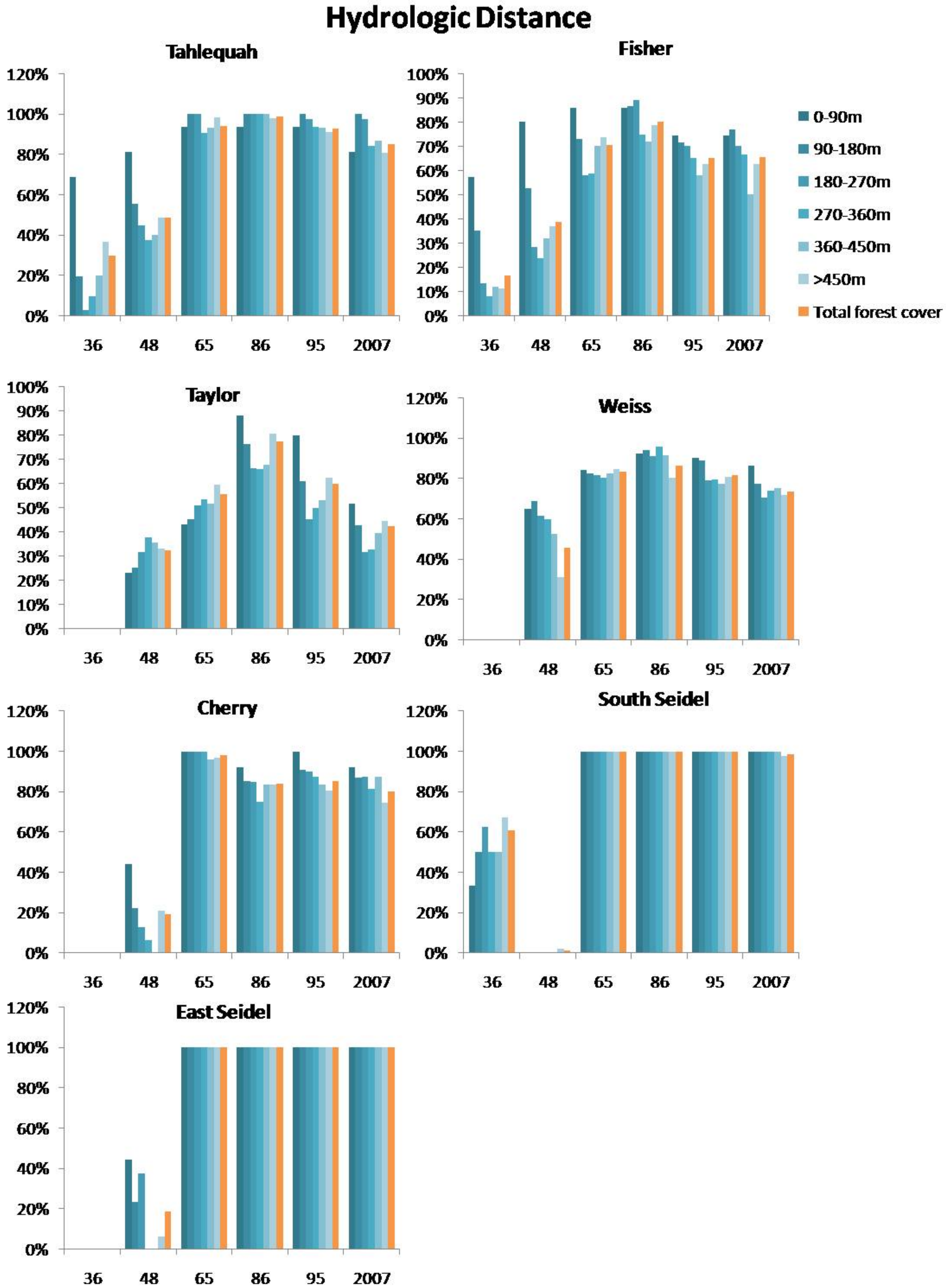

Figure 5 shows the results of the forest cover by hydrologic distance from stream channel for all basins not shown in Figure 3. Taylor, Weiss, and Cherry basins show 0% forest cover in 1936 because data were not available for those areas in that year.

