Historic Channel Changes and Geomorphology Of the upper Yellowstone River, Gardiner to Springdale, Montana

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DRAFT Project Completion Report prepared for Park Conservation District and Upper Yellowstone River Task Force

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By

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Preface

Author's Note: Contractual obligations require that this report also summarize the geomorphic analysis of cumulative effects currently being performed in co-operation with other upper Yellowstone River project participants. This work is being done in support of the U.S. Army Corps of Engineers, Special Area Management Plan development and includes further analysis of geomorphic effects of channel modification and integration of hydraulic modeling results from U.S. Geological Survey, Water Resources Division (Helena, MT—water and sediment models) and Biological Resources Division (Ft. Collins, CO – 2-D hydraulic model). A final project report will be prepared upon completion of those tasks.

Acknowledgments: We would like to thank John Bailey (Task Force Chair), Liz-Galli Noble (Task Force coordinator), and members of the upper Yellowstone River Task Force for their continued interest and support for the project. Many DNRC folks contributed to this project: Dr. Jane Horton provided patient and extensive GIS support along with Kris Hardman. Milt Popovich II provided essential network and computer support. Michael Roberts, Larry Dolan, Paul Azevedo, Mike Lesnik and Rich Moy (DNRC) assisted with fieldwork. Amy Miller, Park Conservation District, (and Liz) cheerfully facilitated landowner access and effectively managed the various grants and contracts that ultimately funded the project. A special thanks to the many Park County landowners who generously provided river access, and to the following agencies who partially funded the work: DNRC Conservation and Resource Development Bureau, U.S. Army Corps of Engineers (Omaha District), U.S. Environmental Protection Agency, and the Park Conservation District.

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Draft Project Completion Report: Historical Channel Changes and Geomorphology of the upper Yellowstone River

By

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Summary

In response to lateral erosion and flooding, caused by 100-year floods in 1974, 1996 and 1997, extensive segments of the upper Yellowstone River have been modified using dikes, levees, riprap, and jetties (barbs). Confinement of river channels by roads, bridges, levees, barbs, and riprap often leads to reduced lateral migration rates, incision of channels, coarsening of the bed, and loss of hydraulic connectivity with side-channels. This investigation (1) mapped the contemporary (1999) fluvial geomorphology of the upper Yellowstone River (85 mile reach from Gardiner to Springdale, Montana) and historic channel changes (1948-1999), (2) developed a process-based geomorphic channel classification (stability and morphology) of the 1999 channel, (3) mapped contemporary and historic (1954, 1973, 1999) channel modifications and revetments, and (4) measured and analyzed retrospective geomorphic effects of channel modifications on channel geometry and hydraulic characteristics (in progress). This draft report presents preliminary findings.

Channel Classification
Contemporary data were collected on: low-water and bankfull-- channel hydraulics (width, depth, slope), channel pattern, and gravel-bar and island characteristics; and low-water--, surface and subsurface particle-size distribution, woody-debris abundance, and natural and human channel confinement. These data were used, in conjunction with information on 1948-1999 channel changes, to develop a modified version of the Montgomery-Buffington channel classification applicable to the upper Yellowstone River. Channel classification provides an objective framework for sampling geomorphic strata, assessing channel stability and channel changes, and for a variety of channel management actions (e.g. permitting, monitoring design).

The classification recognizes seven distinct channel types and the spatial distribution is largely controlled by Paradise Valley, Pinedale glacial history. Pleistocene glaciers, originating from an ice cap in Yellowstone National Park, advanced down the Paradise valley with maximums approximately 20,000 years ago and 130,000 years ago. The Paradise Valley glacial history has strongly influenced the current-day distribution of valley slopes, lateral channel confinement, sediment composition and location of sediment sources--these factors, in turn, largely control the distribution of channel types in the study area.

Very stable, entrenched, *bedrock*, *cascade*, and *plane-bed* channels occur mainly between Gardiner and Mill Creek and have changed little since 1948 (49 % of channel length). *Pool-riffle* and *anabranching* (multiple-thread) channels occur throughout the downstream drainage (40% of length), are more dynamic and locally show significant change in response to the 1974 and 1996-97 floods. *Anabranching/braided* channels are located in several segments between Pine Creek and Mission Creek (11% of channel length) and are the most dynamic with the largest rates of lateral migration and occurrences of rapid lateral change (avulsion). Of the total channel length between Gardiner and Springdale, about 14 % (12 miles) was classified as strongly affected by channel modification (riprap, levees, etc); another 6 % (4.9 miles) was affected by combined natural and human constraints. The most common *Forced* morphology is where anabranching channels are constrained to pool-riffle or plane-bed channels (e.g. main channel near head of Armstrong and Nelson's Spring Creek; Livingston area).

[1] Water Resource Division-Water Management Bureau, , Montana Department of Natural Resources and Conservation. Helena, Montana. 59620

Contemporary and Historic Channel Modification

A Channel Modification and Bank Erosion Inventory was prepared for the upper Yellowstone River from Gardiner, MT to Springdale, MT. Using the NRCS Physical Features Inventory (1998) as a starting point, 1999 aerial photos of the channel from Gardiner to Springdale were viewed in stereo and a variety of adjustments to the NRCS-PFI were made. The CMBEI was edited to include all channel and flood plain modifications (for example, riprap, jetties, barbs, dikes, levees, road prisms) present on the 4-11-1999 aerial photos. Current (1999) channel modifications, by channel type, are shown below:

Upper Yellowstone River: 1999 Channel and Floodplain Modifications by Montgomery-Buffingtion Channel Type – Carbella Bridge to Springdale Bridge.

	Channel/Flood plain Modification		
Channel Type	**Dikes (ft)**	**Riprap (ft)**	**Point-structures (#)**
Anabranch	32,497	31,231	43
anabranch/braided	12,980	22,654	85
Bedrock	5,747	3,718	11
Cascade	7,289	3,987	0
plane bed	9,429	25,219	46
pool-riffle	24,314	24,738	112
TOTAL	92,256	111,547	297

To better understand the history of channel modification and its effects on fluvial geomorphology, a historic inventory was compiled using information from several sources. Historic aerial photos were examined in stereo for the 1954, 1973, 1976, and 1987 photo series, and modifications were mapped on the associated channel mosaics for each year. Linear channel and flood plain modifications (e.g. dikes, levees, road prisms) have increased 265% (from 34,700 to 92,250 feet) between 1954 and 1999, while riprap increased 400% (from 27,400 to 111, 260 feet) and point structures (i.e. jetties and barbs) increased 600% (from 47 to 292). About 50% of the riprap and 80% of the point structures are located along pool-riffle, anabranching, and anabranching-braided channel types that comprise 50% of the study area.

The historic time-sequence of channel modifications was mapped for eight geographic regions: 1) Gardiner to Carbella Bridge; 2) Carbella Bridge to Eight Mile Creek; 3) Eight Mile Creek to Pine Creek Bridge; 4a) Pine Creek Bridge to Carters Bridge; 4b) Carters Bridge to I-90 Bridge; 5) I-90 Bridge to RR-Bridge; 6) RR-Bridge to Shields River; and 7) Shields River to Springdale).

Information is summarized, for the channel extending from the Pine Creek to the I-90 Bridge (for the years 1954, 1973, 1987 and 1999) below:

Upper Yellowstone River Channel and Floodplain Modifications
I-90 Bridge to Pine Creek Bridge: 1954, 1973, 1987, 1999

	1954	**1973**	**1987**	**1999**
dikes/levees*	11912	36554	34702	45204
riprap	3688	22132	30114	32684
Total Linear (ft)	**15600**	**58686**	**64816**	**77888**
Barbs, jetties, etc. (no. of points)	**19**	**45**	**36**	**129**

* includes road-fill prisms that restrict lateral movement or flooding

The I-90 Bridge to Pine Creek Bridge segment is not representative of the entire study area, but is of particular interest because it is one of the more dynamic segments of channel and experienced significant channel changes in the 1996-97 floods; the segment also contains portions of the urban area of Livingston, several important bridges, the spring creeks and other areas of high recreational value, and important farm and ranchland.

