Transactions in GIS, 2004, 8(3): 367–383

Research Article

GIS Methodology for Characterizing Historical Conditions of the Willamette River Flood Plain, Oregon

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Abstract

Recent environmental developments have stimulated an interest in conservation and restoration of the historical Willamette River flood plain, both to protect against flooding and to provide wildlife habitat. In order to best utilize scarce resources, we characterized historical and modern river channel and flood-plain conditions to evaluate changes and help prioritize restoration sites. Using cartographic and photographic data sources, we developed a Geographic Information System (GIS) to map active channels, side channels, islands and tributaries for four separate dates, as well as riparian and flood-plain vegetation characteristics for pre-European settlement and modern time periods. Coverages based on flood records and other boundaries were used to partition the flood plain into spatial subsets for analysis. The GIS allowed comparisons between historical and present conditions for a variety of environmental factors. Much of the pre-settlement channel complexity has been removed. Total channel length in 1995 was 26% less than in 1850, with almost 58% of the river's side channels disconnected from the system. In addition, we found a 72% loss of flood-plain forest from 1850 to 1995, since it was converted to agricultural and urban land uses. Selected river and flood-plain variables were made available for a spatial model to prioritize potential locations for flood-plain restoration.

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1 Introduction

One of the signs of progressive environmental management is the ability to incorporate modern techniques to solve problems born out of a long legacy of ecological change. A series of events surrounding the Willamette River in northwest Oregon has recently inspired new directions in floodplain management which may provide opportunities to substantially improve environmental conditions in a variety of ways. Floodplain restoration has been proposed through a joint effort among public and private entities to achieve many environmental management goals (Willamette Riverkeeper 1996, Gardiner 1999). The proposal is to reclaim riparian farmlands to allow replanting of native floodplain forests and recovery of riparian wetlands. Among the many potential benefits of restoration are flood control and habitat improvement, concerns made more crucial following a major flood event in 1996 as well as the continued decline of anadromous salmon runs on the Willamette River. Scientific research to support floodplain restoration in the Willamette Valley has now gained considerable momentum, concurrent with increasing public regard for pollution, recreation, scenic, and wildlife issues along the Willamette River (WRI 2001).

There are a variety of ecological, geomorphological, and hydrological connections between rivers and their flood plains (Petts et al. 1992, Malanson 1993, Large and Petts 1996, Newson 1997). Most of the ecological qualities of a river are directly influenced by its surrounding landscape as well as the human activities that the landscape supports (Décamps et al. 1988, White 1995, Naiman et al. 1988, Gurnell 1997b, Ward et al. 1999). In addition, a river has a direct influence on its surroundings, frequently altering the physical and biological conditions of its flood plain (Shankman 1993, Brookes 1996). Current science supports the notion of a river as a complex dynamic physical and ecological system, with a necessary level of natural integrity required to function effectively (Gregory et al. 1991, Graf 2001). There are significant economic and ecological advantages to be gained from the restoration of large river flood plains (Bayley 1995), and the science of floodplain restoration is developing rapidly (Boon et al. 1992, NRC-CRAE 1992, Sedell et al. 1992, Schiemer et al. 1999).

The capacity of a Geographic Information System (GIS) to portray, analyze, and model spatio-temporal information makes it ideal for river flood-plain studies (Iverson and Risser 1987, Lam 1989, Allen 1994, Muller 1997). Many aspects of floodplain management have been enhanced by the incorporation of a GIS, including riparian buffer analysis and delineation (Narumalani et al. 1997, Moser et al. 2004), channel planform change (Doward et al. 1994, Mossa and McLean 1997, Gurnell 1997a, Graf 2000, Winterbottom and Gilvear 2000), and floodplain vegetation change (Johnson et al. 1995, Allen 1999, Dixon and Carter 1999, Gutowsky 2000). A GIS can integrate spatial data from a variety of sources, and this feature enhances location models which rank potential restoration sites based on numerous economical, ecological, and physical variables (Llewellyn et al. 1996, Russell et al. 1997, Iverson et al. 2001).

1.1 Study area

The Willamette River basin provides an ideal setting to develop the principles of floodplain restoration (Figure 1). Running about 300 km from south of Eugene to its confluence with the Columbia River north of Portland, the mainstem Willamette is the thirteenth largest river in the United States with a mean annual flow of 900 m^3/s (Willamette Riverkeeper 1996, Gardiner 1999). It drains a 29,700 km^2 basin which is dominated by intensively