Discussion

Land-cover history and change

Numerous studies have found that land-cover changes correlate with changes in watershed condition. Factors known to relate to watershed condition include total forest cover throughout the basin (Booth et al. 2002), riparian forest cover (Naiman et al. 2000), impervious surface (Walsh et al. 2005, Booth et al. 2002, Alberti et al. 2007), agriculture (Cuffney et al. 2009, Harding et al. 1998) and timber harvest (Moore and Wondzell 2005, Fuchs et al. 2003, Haggerty et al. 2004). Most previous studies have generally focused on relating stream responses to changes in a single type of land cover at a snapshot in time. Our analysis isolates individual land-cover impacts by quantifying transitions through multiple stages of dominant land use and forest cover patterns for each study watershed. Reconstructing the long-term history of a watershed raises new questions about the relative importance of the duration, intensity, and time that has elapsed since a given impact as well as the interactions among multiple impacts over time. These findings confound simple relations between watershed condition and land-cover characteristics for any moment in time because there may be legacy effects of previous land uses.

The study watersheds all experienced significant deforestation prior to 1965, a period of afforestation up until 1986. Currently, the treatment catchments are on a relatively slow trajectory of deforestation based on the rate of changes observed from 1986 to 2007. However, the timing, extent and spatial distribution of forest cover loss differed in modest but possibly important ways for each basin. Previous studies have found that logging can significantly alter aquatic macroinvertebrate communities and increase peak stream flows (ref e.g., Stencil et al). However, the degree to which, the effects of sedimentation and wood removal on ecosystem function remains unknown. Other studies have demonstrated that logging effects diminish within the first two decades following logging as forest cover regenerates (). The Tahlequah, Cherry, Weiss and all three control catchments experienced an intense but relatively short period of deforestation, and all recovered to more than 80% forest cover between 1965 and 1986 (Figure 2), at least two decades prior to the start of the Critical Areas effectiveness study. According to previous studies (Fuchs et al. 2003, Haggerty et al. 2004, Moore and Wondzell 2005), the hydrology of these basins has likely recovered from logging effects. In contrast, the Judd, Fisher and Taylor basins experienced similar deforestation, but only recovered to approximately 65-75% forest cover between 1965 and 1986. To what extent this subtle difference in forest recovery may lead to differences in watershed condition is unclear.

Watershed condition, specifically the presence of agriculture, prior to development likely influences the sensitivity of individual watersheds to urbanization (Brown et al. 2009). We found that Fisher, Judd and Taylor had the most significant agricultural history of all our study catchments. Residential and commercial development in these catchments occurred on both previously cleared (or agricultural) lands and previously forested lands. In contrast, the majority of development that occurred in the Cherry, Weiss and Tahlequah catchments occurred on forested land, with little or no intervening agricultural stage (Tables 5 and 6). This differential history may influence the sensitivity of these catchments to future residential and commercial development. Brown and others (2009) suggest that aquatic macroinvertebrate communities in basins with an agricultural history have already sustained significant declines prior to urban development, and therefore urban development does not have a strong additional effect. In contrast, forested basins are likely to have relatively intact aquatic macroinvertebrate communities that will be significantly altered as the basin develops. Based on the findings of Brown et al. (2009), we therefore would expect that Fisher, Judd and Taylor would be starting out in a more degraded macroinvertebrate community and therefore show less of a decrease in BIBI over time compared to Cherry, Weiss, and Tahlequah as development in these catchments increases.