Historical Channel Changes

Reconnaissance-level, lateral channel changes (1948/49 to 1999) were estimated by digitizing the centerline trace of the low-water channel on the partially rectified channel mosaics for those years. Accuracy of the digitized centerline trace, limits detection of lateral changes to a range of about ± 20 feet to ± 50 feet. The digitized channel traces were overlaid in a GIS and areas of low (or no) change were identified by the close agreement of the two lines. Channel locations where the lines diverged greater than 50 feet were identified for further data collection and analysis. Extensive channel modification (e.g. bank stabilization and flood plain constriction) over the last 50 years, has locally constrained the channel and floodplain, but the overall stability and general physical characteristics of about 80% of the 85 mile Gardiner to Springdale study area remain similar to those of the Yellowstone River in 1948.

Comparison of 1948-49 and 1999 main-channel, low water, centerline length (Gardiner to Springdale), shows that channel length has remained essentially constant, although lateral channel position has changed remarkably in some areas (especially anabranching/braided channels) -- an indication of maintenance of a relatively stable channel slope. The largest change was a 2% reduction in length of the channel segment extending from Carbella to Eightmile Creek. A similar comparison of the change in length and type of side channels, found between Gardiner and Springdale, shows that the total length has increased by about 16 % between 1948-49 and 1999.

Effects of Fires and Floods

Large floods (~100 yr or greater R.I. events) have occurred in 1894, 1918, 1974, 1996, and 1997 the upper Yellowstone basin. The standard model of channel response to large floods indicates that other factors being equal, large floods may be more likely to cause lasting channel changes in narrow steep valleys, than in broad, low-gradient valleys. The upper Yellowstone River deviates from this model of channel response, with most flood related channel changes occurring in multiple-thread and pool-riffle channel types that are relatively unconfined and of lower gradient, compared with plane-bed and cascade channel types dominant in the upper basin (Gardiner to Mill Creek) where the channel is the most entrenched and confined by fluvio-glacial terraces. A likely explanation for this deviation is that in spite of the lateral confinement and increased flood power, the resisting forces (e.g. very coarse bed material) in the channel bed and banks remain dominant.

The Yellowstone wildfires of 1988 covered an extensive portion of Yellowstone National Park that contributes runoff to the downstream study area. The 1988 fire affected about 20% of the watershed upstream from Livingston, and this upper elevation part of the basin provides about 80% of the annual runoff measured at Livingston. Wildfire can significantly increase runoff and affect sediment yields for several years following a fire. Research (Ewing 1996) indicates that the effects of the 1988 fires on runoff and were localized and did not produce measurable changes in flow characteristics of the Yellowstone River at Corwin Springs, MT. Analysis of the effects of the 1988 fires on upper Yellowstone River runoff (Phil Farnes, written communication 2002) shows post-fire effects may have lead to a small increase (~5 to 7%) in the 1997 flood peak at Livingston for a duration of one day—the corresponding geomorphic effect of this increase is not significant. Although the 1988 fires did have a significant effect on post-fire suspended-sediment loads and turbidity at Corwin Springs and in the Lamar basin (Ewing 1996), the effect on downstream channel morphology and stability was negligible. Potential effects of the 1988 fires on coarse-sediment supply to the downstream channel network was evaluated by several retrospective analyses including, interpretation of pre and post-fire aerial photos (1983, 1987, 1991, 1999), examination of channel deposits, and analysis of long-term stream gaging records (USGS station at Corwin Springs) – no evidence of downstream effects was found.

Channel changes in the 1974 and 1996-1997 floods occurred primarily through lateral erosion in pool-riffle channel segments and through avulsion and lateral erosion in anabranching channel segments. It appears that a channel response model for these segments of the upper Yellowstone includes relatively rapid lateral changes through avulsion in large events (e.g. 50 to 100 year floods), which establish the dominant lateral channel configuration. Between these events, more frequent flows with return periods close to the conventional "bankfull" discharge (e.g. 2 to 5- year floods) shape and maintain the average characteristics of the individual anabranches.

Effects of Channel Modification

Within the 12 miles (20 km) of channel affected primarily by man, local channel response includes channel incision and aggradation (Livingston area), reduced lateral migration, and modification of channel alignment. In spite of these modifications, the channel is remarkably resilient due largely to the coarse bed and bank material and the fact that channel confinement in most reaches is generally limited to one bank and has not always effectively constrained the channel in large floods. Retrospective analysis of 1948 to 1999 spatial distribution and type of side-channels shows a net increase in side-channel length and maintenance of river/floodplain connectivity in all but the Livingston urban area that is frequently rip-rapped and/or leveed on both banks.

Detailed mapping of lateral channel changes (1948-49 to 1999) and preliminary sediment budget analysis shows that primary sources of coarse sediment to the upper Yellowstone are from within the channel and include large (long, high) banks, lower relief floodplain areas (with large lateral erosion rates) and, banks of "bankfull" islands. While the general channel pattern and slope have remained similar for many channel segments, channel modification has locally affected channel width and slope and may have contributed to channel incision in strongly constrained channel segments. The influx of coarse sediment generated by the 1996-97 floods, may currently provide sufficient sediment to temporarily offset channel incision tendencies induced by channel modifications established in the 1990's.

Preliminary analysis indicates that at low flow, substantially revetted or laterally confined channel reaches (partial bedrock control) are somewhat narrower and steeper than similar channel types lacking confinement. In addition, unit stream power (as measured by USGS-BRD), a measure of energy expended in the channel, is highest in channel segments controlled by bedrock or extensively revetted. Examination of channel characteristics above and below, and before and after, construction of the 14 bridges that cross the upper Yellowstone, shows that bridge effects on channel processes range from small (e.g. Corwin Springs) to large (I-90 and near Shields River) -- the most common effect being floodplain constriction and upstream aggradation.

A one-dimensional, step-backwater hydraulic model was developed (USGS-WRD) for flood plain delineation and can also be used to evaluate historic effects of channel confinement on water-surface elevations of floods (USGS-WRD). A sediment-transport model developed by USGS-WRD can be used to examine potential cumulative effects, of different channel hypothetical stabilization scenarios on channel characteristics and stability. The USGS-BRD has developed a 2-D hydraulic, fish-habitat model for selected channel segments and this can also be used as part of an integrated analysis of channel modification effects on channel hydraulics and morphology.

Information collected on historic channel changes and channel modification (below) is being integrated to provide an analysis of how the Yellowstone River has changed over time and in response to historic channel modification. Detailed information collected on historic channel changes and historic channel modification provides the basis for developing case histories of channel modification and the associated channel response. Hypothesis tests and other statistical methods, applicable for comparison of control and treatment populations, are being used to assess the historic effects of channel modifications (work in progress). Hydraulic information recently provided by USACE and USGS-BRD, are being used to supplement that provided by USGS-WRD, and the combined information will be used to compare hydraulic geometry of modified and unmodified channel reaches.

I. Contemporary and Historic Channel Mapping

Introduction

The Upper Yellowstone River project area includes the valley bottom, flood plain and river channel that extends from Gardiner, MT to Springdale, MT--a valley distance of about 80 miles (Figure 1). Channel and flood plain mapping and analysis of historic channel processes and changes were conducted at varying scales and levels of detail within the overall study area. Through a cooperative effort, sponsored by the Upper Yellowstone River Task Force, mapping information for cumulative effects analysis (CEA) was collected at several spatial and temporal scales. Table 1. summarizes the information and some of its uses by the geomorphology project. Topographic and orthographic mapping (Table 2) of the river channel and flood plain provided the basic framework for describing contemporary river channel and flood plain attributes and evaluating historic channel changes. The mapping also provides an excellent framework for monitoring future channel changes. Contemporary orthophotography, at small (1:24,000) and large (1:6000 to 1:8000) scales, was used as a base to map and describe a variety of physical channel features. Partially rectified, digital channel mosaics for key historic years was used to map historic channel changes; time-sequence, topographic maps were prepared for several large eroding banks to facilitate estimates of historic erosion rates and volumes (see Appendix A for a more complete description of channel mapping methods).