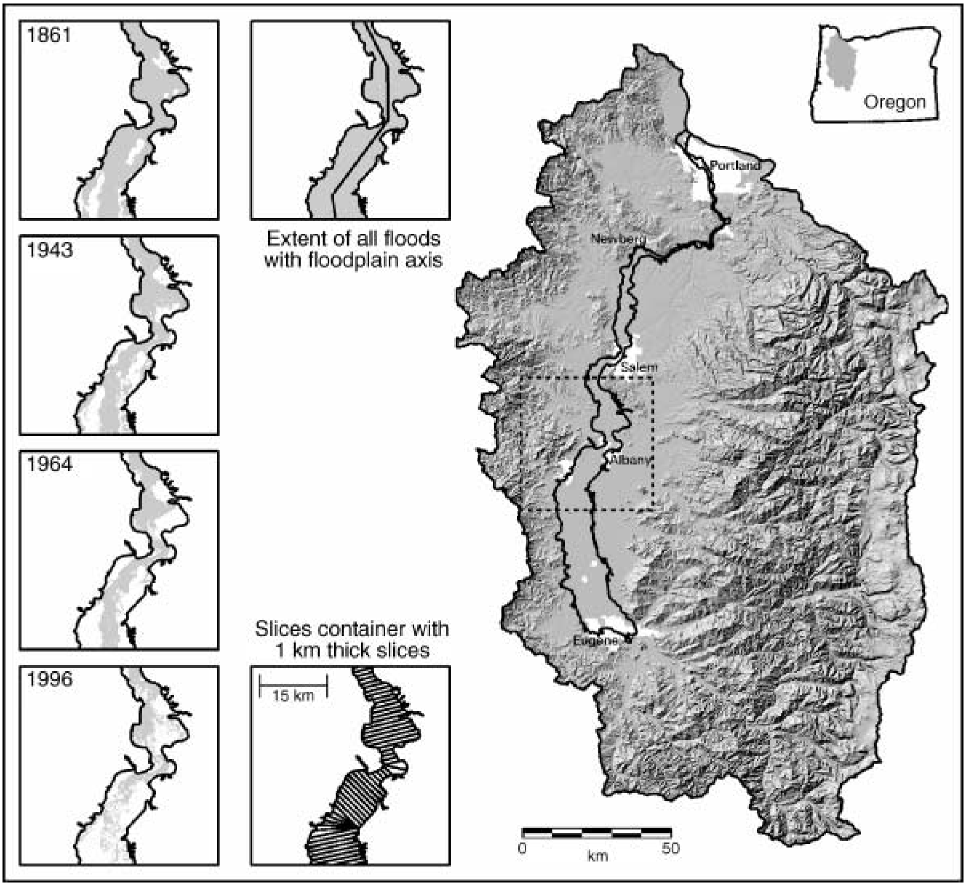

Figure 1 The Willamette River basin in northwest Oregon. The slices analysis coverage was created by combining the flood extents for four major floods (1861, 1943, 1964, and 1996) and then constructing a floodplain axis line to define perpendicular segments at 1 km lengths

managed upland forests in the Cascade and Coast Range mountains and highly productive agricultural fields throughout the valley floor. Only 6% of the basin area is occupied by urban land cover, yet that land houses over 2.4 million people (67% of Oregon's population). The Willamette valley is over 175 km long and about 40 km wide, and consists of deep Missoula flood silts broken by volcanic remnants (Hulse et al. 2002).

The Willamette River drains fractured basalt lava flows in the Cascade mountains and descends through heavily wooded Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) forests to its valley floor, where it continues north to the Columbia River through thick riparian hardwood forests of alder (*Alnus* spp.), willow (*Salix* spp.), bigleaf maple (*Acer macrophyllum*), Oregon ash (*Fraxinus latifolia*), Oregon white oak (*Quercus garryana*), black cottonwood (*Populus trichocarpa*) and others (Towle 1982). Flowing across numerous gravel-lined channels in its upper stretches from Eugene to Albany, the river cuts through sedimentary deposits in its middle stretch from Albany to Newberg, and then enters a highly constrained lower reach from Newberg

Pool over the Willamette Falls to Portland (Figure 1). Below Portland, it leaves the Willamette Valley and enters the Columbia River over 500 km from its source at Waldo Lake (Sedell and Froggatt 1984, Dykaar and Wigington 2000).

The modern Willamette River has changed dramatically since the initial settlement of the valley by Europeans in the 1830s. Extensive floodplain hardwood forests were removed, both to fuel steamboats and to clear land for agriculture. The braided gravel channels in the upper reaches of the valley were channelized and their river banks hardened by revetments and other structures. As a result, the river system is much less complex than it was 150 years ago, with almost 50% of the historical channels removed from some portions of the river network (Sedell and Froggatt 1984, Benner and Sedell 1997). Thirteen tributary dams now regulate the river. These impoundments reduce the frequency and severity of major floods and block sediment flow, a process which allows downcutting of the river channel and further inhibits overflow events (Dykaar and Wigington 2000). Riparian vegetation, which was once in a dynamic equilibrium with flooding, now appears to be stabilizing as a mature hardwood forest, with disturbance made less frequent by a lack of overbank events (Gutowsky 2000). In addition, the river is recovering from over a century of human pollution, especially from cities and pulp mills. In the 1930s the river's water quality was so bad that anadromous salmon could barely survive the swim through Portland harbor because of precipitously low dissolved oxygen content (Willamette Riverkeeper 1996, Mullane 1997). Only through aggressive efforts in the last 40 years has the water quality recovered to make recreational use of the river again feasible. Such efforts were rewarded by the designation of the Willamette in 1998 as one of the fourteen initial American Heritage Rivers (Gardiner 1999).