Riparian forest-cover analysis

Retaining forest cover within the riparian zone can protect streams from land-cover changes occurring throughout the basins (Sweeney 1993, Vuori and Joensuu 1996), although protection depends to some extent on the width of the buffers (Haggerty et al. 2004). During the logging period from 1936 to 1948, all the basins except Taylor and East Seidel retained 40 to 60% percent of their riparian (defined as areas within 90 meters of the stream channel) forest cover even though by 1948 these basins overall were only 20 to 40% forested (Figures 4 and 5). The retention of forest cover within the riparian zone may have reduced the impacts of early logging on overall watershed condition. If this is the case, most of the basins in the study should have maintained relatively good watershed condition, even during the periods of extensive logging in 1930s and 1940s. The exceptions to this are the Taylor and East Seidel basins, which both retained very little riparian forest during early deforestation. The lack of riparian forest may not have had much long-term impact for East Seidel, which was completely re-forested by 1965. However, the extent of afforestation in the Taylor basin only reached a level of about 65% in 1986, before starting to decline. In more recent decades, more riparian forest has been retained in the Taylor basin relative to the basin overall.

Distance was measured using both hydrologic and Euclidean distance. For some basins, the two measures resulted in qualitatively different results. However, overall, the trend towards greater protection of riparian forest cover (as opposed to forest cover in the rest of the catchment) was more pronounced when distance was measured using hydrologic rather than Euclidean distance (Figure 4). Because hydrologic distance is based on topography, it seems plausible that this measure may be capturing patterns of forest cover within each basin with greater accuracy than Euclidean distance. Topographic features such as steep slopes near small streams may have made logging up to the stream edge difficult.

Temporal intercorrelations in land-cover change

These findings demonstrate that Fisher, Judd and Taylor basins were cleared earlier and remained deforested longer, experienced more agricultural development, and began to develop earlier and to a greater extent than the other three treatment basins (Cherry, Weiss, and Tahlequah). Based on these historical characteristics, at the start of the Critical Areas Effectiveness study in 2007, the Fisher, Judd and Taylor catchments should have the most impaired watershed condition of all the study catchments. However, it is important to note that although there are real differences in land-cover history among the basins, it is not yet known whether these differences lead to differential ecological outcomes (though this is the focus of the broader study of which this is a part).

These findings also raise an additional important consideration that pertains to all studies attempting to link land cover to ecological condition: that land-cover characteristics within and across time periods are not independent. King and others (2009) found that intercorrelations among commonly used predictor variables challenge our ability to detect causal relationships between land cover and ecological stream indicators. In this study, we find similar issues inherent to comparing historical land use to current watershed condition. For example, Judd, Fisher and Taylor did not recover as much forested land as the other six basins. This is likely because these basins were also converted to agricultural land use, leaving less land available for afforestation. This correlation makes it difficult to distinguish between the effects of lower overall forest cover and the presence of agriculture. In addition, when development first started in these areas, existing agricultural areas were more likely to convert to residential and commercial development than to forested lands. Therefore, those basins with an agricultural history may be more prone to develop earlier. Early settlement in a particular area is likely due to a combination of factors including the underlying geomorphology of the basin and proximity to more developed cultural centers, in this case the City of Seattle.

Lastly, changes in forest cover are not independent over time. In this study, areas that were forested in one time period were cleared in the next and regenerating during the yet the time period. This correlation challenges our ability to relate historic to present day conditions because the direction of the relationship switches depending on the time period selected. Studies investigating the effects of historic conditions on present day conditions often select one point in time (e.g. Harding et al. 1998) because it is difficult to obtain data and to analyze more than one time period. However, these studies may be missing important information about impacts that occurred before or after the time period selected for the analysis.

Conclusions

The land cover history of any given watershed potentially has significant implications for the current as well as the trajectory of watershed condition over time. Significant intercorrelations among land-cover characteristics within and across any given point in time challenges our ability to attribute changes in watershed condition to any particular land use or land-cover change event. However, understanding the long-term history of a given watershed is likely to be informative in explaining observed changes over time. In particular, understanding the variation in land-cover change history is potentially important for understanding and explaining variation in the relationship between land-cover change and watershed condition. Although it is difficult and time consuming to reconstruct land-cover conditions for all watersheds, it is worthwhile to at least develop a broad understanding of historic land-cover conditions for those areas that will be intensively monitored. There is a significant need for long-term monitoring of watershed condition, and building an understanding of the overall trajectory of the system is likely to be important in properly interpreting the results of those monitoring efforts.