1999 Project Orthophotography and Topographic Mapping

Through a cooperative effort of the Task Force, Park CD, USFS, DNRC and USACE, contemporary aerial photos were acquired on April 11, 1999. One-meter pixel resolution, black and white, orthophotos at a scale of 1:12,000, were prepared for the channel corridor between Gardiner and Springdale by U.S. Forest Service, Region 1-Geospatial Data Section. Higher resolution (0.2 meter pixel resolution) 1:8000 scale, black and white and 1:6000 scale color (Carters Bridge to Livingston) orthophotos were provided by USACE (contractor Surdex) along with supporting digital terrain models and topographic contours. All map products and field surveys were referenced to the Montana State Plane, North American Datum of 1983 (feet) and the North American Vertical Datum of 1988 (feet) (see Appendix A for methods).

Historic Aerial Photo Inventory and Channel Mosaics

Partially rectified digital photo mosaics were prepared (by contractor) for the historic aerial photos listed in Table 3. Historic coverage of most of the Gardiner to Springdale channel corridor was obtained for 1948/49, 1954, 1965, 1973, 1976, and 1991 (additional partial coverage was obtained for 1943, 1983, 1987 and 1988). Key years selected for historic geomorphic analysis are 1948/49, 1973, 1976, and 1991. The analysis presented here focuses on changes between channel features in 1948-49 and 1999. (See Appendix A for methods).

Table 1. Primary sources of mapping information used by Geomorphology Study.

Item	Source	Date	Geomorphic Use
Historic Channel Mosaics and Topographic Mapping	Positive Systems, Inc; Horizons, Inc	Sep 2002	Map time-sequence of historic channel modification. Map physical channel changes over time; estimate historic erosion rates from large banks
Physical Features Inventory[1]	NRCS/ DNRC	Oct 1998	Location and description of channel modifications; selection of sites for comparison and evaluation of channel changes
Park Co. Soil Mapping	NRCS	Dec 2002	General characterization of flood plain soil and bank material for channel classification; geomorphic floodplain delineation and sediment budget analysis
MBMG 1:100,000 Geologic Mapping	MBMG	2002	Channel description and classification
STAR3i Radar Imagery	YCES/MSU	2000	Glacial geology; physical watershed characteristics and channel classification; evaluation for use in lower Yellowstone River Basin
1:24000(1999) orthophotos[1]	USFS	Nov 2000	Channel description and classification (Gardiner to Point of Rocks; Mission Cr. to Springdale)
1:6000 and 1:8000 orthophotos (1999)[1]	USACE	Oct 2001	Channel description and classification (Point of Rocks to Mission Creek); channel geometry data; sediment budget; control for historic photo mosaics
1:6000 and 1:8000 topographic maps (1999) [1]	USACE	Oct 2001	Channel description and classification (Point of Rocks to Mission Creek); channel geometry data (width, slope); sediment budget
1:24,000 scale NWI[1]	USFWS	Sept 2001	Channel description and classification
Channel Geometry[1]	USGS-WRD USGS-BRD	2002-2003	Channel description and classification ; empirical measures of channel geometry change; sediment budget
Riparian Trends[1]	UM	2002	Pre-1948 rates of fluvial processes ; flood plain turnover / sediment storage / sediment budget
Channel Profile/Detail[1]	DNRC-WRD	Dec 2001	Detailed GPS-channel survey Mallards Rest to 9th Street Bridge; Channel description and classification ; sediment budget

[1] Work conducted as part of (or in support of) Upper Yellowstone River Cumulative Effects Investigation

Table 2. Contemporary Orthographic and Topographic Mapping

Channel Segment	Orthophoto			Topography	
	B&W 1:24000	B&W 1:8000	color 1:6000	1:8000 (4 ft. c.i.)	1:6000 (2 ft. c.i.)
Gardiner to Springdale	X				
Point of Rocks to Carters Bridge		X		X	
Carters Bridge to Boulder Road			X		X
Boulder Road to Mission Creek		X		X	

Table 3. Historic Upper Yellowstone River Photos

Year	Scale	Source	Emulsion	Est # photos
1943	~1:20,000	Nat'l Archives(Dept. Army)	BW	20
1948-49	1:37,400 1:20,000	USGS Denver	BW	89
1954	1:15,840	Natl Archives	BW	95
1965	1:20,000	NRCS Slt Lk	BW	77
1973	1:15,840	MDT Helena	BW	95
1976	1:24,000	USACE Omaha	BW	74
1987	1:6,000	MDT Helena	BW	30
1991	1:40,000	USGS-NAPP	BW	40

II. Geomorphic Channel Description, Mapping and Classification.

Introduction

Geomorphic classification of the Upper Yellowstone River provides a framework for understanding the relationship between the form and condition of the channel and the physical and biological processes that shape and maintain its bed, banks and island complexes. A variety of channel classification schemes are available for describing the fluvial geomorphology of river channels (Kellerhals et al. 1976; Rust 1978; Naiman et al. 1992; Nanson and Croke 1992; Rosgen 1994; Kondolf 1995; Poole et al. 1997; Montgomery and Buffington 1993, 1997). Each classification scheme has advantages and disadvantages and several schemes were applied to the Upper Yellowstone River (including the Montgomery Buffington; Nanson and Croke, and Rosgen); only the Montgomery-Buffington Classification, as modified for this investigation, is given here. The classification presented serves as a basis for:

1). Identifying homogeneous channel segments (similar 'channel types' and sequences of occurrence) and their overall relationship to the channel network up and downstream.
2. Assessing the relative vertical and lateral channel stability of homogeneous channel segments.
3. Identifying geomorphic strata from which representative samples can be extracted for further detailed study.

Sampling Strategy

Geomorphological information was collected at four spatial scales in the Upper Yellowstone River Basin:

1) **Study Area:** Physical channel characteristics (channel classification) and historic channel changes of the entire Yellowstone River from Gardiner, MT to Springdale, MT were described at a reconnaissance level.

2) **Detail Study Segments**: Detailed mapping of channel characteristics and analysis of channel processes was performed within 12 designated Geomorphology Detail Study Segments.

3) **Detail Study Reaches**: More detailed mapping of channel characteristics (gravel-bars, islands, bed-material size distribution, LWD amount, etc) and historic channel changes was conducted for selected reaches located within Study Segments (most emphasis for field data collection was between Mallards Rest and Livingston, although other areas were examined -- Plates 5 to 12).

4) **Data Collection Sites**: Information collected at specific points, in support of both the Reconnaissance and detail-level analyses.

Geomorphology Detail Study Segments (Geosegments):
Detail Study Segments (Figure 2 and Table 4) were selected to provide:

1. Representative sample of various channel types
2. Framework for sampling channel reaches with low, medium or high level of channel modification
3. Control for isolating upstream/downstream influences (e.g. fire effects)
4. Coverage of problem segments of interest to Task Force and regulatory agencies
5. Coverage of channel segments of interest to hydraulic, riparian, or fish researchers.

Geosegments were delineated to include the active flood plain and adjacent area that may contribute sediment directly to the channel; the boundary shown is approximate and subject to revision based on more careful stereo photo interpretation (and soil mapping and hydraulic data). Detail study segments are of varying length and comprise about 70% of the 80-mile study area.

Table 4. Upper Yellowstone River Geomorphology Study (Geosegments) Segments

Segment	Name	Length (ft; mi)	Data Collected
1	Corwin Springs	15,600 2.9	A
2	Miner	11,200 2.1	A
3	Point of Rocks	14,000 2.7	A
4	Emigrant-Chicory	34,500 6.5	A
5	Mill Cr.-Loch Leven	39,800 7.5	A
6	**Mallards Rest-Pine Creek**	**22,400 4.2**	**A, B**
7	**Pine Creek-Depuys**	**33,200 6.3**	**A, B**
8	**Depuys-Carter Bridge**	**8,000 1.5**	**A, B**
9	**Carters Bridge-Fairgrounds**	**25,000 4.7**	**A, B**
10	Fairgrounds-Ferry Creek	19,000 3.6	A,
11	**Shields R.-Windsor Ranch**	**38,000 7.2**	**A,**
12	Elton-Springdale	40,000 7.6	A,
		6.8miles	

PRIMARY DATA

A. Development of longitudinal channel profile. Delineation of low- water main channel and side channels on 1948-49 and 1999 photo mosaics; delineation of sediment sources (eroding banks) on 1999 photo mosaics.
B. Delineation of low water and bankfull channel features (bank or water line, islands, gravel bars) in 1948-49 and 1999; mapping of LWD.
C. Selected reaches only (6,7,8, 9, 11)--detail historic channel changes from plan maps developed from historic channel mosaics. Estimation of morphology-based sediment budget where data allows.