The combination of events surrounding the Willamette River's recovery has led many scientists and politicians to call for a continued recovery plan which would include restoration of historical flood plain (Frenkel et al. 1991). In 1998, the Willamette Restoration Initiative was established by State Executive Order 98-18 to develop a "basinwide strategy to protect and restore fish and wildlife habitat, increase populations of declining species, enhance water quality, and properly manage floodplain areas – all within the context of human habitation and continuing basin growth (WRI 2001: ii)." The restoration effort has been joined by the U.S. Army Corps of Engineers (ACOE), which has funded a floodplain restoration feasibility study (Gardiner 1999), as well as the U.S. Fish and Wildlife Service, which has acquired riparian farmland for restoration of native forests and wetlands. One important task is to determine which floodplain lands are most suitable for restoration (NRC-CRAE 1992, Gregory 1999).

1.2 *Objectives*

In the face of limited funding and given an expansive flood plain, decision makers required a scientific method of prioritizing floodplain restoration efforts (Gregory 1999). To address this need, we developed a GIS to characterize the historical flood plain and to help select potential areas for riparian restoration.

The goal of our research was to develop GIS methodologies for the temporal analysis of the flood plain, keeping in mind the requirements of a spatial model that would identify potential areas for riparian restoration. The purpose of this paper is to present the GIS methodology for characterizing historical and present-day floodplain conditions. The complete results of the historical analysis and restoration modeling are quite extensive and are presented elsewhere in great detail (Hulse et al. 2002, Gregory et al. 2004). It is important to note that the data presented here may not exactly match those works, as summaries were prepared independently.

2 Methods

There were three basic steps to the methodology. First, we created polygon coverages based on the functional extent of the flood plain to define the study area and subregions of interest. Then, we mapped the river channel extents at four separate dates. Finally, we mapped floodplain vegetation for two periods with reliable land cover data. After the creation of these spatial data layers, the GIS was available for queries to produce numerical data for the generation of tables, graphs and GIS-based output maps, as well as to drive a restoration siting model.

2.1 Generation of floodplain extent

Because of the linear nature of rivers, a useful technique for describing floodplain features is to partition the flood plain into segments along the length of the river (Downward et al. 1994, Mossa and McLean 1997, Gurnell 1997a). Structuring the flood plain in this manner allows comparison of upstream and downstream characteristics, which can vary widely depending on channel slope, channel constrictions, and other geomorphological considerations (Petts and Calow 1996). Furthermore, using the flood-plain length instead of river length allows consistency over time, since river distances change regularly. For this study, the flood plain was delineated based on the historical flood record, and then for analytical purposes this area was subdivided into longitudinal sections, or ‘slices,’ along the length of the flood plain (based on suggestions from Dr. Hervé Piégay , Université Lyon, 18, rue Chevreul, 69007 Lyon, France).

The floodplain extent was determined using historical flood maps created by the U.S. Army Corps of Engineers (ACOE) for major floods in 1861 (the largest on record), 1943, and 1964. These paper maps were based on eyewitness reports, photographs, high water marks, and other information. The maps were manually digitized into vector polygon coverages denoting the spatial extent of floodwaters. For a fourth flood in February 1996, the ACOE created a detailed coverage based on aerial photography acquired during the flood. A combined flood extent layer was created from the spatial union of the four floods, with most internal ‘islands’ (areas of higher ground that were not underwater but were completely surrounded by floodwater) removed to create an unbroken boundary (Figure 1).

Following the delineation of the maximum lateral floodplain extent, we created a coverage that subdivided the entire flood plain into 227 unequal sections defined by normal lines perpendicular to the floodplain axis intersected at 1 km transect points (Figure 1). The floodplain axis was drawn to maximize separation of the flood plain into longitudinal segments, which could then be used to divide the flood plain into significant reaches. Where the axis changed directions, irregular wedge-shaped slices were formed. These transitional slices, where the floodplain axis changes direction, created interpretation problems due to their irregular shape, and so they were labeled as ‘corners’ for identification during analysis. The coverage required extensive hand editing to label polygon attributes and perform fine-scale adjustments.

In addition, two other analysis containers were created. The first was the 100-year flood plain as defined by Federal Emergency Management Agency (FEMA) National Flood Insurance Program maps (http://www.fema.gov/mit/tsd/). Digital forms of these maps were appended, edgematched, and then reselected for 100-year flood plain. The last container was the boundary of the Willamette River Greenway (WRG), as drawn on paper maps (ODOT 1976). The WRG is a land use designation created by state legislation to restrict non-essential land development within immediate proximity of the river. To translate the greenway boundary into a digital coverage, the line work was screen digitized over a collection of 1995-era digital orthophotographs.

2.2 Channel mapping

The next phase of the methodology was mapping the historical extent of the river channel for four different time periods using separate data sources and approaches (Figure 2).