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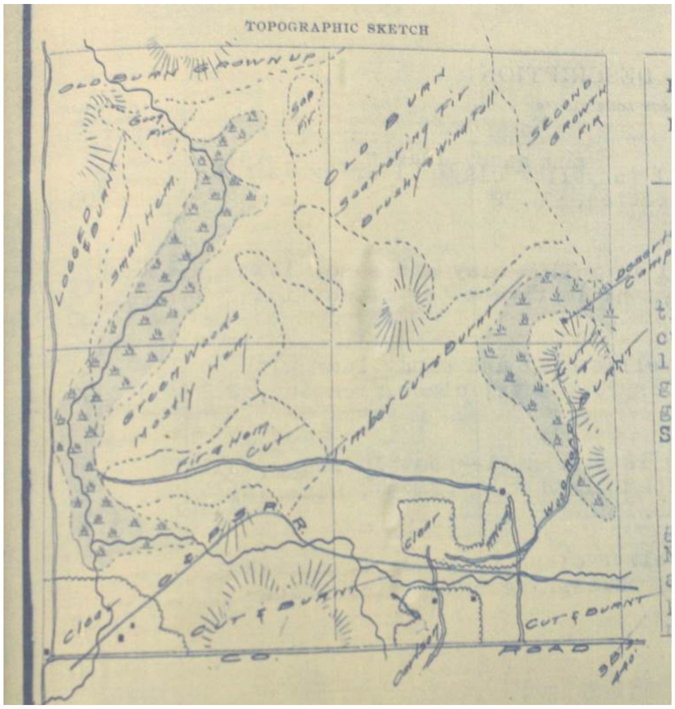
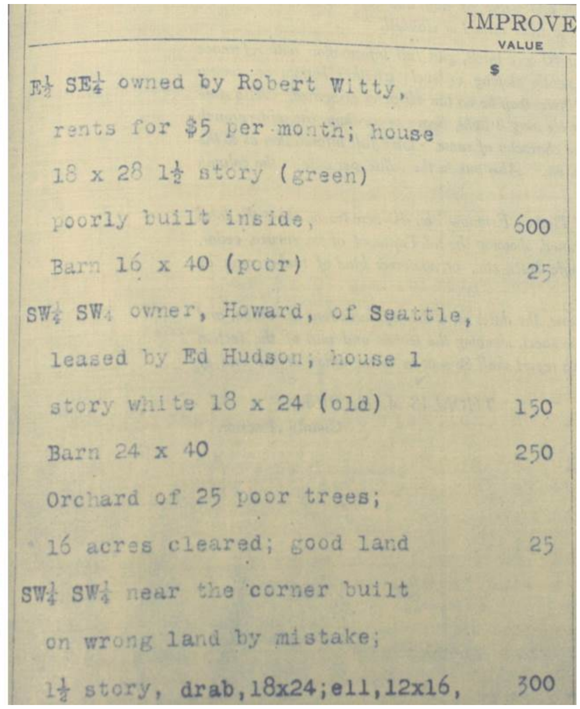
Appendix A: Data examples





IMPROVE

VALUE

$

E½ SE¼ owned by Robert Witty,	
rents for $5 per month; house	
18 x 28 1½ story (green)	
poorly built inside,	600
Barn 16 x 40 (poor)	25
SW¼ SW¼ owner, Howard, of Seattle,	
leased by Ed Hudson; house 1	
story white 18 x 24 (old)	150
Barn 24 x 40	250
Orchard of 25 poor trees;	
16 acres cleared; good land	25
SW¼ SW¼ near the corner built	
on wrong land by mistake;	
1½ story, drab, 18x24; ell, 12x16,	300

Figure 6 Timber cruise map from TN22 RN6 and associated notes.