Channel Description and Mapping

General Methods

Delineation and mapping of fluvial features was accomplished primarily through stereo interpretation of aerial photography. This interpretation was supplemented by project topographic mapping, field survey (GPS) and geomorphic mapping. Descriptive and interpretative mapping information was compiled into a Geographic Information System for analysis. Channel and flood plain features mapped are given in Table 5. Emphasis was placed on mapping and description of hydraulic units, gravel bars, islands, sediment sources and availability, bed and bank-material, channel modifications, woody debris, and civil works.

Table 5. Contemporary (1999) and Historic* Channel Features Mapped

Active Channel	Floodplain/Valley Flat
Waters edge* (date of photos)	**Terraces**
Channel bank line* -main channel* -side channel(s)* -cutoffs/avulsions*	**General Vegetation**[1] -grassland -shrubs -woodland (conifer/cottonwood)
Gravel bars* -point* -lateral/alternate* -mid-channel/ diagonal*	**Levees and Dikes** *(natural and man made)
Hydraulic units -thalweg (est.) -pools -riffles/rapids/plane bed -aquatic habitat units (USGS-BRD)	**Paleohydrology/Channels** -old channels (Pleistocene/Holocene) -Glacial deposits -cutoffs/oxbows -meander scrolls
Islands/multiple bar complexes -vegetation (bare, grass/shrub, woodland)	**Soils** (and other relevant resource data available in GIS coverages ?)
Sediment Sources and Availability	
Bed-material type -boulder/cobble/gravel/sand	
Structural bank/channel Modifications* -riprap,jetties, grade controls -alternative (organic revetments, cars etc.)	
Channel Obstructions/Debris* -Large woody debris -Bedrock	
Civil Structures* -bridge works* -irrigation diversions (intakes, head gates, pumps)	

*Where historic photo scale and resolution allow

Information required for channel classification was obtained through field mapping on 1:24000 scale orthophotos, interpretation of 1; 24,000; 1:8000; and 1:6000 scale, stereo air-photos, and other sources (Table 1). Channel slope and profile data were developed for the upper part of the study area (Gardiner to Point of Rocks) from elevation data collected by the U.S. Forest Service in preparation of the 1999, 1:24000 scale orthophotos. Channel slope and profile data for the study area segment extending from Point of Rocks to the Shields River were extracted from the 1:6000 scale (2-foot contour interval) and

1:8000 scale (4-foot contour interval) topographic mapping. Interpretative information on channel pattern, natural confinement, sediment sources, gravel-bars, and large-woody debris was acquired through a mixture of fieldwork, stereo photo interpretation, and GIS analysis of the 1999 orthophotos and topographic mapping. (See Appendix B. for details on channel description methods.)

Bankfull and low-water channel features

Channel features (bank or water line, gravel bars, and islands) were mapped at the estimated bankfull discharge (~20,000 cfs) and at the low-flow discharge (~1500 to 5000 cfs) at the time of the aerial photography. The centerline trace of the low-water channel was also mapped for use in reconnaissance-level analysis of historic channel changes and development of a low- water channel profile.

Bankfull features for 1999 were mapped based on stereo photo interpretation of 1:6000 and 1:8000 scale aerial photos, field survey and visual observations. The delineation of features was also guided by the project topographic mapping, which also allowed estimation of the bankfull water surface elevation. Comparison of the estimated bankfull channel elevation with the water surface elevation at a discharge of 18,000 to 20,300 cfs (approximately 2 to 5 year recurrence interval floods) showed reasonable agreement in about 90% of the channel area mapped (see Appendix B. for detailed description of mapping methods).

Bankfull channel features (e.g. bankline, bankfull islands) and low- water channel features (e.g. waters edge, islands, gravel bars) were mapped for Geosegments 6,7,8, and 9/10[2] using the 1948-49 and 1999 aerial photos and channel mosaics. Channel features were mapped into a GIS as attributed polyline and polygon data to facilitate subsequent analysis of feature change (e.g. erosion, deposition, stable or no change) over the 1948-49 to 1999 time period.

Bed-Material Description

The texture and size-distribution of riverbed sediments are important variables that influence the quality of fish habitat, distribution of riparian growing sites, hydraulic roughness, particle entrainment, channel stability, and sediment transport. Accordingly bed-material was sampled using several methods. The focus of the sediment description was to provide information for geomorphic channel description and classification, geomorphic analysis, and data for use in sediment-transport modeling (USGS-WRD).

Surface bed-material size distribution was measured through the use of "pebble-counts" at 40 locations. Subsurface-size distributions were measured at eight sites. Additional reconnaissance-level mapping was done using the methods of Montgomery and Buffington (1998). Data collection was focused in the Pine Creek to Carter's Bridge reach and provided to USGS -WRD for use in sediment transport model. The upper Yellowstone River has a coarse, cobble-gravel, bedded channel for most of its length within the study area (Figure 2a). Particle size varies at the reach scale in pool-riffle sequences and along individual gravel bars (Figure 2b). Broad-scale variation occurs between Gardiner and Springdale, with coarser cobble-boulder sediments predominate upstream from Mallards Rest. Downstream sediment sources fine somewhat (gravel-cobble), however particle size remains coarse downstream, fining somewhat between Livingston and Mission Creek and then coarsening as bedrock is encountered upstream of Springdale (see Appendices C, D and E for detailed methods and data).

Channel Slope and Profile

The longitudinal profile of the upper Yellowstone River between Gardiner and the Shields River confluence (Figure 3) was separated into 11 segments of similar slope and ordinary least-square regression lines were fit to each segment to estimate its average low-flow, water-surface slope. Average channel slope ranges from 0.0011 (plane bed channels near Tom Miner Cr) to 0.0038 (Yankee Jim Canyon and Gardiner area cascade channels). Preliminary analysis of profile characteristics indicates that

[2] The Livingston area including the lower part of Geosegment 9 and upper portion of 10

plane-bed channels display the smallest variation in slope with bedrock-cascade (Yankee Jim Canyon) and externally forced (revetment or bedrock) channels having both the greatest variation and highest slopes (as high as 0.01). Geomorphology Detail Study Segments 1-11 (Figure 2) adequately sample all of the slope environments, with the exception of the bedrock-cascade reaches between Gardiner and Tom Miner Creek and the Shields River and Springdale—reaches not relevant to this investigation (see Appendix B for methods).

Field-survey (GPS) data for a detailed channel profile were collected between September 10 and 27, 2001 (Q range at Livingston 1160 to 1360 cfs). GPS observations were taken to provide information for several purposes channel profile, bank erosion mapping, estimation of bankfull stage (usually not "bank-top"), and locating various features of interest. *NOTE: A detailed channel profile based on the GPS survey, USGS and USACE cross-section survey data, and USGS-BRD 3-D topography (several channel segments between Mallards Rest and Livingston) is being compiled for the channel segment extending from Mallards Rest to Livingston).*

Sediment Sources and Availability

Sources of coarse sediment that contribute to the bed-material load of the Upper Yellowstone River were mapped and classified as external or internal. External sources are those that can be considered independent of main stem channel processes on a time scale of perhaps 25 to 100 years; external sources include tributary inputs (relative importance indicated by tributary size, channel, sediment and delta characteristics) and historic and contemporary mass wasting along terrace or hill slopes proximate, but not in direct contact with the active channel. Internal sources include bank erosion through fluvial entrainment and mass wasting, gravel-bars that serve primarily as storage elements, with varying residence times, and entire channel reaches that are primarily sediment storage/source zones. Channel survey and photogrammetric methods were used to estimate the time-series of sediment production from 7 large eroding banks. Internal sediment production from within the channel was found to be the dominant source of coarse sediment (bed material) to the channel[3].

Bed and bank material type were described using qualitative methods. Qualitative description was accomplished through field reconnaissance and mapping from large-scale aerial photos. Bank material was generally classified into broad units based on the dominant size of material and the bank structure (e.g. simple/composite) using the Montgomery-Buffington Textural Classification. *NOTE: The current erosion status and importance as a sediment source, is being determined for the 1999 eroding banks identified in the CMBEI (2002). Banks are being stratified by rate of retreat, bank height and material type*.