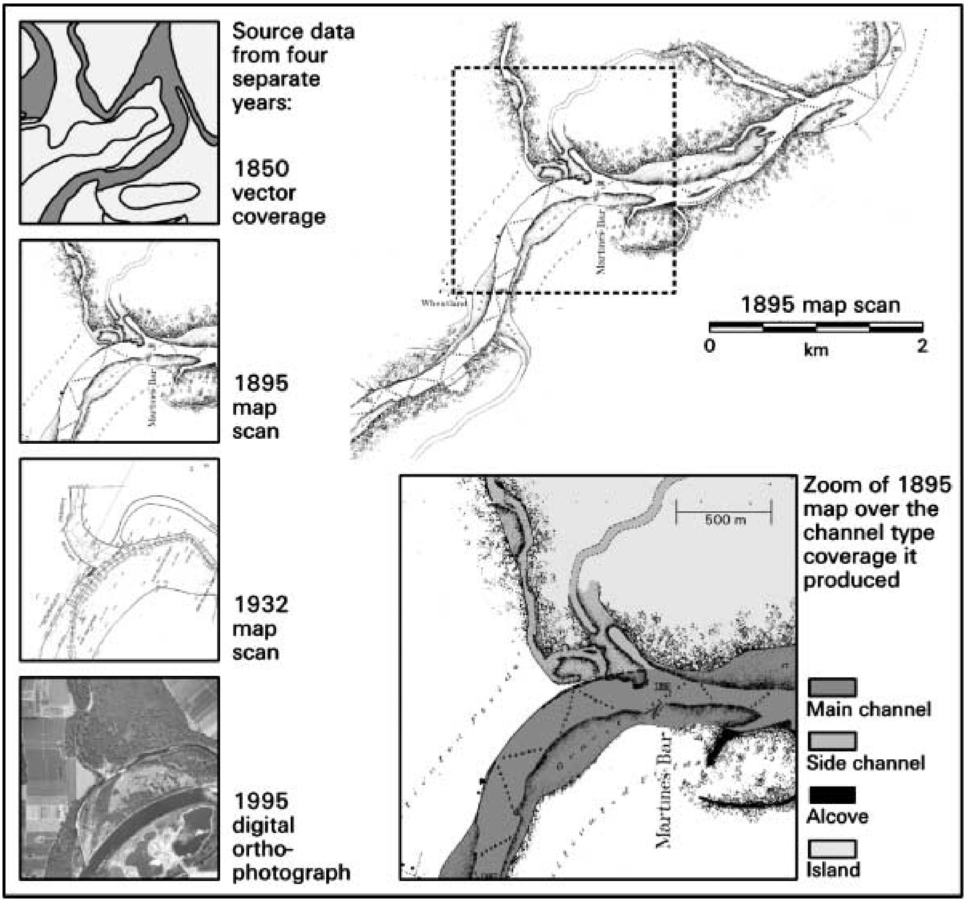

Figure 2 River channel maps for four separate years were constructed from General Lands Office survey records (1850), U.S. Army Corps of Engineers river maps (1895 and 1932) and digital orthophotography (1995). In each case, polygons were digitized from the source data to represent the river's main channel, side channels, alcoves, and islands

For each period, we outlined the active channel of the river and labeled polygons for main channel, secondary (side) channel, tributary, alcove (remnant slough that connects to the main channel), and island.

The initial channel mapping effort was based on detailed interpretation of General Land Office (GLO) survey records (Schulte and Mladenoff 2001) by the Oregon Natural Heritage Program (Christy and Alverson 2004). While laying out the township and range boundaries for the Willamette Valley, GLO surveyors pinpointed the river channels and main tributaries that crossed boundaries and mapped their general positions within the section. In most cases, their plat maps included line drawings indicating the location of both banks for rivers and single lines for streams. Technicians interpreted those maps and survey reports to create detailed vector coverages using a digital version of the township and range grid as a reference. While it took forty years (1850–1890) to survey the entire valley (Christy and Alverson 2004), the townships near the river were finished in the first ten years, so the initial date (1850) was assigned to the channel map derived from this source.

The ACOE conducted thorough surveys of the Willamette River in 1895 and 1932, and created a series of navigation-grade maps for each date (ACOE 1895, 1932). The 1895 series consisted of fifteen maps at 1:12000 scale. In 1932 the ACOE used a scale of 1:5000, which took 52 maps to cover the river from Eugene to Portland. Paper copies of these maps were scanned and imported into GIS software as raster files. The images were georectified to a common geographic reference system using the township and range registration marks drawn on the maps and some semi-permanent features (rock formations, bridges, ferry crossings, etc.). The map elements were then converted to digital coverages using an automated pattern recognition tool (ESRI ArcScan) and a significant amount of screen editing and attributing. From these two series of maps, we obtained coverages for river active channel (or high flow), river low flow channel, river maximum depth, river structures (dams, spillways, etc.), riverbank roads and railroads, and riverbank vegetation.

To map the 1995 river channel, we created mosaics from 164 separate panchromatic digital orthophotographs at a pixel resolution of 0.67 m. Channel features and other water bodies were screen digitized and attributed using visual reference. Where the high water line was obscured by clouds, shadows or other features, expert judgment was used to continue the digitizing, often with ancillary data or field reference.

For each of the four dates, a river thalweg line coverage was screen digitized to identify the main channel and provide a reference for river length. For 1850, the thalweg was located at the channel centerline. The ACOE river survey maps from 1895 and 1932 included depth soundings, which we used to delineate the main channel. For 1995, we used visual clues to delineate the main channel. The thalweg coverage was coded to indicate channel complexity by labeling each line segment as either single channel, multiple channel, or tributary junction (minimum length for coding was 500 m) (Figure 3). In addition, the thalweg was similarly coded to indicate the presence of revetments or wing dams on one or both banks as a measure of structural complexity.

2.3 *Flood-plain vegetation mapping*

Vegetation cover for the flood plain was characterized for two dates, 1850 and 1995. Ideally, this would have been done for 1895 and 1932 as well, but the ACOE river survey maps only included scant descriptions of streambank vegetation, and complete land cover data for the entire flood plain were not available.

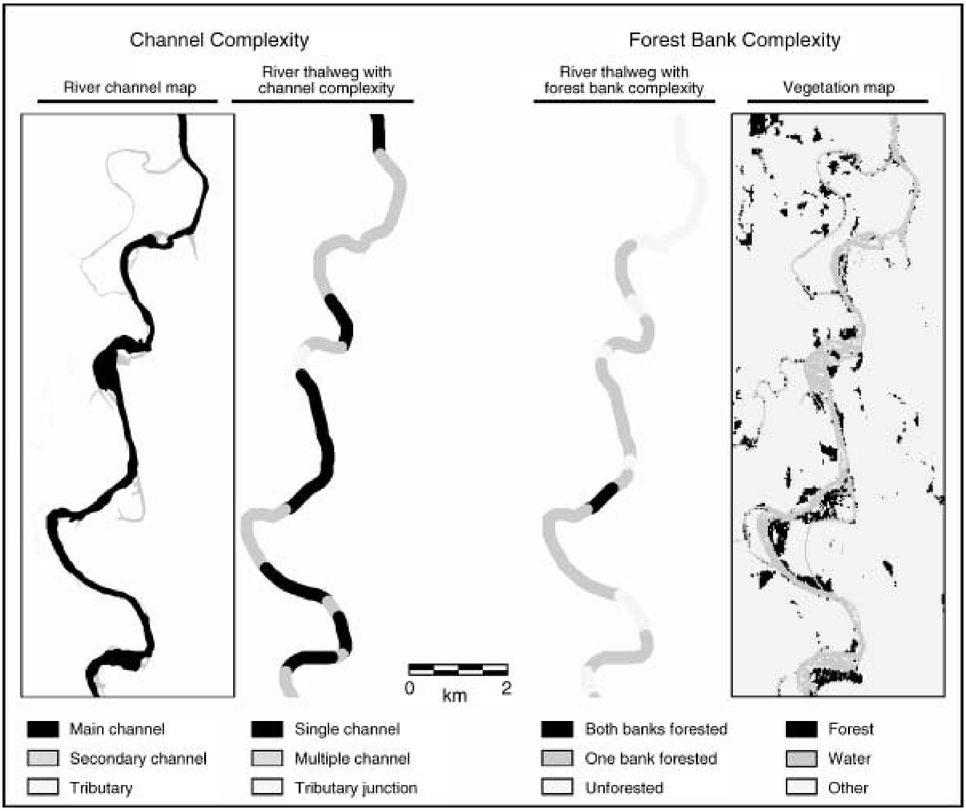

Figure 3 For each river channel map, a thalweg line coverage was drawn along the centerline or deepest channel. The channel and forest bank complexity attributes were determined for the thalweg line using visual reference from the active channel coverage and vegetation maps (for 1850 and 1995). Each river length was coded to indicate the complexity along that segment

The 1850 land cover characterization was generated by the same process as the 1850 channels, using the GLO plat maps and survey notes (Christy and Alverson 2004). The interpreters mapped the Willamette valley for 55 different land cover classes, based on the detailed descriptions of surveyors, as well as modern topographic and soils data. Their line work was developed into a polygon coverage that was rasterized to 25 m pixels.

The 1995-era data came from a land cover/land use map developed for a regional project (Hulse et al. 2002). The primary source for the map was a multi-temporal Landsat Thematic Mapper (TM) data set from 1992, interpreted into 40 different land cover classes at 25 m pixel resolution (Oetter et al. 2001). This base map was then amended and enhanced by the addition of geospatial information and GIS coverages for agricultural fields, census data, transportation routes, land use zoning, and water bodies to produce a 58-class land use/land cover map (Hulse et al. 2002).

To allow effective comparisons between the two land cover data sources, each 1850 land cover code was cross-referenced to a modern code (Hulse et al. 2002). This procedure required several assumptions to reconcile detailed nineteenth-century ground-level notes with the broad land cover classes derived from modern remote sensing imagery. For example, community-level subclasses of prairie and savanna were collapsed into one very broad class named 'natural shrub and grasslands.' Different woodland classes were cross-referenced to either 'open forest' or 'semi-open forest.' Further details can be found in Hulse et al. (2002).

As an index for riparian management, we mapped streambank vegetation within the flood plain. For both 1850 and 1995, the river channel coverages were buffered away from the water (inward buffer for islands) to identify pixels immediately adjacent to the water. A similar procedure was used to capture pixels within a 'riparian zone of influence' (Gregory et al. 1991), defined as the area within 30 and 120 m of the active channel edge. To tally the riparian pixels, raster masks based on the channel vector coverages were used to query vegetation cover images.

For each of the four dates, streambank vegetation descriptions were used to generate a forest bank complexity index. The river thalweg line coverage was attributed to indicate the presence of riparian forest on none, one, or both banks. This allowed a direct comparison for riparian forest cover for the four dates, including 1895 and 1932, which lacked areal flood-plain data (Figure 3).