Large Woody Debris

Large woody debris (LWD) may have a significant affect on channel morphology, channel stability and aquatic habitat diversity of the upper Yellowstone River. Large elements or accumulations of LWD may influence channel processes in several ways. Primary affects include alteration of the local hydraulics of in-channel flows leading to modified patterns of local scour and deposition and altered channel geometry and roughness. Secondary affects include influences of LWD on reach-scale channel dimensions and roughness, the distribution of overbank flows, and bank erosion (Lisle 1995; Piegay and Gurnell 1997; Piegay et al. 1999).

Information on LWD was collected by digitizing the trace of individual pieces of LWD as shown on the 1:6000 and 1:8000 scale, 1999 orthophotos (Figure 3a). At the scale of the photos, the minimum diameter of LWD recognizable was about 0.5 ft. Statistics on the number of individual pieces and their length was compiled in a GIS for analysis of spatial distribution and abundance. *NOTE: The spatial*

[3] The Shields River may be an exception.

distribution and abundance of LWD is being determined by channel type, and analysis of LWD characteristics in modified and unmodified channels is being analyzed.

Topographic Mapping of Large Eroding Banks

Historic erosion rates and volumes were analyzed for seven large eroding banks (Table 6) located along the upper Yellowstone River between Livingston and Corwin Springs, Montana. To facilitate the analysis, topographic maps were prepared for 1948/49, 1973, 1976, and 1991) at each of the sites. Ground control points were established to control the historic photo sequence at each site and a topographic mapping contractor prepared digital terrain models (DTM) and contour maps of the seven selected sites. These DTMs were then used to estimate the progressive amounts of erosion and volumetric contributions for each time period and site.

Table 6. Map Areas for Historic Topographic and Planimetric Channel Mapping

	Years:1948/49 ; 1973; 1976; 1991		**Total Planimetry and Contouring**	
Eroding Bank Location	**Planimetry (Acres)**	**Contouring (Acres)**	**Planimetry (Acres)**	**Contouring (Acres)**
Corwin Springs (north of bridge)	14	6	56	24
Mallard's Rest (downstream l.bank)	29	12	116	48
Pine Creek (Upstream from bridge)	34	12	136	48
Weeping Wall	45	22	180	88
Deep Creek Area	51	10	204	40
O'Haire/Dana Spring Creek Area	--	100	-----	400
Trail Creek Area	45	12	180	48

Side-Channel classification and mapping

Side channels of the upper Yellowstone are associated with the pool-riffle, anabranching, and anabranching/braided channel types. Over 50% of the study area in plane-bed, cascade and bedrock types are single-thread and have lateral processes so minor that side channels are seldom formed.

Because side-channels were identified as important fishery resources and their connection to the main channel could be affected by channel modifications, the type and abundance (length) of side channels were mapped (Gardiner to Springdale) for assessment of changes between 1948-49 and 1999. Of particular interest is how the abundance (length by type) may have changed as a function of sequential channel modifications over time.

The trace of side channels shown on the 1948-49 and 1999 photo mosaics was digitized and channels were classified into one of 11 types (Table 7) for each year (Figure 3b. and Plate 13). The side-channel classification developed for this study is process-based and distinguishes primarily between side channels associated with gravel bars in the active (e.g. bankfull) channel and lateral side channels that are less dominant anabranches in multiple-thread channel reaches. Side channels associated with active gravel bars generally are "younger", shorter, have less bank vegetation, and at a given river stage tend to carry more flow than the lateral side channels. Lateral side channels are somewhat distal to the main channel and are associated more with the flood plain than the active channel--although the inlet channel is located within the active channel area.

Classification of side channels is somewhat flow-dependent and could also be done on the basis of frequency, duration and magnitude of streamflow in the channels (USGS-BRD hydraulic habitat analysis may provide this information for part of the study area). While this classification is not directly flow dependent, comparisons of the amount and spatial distribution of side-channel types over time requires that flows be similar for comparison periods or that flow variation be accounted for (see Appendix B).

Table 7. Upper Yellowstone River Side-Channel Classification

Side Channel Type	Fluvial Environment	Description	Flow condition Descriptors *
Sidegb	Active channel	Associated with gavel bar	No suffix=surface flow continuous with main channel bw=ponded back water not connected with main channel dry=no surface water present
Sidegbbw	Active channel	Associated with gavel bar	
Sidegbdry	Active channel	Associated with gavel bar	
Sidemidgb	Active channel	Associated with mid-channel of gravel bar	
Sidemidgbbw	Active channel	Associated with mid-channel of gravel bar	
Sidelat	Active channel/ flood plain	Lateral channel anabranch/ cut off channel	
sidelatbw	Active channel/ flood plain	Lateral channel anabranch/ cut off channel	
sidelatdry	Active channel/ flood plain	Lateral channel anabranch/ cut off channel	
Sidelatspr	Flood plain	Lateral channel/ spring creek	
Sidelatfp	Active channel/ flood plain	Side channel/ converted to fish ponds	
Sidelatirr	Active Channel/ flood plain	Side channel incorporated into irrigation diversion / water conveyance	

*suffix added to channel type attribute (e.g. sidegbdry or sidegbbw) to reflect general streamflow in side channel at time of historic aerial photography

Geomorphic Channel Classification

The process-based channel classification developed by Montgomery and Buffington (1993; 1997) synthesizes stream morphologies into seven distinct channel types on the basis of bed-material size, bedform and channel pattern, dominant roughness elements and sediment sources, sediment storage, confinement, and relative pool spacing. In addition to recognizing distinct channel morphologies and the processes associated with their formation and maintenance, the Montgomery-Buffington Classification also recognizes the organization of channel types into sequences that reflect their process-based roles in the channel network: sediment source reaches, transport reaches and response reaches. Further consideration is given to whether bed-material transport in channel reaches is transport or supply limited[4] and the effects of external forcing by confinement (e.g. bedrock), riparian vegetation, and woody debris (Montgomery and Buffington 1993; 1997). Predominately alluvial channel reaches partly affected by natural obstructions (e.g. bedrock) or alluvial reaches significantly affected by bank stabilization were delineated as a special class of externally forced channel morphology. Channel types were assigned based on the criteria given in Table 8.

The MB classification, which has been primarily applied to small, forested mountain watersheds in the Pacific Northwest, was modified to better apply to the upper Yellowstone River and an anabranching channel type was added to accommodate the multiple channel-island configuration channels. Channel types were assigned to 58 channel segments along the 86.8 mile channel length between Gardiner and Springdale, MT (Table 9.) Channel segments varied from about 0.2 miles to 7 miles in length, with most in the range of about 0.3 miles to 1 mile (Figure 4); a more detailed classification is shown on map Plates 1 to 4.

Table 9. Distribution of Predominate* Channel Montgomery-Buffington Channel Types In the Upper Yellowstone River Basin between Gardiner and Springdale, MT

Channel Type	Length (Miles)	Percent of Total Length	Example Occurrences
Bedrock	5.0	5.8	Yankee Jim Canyon; east of Livingston and downstream
Cascade	9.6	11.0	Gardiner to Corwin Springs
Anabranching/ Braided	9.4	10.9	Portion of Spring Creek Area; Downstream Shields River; Mission Cr area
Anabranching	13.6	15.7	Upstream Emigrant Bridge; Livingston area; Spring Creeks
Pool/Riffle	20.9	24.0	Pine Creek area
Plane Bed	28.3	32.6	Mill Creek area
Total	86.8	100	
Channel Affected by Human (e.g. riprap) or Combined Human and Natural (e.g. bedrock) Forcing			
Human	11.8	13.6	Livingston Area
Combined Natural And Human	4.9	5.6	Allenspur area/ bedrock and revetment
Total	16.7	19.2	

* This information condensed from a more detailed delineation that includes combined channel types (e.g. an/pr) and effects of forcing.