3 Results

The GIS approach to mapping historical and current floodplain conditions in the Willamette River flood plain produced a vast quantity of information; each of the 227 river slices was queried across the four dates for channel type and area, streambank vegetation, channel complexity, structural complexity, and forest bank complexity. A brief synopsis of the results is presented here to demonstrate the methods. A more in-depth ecological explanation of the findings can be found in Hulse et al. (2002) and Gregory et al. (2004).

Seven separate analysis containers were produced to analyze flood-plain features (Table 1). The first four were flood extents, and the largest was that of the 1861 flood,

Table 1 Reach and total areas (ha) of seven different spatial analysis coverages within the study area

	River Reach			
Coverage	Lower (km 1–71)	Middle (km 72–151)	Upper (km 152–227)	Total
1861 flood[1]	2,819	34,936	70,020	107,774
1943 flood[2]	3,205	30,754	49,500	83,459
1964 flood[3]	4,134	26,269	26,344	56,747
1996 flood	4,341	21,390	11,586	37,317
Slices	7,173	36,906	82,208	126,287
FEMA	3,818	28,581	40,425	72,823
WRG	7,659	7,467	7,184	22,310

1. The 1861 flood map was incomplete for flood-plain slices 1–40.
2. The 1943 flood map was incomplete for flood-plain slices 1–26.
3. The 1964 flood map was incomplete for flood-plain slices 1–5.

for at least two reasons. By many accounts, the 1861 flood was the greatest Willamette flood in post-settlement history (Hulse et al. 2002). In addition, the 1861 flood extent coverage was derived from a map based largely on extrapolation of historical information, so some smoothing likely occurred. The smallest flood extent was the 1996 flood, which resulted from a variety of factors, including the effectiveness of flood control projects, the improved precision of modern photo-based mapping techniques, and the fact that the 1996 flood was simply not as large as many earlier floods. For each of the flood extent maps, the majority of inundated land was found in the upper reach of the river, between Eugene and Albany, where the flood plain is broad and flat and there are few channel constrictions. In the lower reach, from Newberg to below Portland, where the river is downcutting through bedrock, the flood plain is very narrow with concomitant small flood extents.

A union of the four flood extent maps was used to create a fifth coverage, named slices, which segmented the entire flood-plain extent into 227 sections. Twenty-five (fewer than 10%) of the slices were located at points where the floodplain axis changed direction. These irregular slices represent only 6.5% of the coverage area. The slices coverage was only 17% larger than the 1861 flood extent, which indicates that much of the floodplain area defined for this study was derived from that flood. The slices coverage is larger because some dryland internal polygons from each flood coverage were included in the maximum flood extent, and the full extent was buffered outward for analysis reasons. The mean slice area is 556 ha; if each slice was 1 km long, this would suggest a mean slice (and floodplain) width of 5.6 km. The sixth container was the FEMA 100-year floodplain coverage, based on post-dam estimates. The FEMA coverage depicts lands restricted by special zoning ordinances within the 100-year flood plain; these areas may be more promising for conservation or restoration. The final analysis container was the 1976-era Willamette River Greenway boundary. As a special-use zoning boundary, this coverage contained the least area, and was used for analysis specific to that designation.

For each of the four channel mapping dates, results for diversity of channel types and areal coverage of each channel type were tabulated by floodplain slice (Table 2). The greatest number and extent of channels was found in the upper reach in 1850. Because of channelization and flood control, the number of channels in this reach dropped dramatically by 1995. In the lower reach, there was less channel reduction, partly because the flood plain was already geologically confined.

The simplification of the Willamette River over time was further evidenced by the channel and forest bank complexity analysis (Table 3). From 1850 to 1990, multiple channel lengths decreased by almost 40%, while single channels increased. Again, the channel change in the upper reach was the most dramatic. The length of river with forests on both banks dropped as well, by over 75% along the whole river. Over 360 separate channel structures, covering over 50% of the river's length, were built from 1850 to 1995 (Hulse et al. 2002). These installations are a major reason for the decline in river channel and riparian forest extent.

The floodplain vegetation analysis was performed for 1850 and 1995; simplified results are shown in Table 4. Overall, the trend has been towards replacement of the native floodplain vegetation, especially riparian hardwood forests and prairies, with agriculture and urban land cover types. A similar trend was observed with streambank vegetation, indicating that forest removal also occurred along the riverbanks. The riparian forest complexity results demonstrate that much of the riparian forest was removed by

Table 2 Summary of lengths and areas for channels and islands in the Willamette River flood plain from 1850–1995