Glacial Geology and Distribution of Channel Types

Pleistocene glaciers, originating from an ice cap in Yellowstone National Park, advanced down the Paradise valley with maximums approximately 20,000 years ago (20 ka--Pinedale)[5] and 130,000 years ago (130 ka--Bull Lake) (Pierce 1979). The maximum northern extent of the most recent (Pinedale)

[4] In transport-limited reaches the bed-material flux is limited only by the energy available to transport material. In supply limited reaches the bed-material flux is limited by the amount of material available for transport.

[5] New cosmogenic ages yield more recent ages than radiocarbon ages given here. Eightmile moraines are 16.5 ± 0.4 ^{3}He ka and 16.2 ± 0.3 ^{10}Be ka, and Chico moraines are 15.7 ± 0.5 ^{10}Be ka. Basalt flows above the floor of valley are 2.2 Ma and may date from the start of the Yellowstone volcanic field (pers. comm. Ken Pierce, USGS).

advance was the vicinity of Eightmile Creek and Chico, where well developed terminal moraines comprised of, poorly-sorted, cobble-boulder till, were deposited by a still-stand of the advancing ice. Subsequently, during de-glaciation about 11,000 years ago (11 ka), the Yellowstone River incised into the coarse glacial till and outwash forming the first set of terraces evident in the valley.

Near Eightmile Creek the glacier formed an extensive outwash fan on the west side of the valley. The surface of the outwash fan terrace is about 200 ft above the present day Yellowstone River at the Eightmile terminal moraines and tapers to about 60 feet above river here near Mallards Rest and 10-20 feet above the river in the vicinity of the Armstrong Spring Creeks. Clarke (1994) attributes the occurrence of the west side spring creeks with the thinning of the shallow aquifer in the outwash.

At some time (as early as 4000 years ago, or late as 14,000 years ago) large catastrophic floods were generated when landslide debris blocked the lower end of Yankee Jim Canyon and impounded water with depths up to 180 feet near Dome Mountain (Pierce 1979; pers. comm.. 2002). The landslide dams were then breached by erosion and released floods that produced down-valley flood depths of up to 30 to 60 feet. The Yankee Jim Canyon Floods left a lasting imprint on the inner-valley surfaces as far downstream as Mill Creek, where flood modified gravels are evident on inset river terraces (Figure 5).

The Paradise Valley is geologically active (the Barney Creek Fault scarp shows 15 ft post-glacial offset). Differential movement along east-side valley faults has resulted in lowering and tilting of the valley (80%) and uplifting of the Beartooth Range (20%). The Yellowstone outlet glacier outwash terrace on the west side of the valley has a northern slope of about 40 ft/mile; the outwash terrace is joined on east by a steeper outwash fan from local glaciers of the Beartooth Range--this outwash surface has a westward slope of 100-150 ft/mile. The present-day Yellowstone River has eroded its valley along this seam between the east edge of the outlet glacier fan and the west edge of the Beartooth outwash.

The Paradise Valley glacial history has strongly influenced the current-day distribution of valley slopes, lateral channel confinement, sediment composition and location of sediment sources--these factors, in turn, largely control the distribution of channel types in the study area. Very stable bedrock, cascade and plane-bed channels occur between Gardiner and Emigrant. Locally several disturbance/sedimentation zones with multiple-thread, or anabranching channels interrupt these. Moderately to very stable, incised to entrenched, single-thread, pool-riffle and plane bed channels occur within much of the channel segment from Emigrant to near Mallards Rest. Downstream from Mallards Rest to Livingston less stable, pool-riffle and anabranchning channels occur and Yellowstone River is classic high gradient (0.005 to 0.001), "wandering", gravel-bed river. In the vicinity of Livingston the anabranching channel is partly constrained (Allenspur to Mayors Landing along east bank) by bedrock (there are occasional occurrences of bedrock throughout the channel downstream from Livingston to Springdale); downstream from Livingston the Yellowstone displays the same channel types as upstream, however a larger portion of the least stable channel type (anabranching/braided) occurs.

Table 8. Geomorphic Classification Scheme Applied to Upper Yellowstone River Channels.

Classification	Channel Type	Natural Confinement	Channel Slope	Pattern	Meander Belt Width	Sediment Texture	Sediment Sources	Sediment Availability	Frequency of Occurrence: *Gravel Bars*	*Large Woody Debris*	*Side Channels*	*Channel Modification*	Channel Stability
Bisson and Montgomery (1996) Montgomery and Buffington (1997)	Bedrock (bed)	High	>0.003	S<1.5	Low	PreCambrian, Paleozoic, or Cretaceous Bedrock	Low	Low (Supply Limited)	Low	Low	Low	Low	Lateral=high Vertical=high
	Cascade (cas)	High	>0.003	S<1.5	Low	Gravel, Cobble, Boulder	Low	Low (Supply Limited)	Low	Low	Low	Low	L=high V=high
	Plane Bed (pln)	Medium High	0.001 to 0.003	S=1.1 to 2	Low	Gravel, Boulder, Cobble	Low	Low (Supply Limited)	Low	Low	Low	Low	L=high V=high
	Pool- Riffle (pr)	Low Medium High	0.001 to 0. 003	S = 1.5-2.5 ?	Medium High	Sand, Cobble, Gravel	Moderate	Moderate / Supply or Transport Limited	Low Mediu m High	Low Medium High	Low Medium	Low Medium High	L=varies V=varies
	Anabranching (an)	Low	<0.002	Multiple Channel	Medium High	Cobble Sand Gravel	High	Transport Limited	High	High	High	High	L=varies V=varies
	Anabranching/ Braided (br)	Low	<0.002	Multiple Channel/ Braided	Medium High	Sand Gravel	High	Transport Limited	High	High	High	High	L=low V=low
	Forced[1] (f)	Varies											

[1] Natural or man-made flow obstructions may force channel types different from the potential type expected for a similar sediment texture, supply rate and transport capacity.

Classification/Description of Contemporary (1999) and Historic Channel Modifications

Channel Modification and Bank Erosion Inventory (CMBEI)
A Channel Modification and Bank Erosion Inventory was prepared for the upper Yellowstone River from Gardiner, MT to Springdale, MT. Using the NRCS Physical Features Inventory (1998) as a starting point, 1999 aerial photos of the channel from Gardiner to Springdale were viewed in stereo and a variety of adjustments to the NRCS-PFI were made: some features were reclassified; spatial extent of features were increased or reduced as appropriate, and new features were added (especially eroding banks). Additional information used to supplement the stereo-photo interpretation included, field notes and mapping done in August and September 2000 and 2001, and the project topographic mapping. As a general rule, the CMBEI was edited to include all features present on the 4-11-1999 aerial photos used for interpretation[6]. Information on the amount and spatial extent of principal 1999 channel modifications (e.g. linear features such as dikes, levees, road prisms; bank revetment (riprap); and point-type structures (barbs, jetties, vanes etc) is given in Tables 10, 11, and 12 (see map Plates 1 to 4 for map presentation of 1999 information).

Historic Channel and Floodplain Modification Inventory
To better understand the history of channel and flood plain modification and its effects on fluvial geomorphology, an historic inventory was compiled. Historic aerial photos were examined in stereo for 1999, (1987 some areas), 1973 and 1954 for the channel extending from Gardiner to Springdale Bridge; channel and floodplain modifications were mapped on corresponding channel mosaics for each year according to eight sub-reaches. Figure 1 shows the Geographic Regions used to compile the channel modification statistics. Tables 10, 11, and 12 and Figures 6, 7, and 8 summarize the results based on the seven Regions (see Appendix F for map presentation of historic channel modification data).

Table 10. Linear feet of mapped linear floodplain modifications by reach - 1999, 1973, and 1954. (Includes identifiable dikes, levees, irrigation ditches, roads, etc.)

Geographic Region	1999	1973	1954
Gardiner Br to Carbella Br	0	0	0
Carbella Br to Eight-mile Cr	4,423	3,572	2,230
Eight-mile Cr to Pine Cr Br	0	0	0
Pine Cr Br to Carters Br	30,568	22,603	4,220
Carters Br to I-90 Br	14,636	13,951	7,692
I-90 Br to Railroad Br	16,484	9,103	6,845
Railroad Br to Shields R	11,786	9,193	2,842
Shields R to Springdale Br	14,359	11,603	10,873
Total Linear Feet	92,256	70,025	34,702

[6] For river management and permitting purposes there is a need to maintain a current inventory of channel modifications. For the geomorphology analysis (statistical comparisons using contemporary information) of effects of channel modification, the CMBEI needs to be current as of the date of the 4-11-99 aerial photos and topographic mapping.