	Length (km)				Area (ha)				
Reach	Primary Channel	Side Channel	Alcove	Total	Primary Channel	Side Channel	Alcove	Island	Total
Lower (km 17–51; Portland-Newberg)[1]									
1850	59.9	6.2	2.4	68.5	1,472.9	109.7	10.3	121.7	1,714.7
1895	60.1	12.6	0.4	73.0	1,480.0	175.9	3.6	154.2	1,813.7
1932	58.1	13.5	0.0	71.6	1,629.9	165.9	0.0	156.2	1,952.0
1995	60.5	14.9	0.5	75.9	1,406.1	169.4	1.7	116.9	1,694.1
% change 1850–1995	0.9%	141.3%	–77.8%	10.8%	–4.5%	54.4%	–83.5%	–4.0%	–1.2%
Middle (km 52–151; Newberg-Albany)									
1850	115.0	34.8	13.6	163.3	2,411.0	308.5	80.7	1,945.9	4,746.0
1895	112.3	46.9	21.9	181.1	2,955.6	370.8	127.3	2,081.1	5,534.8
1932	114.8	38.7	9.8	163.3	2,609.6	369.9	75.0	1,944.7	4,999.3
1995	113.9	34.1	15.0	163.0	2,114.8	208.6	70.9	1,776.9	4,171.2
% change 1850–1995	–0.9%	–2.1%	10.6%	–0.2%	–12.3%	–32.4%	–12.1%	–8.7%	–12.1%
Upper (km 152–227; Albany-Eugene)									
1850	117.8	193.2	28.5	339.5	1,946.1	1,058.7	181.5	6,896.9	10,083.2
1895	98.8	117.6	21.7	238.1	2,118.2	936.1	134.9	4,744.1	7,933.2
1932	99.2	131.0	22.2	252.4	1,865.3	723.3	69.8	3,686.1	6,344.4
1995	100.4	50.2	34.6	185.2	1,536.0	279.9	103.3	1,412.7	3,331.9
% change 1850–1995	–14.8%	–74.0%	21.4%	–45.4%	–21.1%	–73.6%	–43.1%	–79.5%	–67.0%
Total (km 17–227; Portland-Eugene)									
1850	292.7	234.1	44.5	571.3	5,830.0	1,477.0	272.5	8,964.5	16,543.9
1895	271.2	177.1	43.9	492.2	6,553.7	1,482.9	265.8	6,979.3	15,281.7
1932	272.1	183.2	32.0	487.3	6,104.8	1,259.1	144.8	5,787.0	13,295.7
1995	274.8	99.1	50.2	424.1	5,056.9	657.8	175.9	3,306.5	9,197.2
% change 1850–1995	–6.1%	–57.7%	12.8%	–25.8%	–13.3%	–55.5%	–35.4%	–63.1%	–44.4%

1. Data sources for 1895 and 1932 were incomplete below Portland, so flood-plain slices 1–16 are excluded from all years in this table.

Table 3 Summary of changes in channel characteristics for the Willamette River from 1850–1995

	Channel complexity[1]			Forest bank complexity[2]				Structural complexity[3]	
	Single channel	Multiple channel	Tributary junction	Unforested riverbank	One bank forested	Both banks forested	Total thalweg length (km)	Number of structures	Length of structures (km)
Lower reach (km 1–51; Columbia R. to Newberg)									
1850	63,521	7,662	3,876	2,150	32,027	40,883	75.1	0	0.0
1995	61,501	10,098	3,285	38,893	29,139	6,852	74.9	138	62.4
Percent change	–3.2%	31.8%	–15.3%	1709.3%	–9.0%	–83.2%	–0.2%	–	–
Middle reach (km 52–151; Newberg to Albany)									
1850	88,321	24,022	2,562	1,604	38,188	75,113	114.9	0	0.0
1995	79,519	29,115	3,458	21,983	59,700	30,409	112.1	117	35.3
Percent change	–10.0%	21.2%	35.0%	1270.6%	56.3%	–59.5%	–2.4%	–	–
Upper reach (km 152–227; Albany to Eugene)									
1850	37,954	82,758	3,815	0	25,679	98,848	124.5	0	0.0
1995	72,194	30,355	3,003	44,653	47,771	13,127	105.6	113	57.3
Percent change	90.2%	–63.3%	–21.3%	–	86.0%	–86.7%	–15.2%	–	–
Total (km 1–227; Columbia R. to Eugene)									
1850	189,796	114,442	10,252	3,754	95,894	214,844	314.5	0	0.0
1995	213,214	69,569	9,745	105,530	136,610	50,389	292.5	368	155.0
Percent change	12.3%	–39.2%	–4.9%	2711.4%	42.5%	–76.5%	–7.0%	–	–

1. Channel complexity is the length of thalweg in meters associated with either single channels, multiple channels, or a tributary junction.
2. Forest bank complexity is the length of thalweg in meters associated with either unforested bank, forest on one bank, or forest on both banks.
3. Structural complexity is the length of thalweg in meters with revetments or other structures along either bank.

Table 4 Summary of changes in riparian vegetation (up to 120 m from riverbank) for the Willamette flood plain from 1850–1995. Totals vary because of an overall loss of channels

	Riparian land cover (ha)					
	Agriculture	Urban	Forest	Wetland	Other Natural	Total
Lower reach (km 1–51)	0	0	1,085	47	743	1,875
1850	102	810	326	2	86	1,326
1995						
% change	–	–	–70.0%	–95.7%	–88.4%	–29.3%
Middle reach (km 52–151)	0	0	3,495	67	1,076	4,638
1850	2,777	437	1,621	99	934	5,868
1995						
% change	–	–	–53.6%	47.8%	–13.2%	26.5%
Upper reach (km 152–227)	0	0	7,019	233	1,846	9,098
1850	4,512	791	1,253	154	1,157	7,867
1995						
% change	–	–	–82.1%	–33.9%	–37.3%	–13.5%
Total	0	0	11,599	347	3,665	15,611
1850	7,391	2,038	3,200	255	2,177	15,061
1995						
% change	–	–	–72.4%	–26.5%	–40.6%	–3.5%

1895 and has not regrown. More detailed analysis allowed determination of the floodplain slices that had the greatest changes. A wide variety of explanatory graphics, tables and maps were produced for a detailed report, and the analysis results were made available for a restoration prioritization model (Hulse et al. 2002, Gregory et al. 2004).