Table 11. Linear feet of mapped bank revetment (riprap) by reach – 1999, 1973, and 1954.

Geographic Region	1999	1973	1954
Gardiner Br to Carbella Br	17411	16997	0
Carbella Br to Eight-mile Cr	22,041	20,196	9,759
Eight-mile Cr to Pine Cr Br	7,128	2,290	0
Pine Cr Br to Carters Br	20,141	12,802	3,688
Carters Br to I-90 Br	12,543	9,300	0
I-90 Br to Railroad Br	11,726	6,310	2,680
Railroad Br to Shields R	8,178	2,818	513
Shields R to Springdale Br	29,502	14,112	10,831
Total Linear Feet	111,259	67,828	27,471

Table 12. Number of point-type channel training structures by reach – 1999, 1973, 1954. (Includes, identifiable barbs, jetties, vanes, etc.)

Geographic Region	1999	1973	1954
Gardiner Br to Carbella Br	3	1	0
Carbella Br to Eight-mile Cr	48	28	2
Eight-mile Cr to Pine Cr Br	42	2	5
Pine Cr Br to Carters Br	93	26	7
Carters Br to I-90 Br	36	19	12
I-90 Br to Railroad Br	23	6	9
Railroad Br to Shields R	13	5	5
Shields R to Springdale Br	37	15	7
Total Number of Points	292	101	47

Gardiner to Carbella

Due to its entrenched channel type, the Gardiner to Carbella sub-reach displayed the fewest point-type channel training structures of the eight sub-reaches across all three mapped years. No barbs were discernable in 1954, one in 1973, and three in 1999. Dikes and levees were similarly non-existent across all three mapped years. Extensive riprap was not evident until the 1973 photos where significant lengths of revetment were present as a result of Hwy 89 construction/improvement. With the highway right-of-way essentially complete by the 1960's, riprap increased only a minor amount between the 1973 and 1999 photo series.

Carbella to Eight-mile Creek

Within this reach most of the significant percentage increases in channel and floodplain modifications occurred between 1954 and 1973. By 1954 approximately 2,200 feet of dikes and 10,000 feet of riprap had been installed in the Carbella to Eight-mile reach. One barb was visible in the vicinity of Emigrant Bridge. Nearly all of the riprap installations were associated with the East River Road; minor segments of dike were associated with an irrigation diversion near the Fridley Creek confluence, the Emigrant Bridge approaches and the railroad near Point of Rocks. By 1973 the amount of floodplain dikes had increased to approximately 3,600 feet; riprap had more than doubled to approximately 20,000 linear feet. Approximately 28 barbs were visible on the 1973 photos. Much of the increase in dikes was due to the installation of the Highway 89 Bridge; riprap and barb increases were due to protecting pasture and the Highway 89 and East River Road corridors. Also, construction of the rest stop along Highway 89 resulting in significant installation of both barbs and riprap along the west bank. By 1999, dikes increased to over 4,400 feet; riprap increased about 10 percent to 22,000 linear feet. The barb count increased to 48.

Eight-mile Creek to Pine Creek Bridge
In contrast to the Carbella to Eight-mile reach, most of the significant percentage increases in channel modifications occurred between 1973 and 1999. In 1954, as well as in 1973 and 1999, no dikes were observed. No riprap was observed in the 1954 photos; approximately 2,300 feet was observed in the 1973 photos. This amount more than tripled to approximately 7,100 feet by 1999. Notably, the number of barbs decreased from 5 to 2 between 1954 and 1973 due to replacement of barbs by riprap. By 1999 42 barbs were observed - most in the reach between Loch Leven and Pine Creek.

Pine Creek Bridge to Carters Bridge
Approximately 4,200 feet of dikes were observed on the 1954 photos – mainly associated with the old railroad grade and Carters Bridge. By 1973 this amount had increased more than five-fold to nearly 23,000 feet. It was during the 1954 to 1973 timeframe that much of the floodplain diking to protect Depuy, Nelson, Jumping Rainbow and the lower portion of Armstrong Spring Creeks occurred. Between 1973 and 1999 the amount of floodplain dikes had increased to over 30,000 feet - most of this associated with protecting the upper portions of Armstrong Spring Creek. Riprap increased from about 3,700 feet in 1954 to nearly 13,000 feet in 1973; by 1999 the tally stood at over 20,000 feet. Similarly, mapped barbs went from 7 in 1954 to 26 in 1973 to 93 in 1999. Much of the bank stabilization increases between 1973 and 1999 (barbs and riprap) occurred to protect existing levees along the left bank and to extend protection along the right bank between Suce Creek and Carters Bridge.

Carters Bridge to I-90 Bridge
By 1954 the amount of mapped floodplain dikes was about 7,700 feet. Save for a small portion of the septa separating the two channels on the downstream end of Siebeck Island, this amount was associated with the old Montana Power ditch. By 1973, the amount of dike within the reach had increased to almost 14,000 feet due to Interstate 90 bridge construction and protection of residential and industrial (aggregate plant) properties on Siebeck Island. Additional increases in length of dike were observed on the 1999 photos to augment existing dikes on Siebeck Island and to protect the sawmill property. Riprap was not evident within this reach on the 1954 photos; by 1973 9,300 feet was observed - mostly to protect Siebeck Island and residential properties on the left bank between Allenspur and the sawmill. Another 3,500 feet of riprap was added between 1973 and 1999 to further protect the sawmill and the I-90 embankment. The number of mapped barbs went from 12 in 1954 to 19 in 1973 to 36 in 1999. Most of the increase in point-type structures occurring between 1973 and 1999 occurred within the Allenspur channel segment.

I-90 Bridge to Railroad Bridge
In 1954 mapped floodplain dikes totaled over 6,800 feet. Most of this length was associated with the railroad bridge and the adjacent business route highway bridge. Minor segments were associated with the old dump and to protect the municipal park. By 1973 an additional 2,300 feet of dike was visible primarily along the channel immediately adjacent to the park. By 1999 the park dike extended down past the municipal ballparks to the golf course. Also by 1999 a significant additional segment of dike was added to the western approach of the business route crossing as a local access route. Riprap in 1954 amounted to 2,700 feet. Most of this was to protect the bridge approaches, the old dump and the municipal park. By 1973 riprap increased to about 6,300 feet mostly to protect the park and also to protect residential areas on the left bank upstream of the 9th Street Bridge. Installations were also observed on the east side of 9th Street Island. By 1999 riprap tallied to almost 12,000 feet. Significant increases were observed along the left bank near the park, upstream of the 9th Street Bridge, and down past the ballparks. An additional 1,500 feet of riprap with associated barbs was added to protect the upstream side of the western approach of the business route crossing. Between 1954 and 1973, the number of barbs decreased from 9 to 6 due to replacement or burial with riprap or erosion (see old crossing upstream of the old dump). By 1999 the number of barbs increased nearly four-fold to 23 due to installations primarily along the left bank adjacent to the golf course.

Distribution of Channel Modifications by Channel Type

The distribution of channel and floodplain modifications by geomorphic channel type (Montgommery-Buffingtion) is given in Table 13. A larger percentage of dikes, riprap and point structures occur in the more dynamic anabranching, anabranching-braided and pool-riffle channel types.

Table 14 and Figure 9 show the relationship between channel type and amount of channel and floodplain modification. Some general patterns emerge: anabranch/braided, anabranch, and pool-riffle together contain the largest concentration of dikes, riprap and barbs – 76 percent, 71 percent and 81 percent, respectively, within 51 percent of the total channel length. The most abundant channel type, plane bed, common in the reaches upstream of Pine Creek and below Livingston, also contains significant percentages of the total amounts of riprap and barbs – 22.6 percent and 15.5 percent respectively. The other two channel types: cascade and bedrock, contain lesser amounts of channel and floodplain modifications in relation to their occurrence within the entire study area.