4 Discussion and Conclusions

The main goal for this research was to develop a mapping method to compare flood plain and river channel features across time periods. This was achieved by developing a GIS to create and analyze spatial data from four dates spanning 150 years. While each year had a different source of data, channel and flood-plain characteristics were compared directly over time by creating georegistered river channel and flood-plain vegetation coverages.

The Willamette River flood plain has changed drastically since European settlement, but the magnitude of those changes varies among the upper, middle, and lower reaches. Consistent with Benner and Sedell (1997), it is clear that the number of channels in the flood plain has been greatly reduced. Channel complexity was once highest in the upper reach of the river (from Eugene to Albany), and this is where the greatest simplification has occurred. In addition, flood-plain forests which were prevalent along the river banks in 1850 have all but been removed. In all three reaches of the river, forest bank complexity has been reduced and native flood plain has been replaced with agricultural fields and other human developments. The lower reach, from Newberg to below Portland, saw the least channel change and flood-plain alteration, but this is primarily because this part of the river is topographically constricted and was historically less complex. Much of the channel change and riparian vegetation removal occurred over 100 years ago, during an aggressive period of river modification (Hulse et al. 2002).

The GIS was used to build a model to quantify conservation and restoration potential for each flood-plain slice, based on the calculation of socioeconomic and biophysical indices (Hulse and Gregory 2001, Hulse et al. 2002). The relatively simple model formulation was based on the assumption that the best sites for restoration would be in flood-plain slices that were not overly developed (low socioeconomic value) and had also seen high levels of historical flood-plain complexity (high biophysical value). The model is flexible in that the threshold for suitable slices can be adjusted to suit new criteria. In fact, all 227 slices could be ranked by either index or a combination of the two. While it is highly unlikely that riparian forests and flood-plain channels will be returned to their historical levels of abundance, opportunities exist along the entire length of the mainstem river for either recovery or preservation of existing channel complexity.

This research project was ideally suited to a GIS approach. In fact, it is difficult to imagine how the tasks could have been accomplished without using a GIS. Forgoing the expense of software and training (Harris et al. 1997), the GIS methodology allowed us to characterize fine-scaled landscape details across a large area over four different time periods. There were errors associated with geographic registration, however, those errors were small in relation to spatial misregistration in the original data. As well, there were certainly errors associated with converting the GLO surveys and ACOE river maps and digital orthophotographs into digital line work. While the complete accuracy and reliability of our data remain unknown, our sources were the best available and are acceptable for regional analysis.

Perhaps the greatest advantage of using a GIS for this research was the flexibility of having the data in digital form (Downward et al. 1994, Russell et al. 1997). Using identity and zonal functions in the GIS software, digital summary estimates of length and area were easily manipulated into spreadsheet software to produce graphs and tables, and to generate the restoration indices. Mapping flood-plain change with a GIS enabled the employment of spatially explicit algorithms for more detailed analyses (Muller 1997). An added advantage was the ability to switch the focus of the study rapidly by replacing the slices coverage with one of the other container coverages. In all, there were seven different analysis containers for summarizing flood-plain characteristics. In addition, the digital data are preserved indefinitely and can be re-analyzed repeatedly by different researchers with different analysis goals.

The major shortcoming of the GIS approach has to do with the digitization and registration of the source data, both of which required extensive manual effort. Although some steps were automated, the conversion of spatial information from paper maps to digital form entailed careful manipulation and detailed attention, both of which required skilled technician time and expense.

In summary, the research goals were achieved by the application of GIS techniques to data creation and analysis for a complex historical flood-plain environment. Without the GIS, it would have been very difficult to integrate the wide variety of source data available or to model and query a spatial extent as large as the Willamette River flood plain. The GIS approach enabled the creation of a digital model to evaluate restoration potential, which will allow decision makers to focus their efforts on the most promising sites. While the GIS was not required to characterize historical changes in the Willamette River flood plain, it was definitely the most efficient method available.

Acknowledgments

This work was partially funded by the U.S. Environmental Protection Agency (EPA) and Oregon State University through the Pacific Northwest Research Consortium as part of cooperative agreement #CR824682. Although the research described in this paper has been funded (wholly or in part) by the EPA, it has not been subjected to the Agency's review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred. We are very grateful for the energetic work and scientific support of Bob Peak and Greg Bertrand at the ACOE district office in Portland, Oregon, and Willa Nehlsen at the U.S. Fish and Wildlife Service. Without their incredible efforts to scan and digitize the historical flood and river maps, this project never would have gotten off the ground. Likewise, the dedication of John Christy, Ed Alverson, and Sue Kolar of the Oregon Natural Heritage Program and The Nature Conservancy were critical to the completion of this research, and we are greatly indebted.

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