Table 13. Upper Yellowstone River: 1999 Channel and Floodplain Modifications by Channel Montgomery-Buffington Channel Type – Carbella Bridge to Springdale Bridge

	Summary Comparison		
Channel Type	**Dikes (ft)**	**Riprap (ft)**	**Point-structures (#)**
Anabranch	32,497	31,231	43
anabranch/braided	12,980	22,654	85
Bedrock	5,747	3,718	11
Cascade	7,289	3,987	0
plane bed	9,429	25,219	46
pool-riffle	24,314	24,738	112
TOTAL	92,256	111,547	297

Table 14. Percent Distribution of 1999 Channel Modifications by Channel Type

Channel Type	*Cas*	*bed*	*anbr*	*an*	*pr*	*pln*	***Total***
length (ft)	50,520	26,483	49,732	75,350	110,271	145,914	458,270
% total	11.0%	5.8%	10.9%	16.4%	24.1%	31.8%	100.0%
dikes (ft)	7,289	5,747	12,980	32,497	24,314	9,429	92,256
% total	7.9%	6.2%	14.1%	35.2%	26.4%	10.2%	100.0%
riprap (ft)	3,987	3,718	22,654	31,231	24,738	25,219	111,547
% total	3.6%	3.3%	20.3%	28.0%	22.2%	22.6%	100.0%
barbs (#)	0	11	85	43	112	46	297
% total	0.0%	3.7%	28.6%	14.5%	37.7%	15.5%	100.0%

III. Mapping and Analysis of Historical Channel Changes.

Introduction

Mapping and analysis of historical river channel changes provides an objective basis for describing how the Upper Yellowstone River channel and flood plain have changed over time and gives insight into likely future channel changes. Reconnaissance-level, historic river channel changes, for the time period 1948/49 to 1999, were estimated from Gardiner to Springdale by comparing successive maps of the channel over time. Within Geosegments 6, 7, 8, 9 and 11, more complete analysis of historic channel changes was done in areas showing evidence of measurable channel change; this included interpretative digitizing of the bankfull channel and low water features (e.g. gravel-bars, islands) using historic aerial photos and partially rectified historic channel mosaics for 1948-49 and 1999 orthphotos (other years, including 1943, 1954, 1973, and 1976 are being added in areas of significant channel changes).

Channel changes due to lateral erosion and avulsion[7] between 1948/49 to 1999 occurred primarily in response to the 100-year recurrence-interval floods in 1974, 1996 and 1997. The most significant channel changes occurred due to avulsion in the anabranching and anabranching/braided channel types (23% of channel length between Gardiner and Springdale). Pool-riffle channel types (20.9%) showed significant lateral erosion (e.g. 600 feet) at several locations, but generally were much less responsive to the floods and maintained the same general features. Bedrock, cascade and plane-bed channel types (50%) showed little if any change.

Determination of the mode (e.g. meander migration, cutoff, avulsion) and rate (e.g. gradual over years vs. single event) of change within different channel types provides a quantitative basis for classifying lateral and vertical channel stability for various channel segments. Systematic examination of the spatial and temporal distribution of channel changes in relation to historic channel forming flows, channel modifications and other geomorphic attributes provides a basis for retrospective assessment of cumulative effect of channel modifications.

Historic Channel Mapping Methods

The temporal sequence of available photography, and its relationship to historic channel forming events is particularly important in selecting years for analysis and in understanding the effect of man-made channel modifications on channel morphology and stability. Accordingly, the extent of aerial photos was inventoried in cooperation with other project investigators, and the following years were selected for acquisition and use: 1948-49, 1954, 1965, 1973, 1976, 1983, 1991, and 1999. Additional coverage for limited areas was also obtained for 1943, 1987 and 1988 (see Appendix A).

Plan channel features (Table 5) were mapped (Work in Progress) in channel reaches selected based on the following criteria:

(1) Scale and resolution of photos,
(2) Spatial coverage of flight line,
(3) Stream discharge at time of flight,
(4) Temporal sequence of photos available for a reach and their relationship to historic channel forming flood events (see Figure 25).

[7] Avulsion is the usually rapid lateral shifting of the main channel due to cutting of a new channel (1st order), or re-occupation of old channels (2nd order…).

Methods for Analysis of Historical Channel Changes

Historical channel changes may be divided into two broad categories, lateral and vertical changes (Table 15). Comparison of channel features digitized from successive years of historic coverage is well suited to delineation of lateral changes; vertical changes, if sufficiently large, may be inferred from changes in channel type (e.g. pattern, gravel bar type and frequency). However, channel survey data or information from detailed topographic channel maps is necessary to quantitatively assess vertical channel changes and the data are limited for the study area.

Table 15. Types of Channel Change and Quantitative Measures.

LATERAL CHANNEL CHANGES		VERTICAL CHANNEL CHANGES	
Type	**Indices/Measures**	**Type**	**Indices/Measures**
Widening/Narrowing: Bank Erosion/Deposition Island Formation	Location/Channel Type Rate Mechanism	**Aggradation** **Or** **Degradation (incision)**	*Planimetric Features:* Channel width Gravel bars: Type Frequency Surface area Sediment size *Longitudinal features:* Profile comparison Volumetric change
Meander Migration	Mode (translation,extension, rotation) Rate/frequency		
Avulsion/Cutoff	Location/Channel Type Frequency		

Vertical Channel Changes

Vertical channel changes are being examined using four approaches (results of the first two are reported here). First, analysis of long-term, stream-gaging records for the two U.S. Geological Survey stream gages (Corwin Springs and near Livingston, MT) was done to assess changes in mean-bed elevation at those sites over time. Second, the study-area wide mapping of 1999 and 1948-49 side channels was used to compare the difference in length of side channels, by side-channel type, and Geographic Region. Changes in the amount and type of side channels should reflect the vertical connectivity of the active (bankfull) channel with the floodplain.

Third, for channel reaches with detailed mapping of planimetric historic changes, several indicators of vertical change are being used to infer the occurrence of vertical changes. Indicators include, transitions in channel pattern (e.g. multiple to single thread channel), inferred changes in channel slope as the result of changes in pattern, and changes in the number, type and areal extent of gravel bars/islands. Fourth, sediment budget analysis provides a means of estimating the long-term coarse-sediment disposition (e.g. aggrading and downcutting trends) in selected channel segments.

Stream gage analysis

Information on the vertical stability of the upper Yellowstone channel was developed for the channel reaches that contain the U.S. Geological Survey stream gauges at Corwin Springs and near Livingston (just downstream from Carters Bridge). Historic stream gauging records for the two stations over the past approximately 35 years were examined and successive plots of stream discharge vs. gage height (e.g. water-surface elevation relative to a datum) were prepared.

Differences in the water-surface elevation, measured at the same stream discharge over a period of time, reflect changes in the average -bed elevation of the cross-section where stream discharge measurements are made. Increases in bed elevation (e.g. aggradation) are indicated by increasing gage height at a constant stream discharge and reductions in gage height, at constant discharge, indicate declines in bed elevation (degradation). Stable alluvial channels typically accommodate snowmelt runoff and associated sediment transport through an annual pattern of scour and fill that involves the active layer of the channel bed[8]. Over the long-term in stable channels, the annual pattern of scour and fill causes fluctuations of bed elevation about a mean value, however there is no consistent increasing or decreasing trend.

Over the past 35 years the channel bed at the Corwin Springs site was very stable (Figures 10 and 11). The total range of vertical fluctuation in bed elevation was about 0.3 feet and the successive rating curve plots lack a significant consistent trend. This degree of vertical stability is probably typical of upper Yellowstone, plane-bed, and channels.

In contrast, the channel bed at the gage near Livingston shows greater fluctuation in bed elevation and several minor trends over the past 37 years (Figures 12 and 13). The total range of variation in bed elevation, at a discharge of 25,000 cfs, was about 1.1 feet. Between 1983 and 1996 the channel was fairly stable. Between 1996 and 2000 the channel aggraded about one foot, and since then has degraded slightly (the 1974 flood did not produce the same channel response in the channel reach). Similar cycles of aggradation followed by degradation, have been documented following large floods and the associated influx of coarse bed material (Lisle _____; others) and this type of bed fluctuation is typical of upper Yellowstone, pool-riffle channel types.

Comparison of Historical Channel Survey Data:
Livingston Urban Area

In the west channel downstream of the I-90 Bridge, water surface elevations were lower during the larger of the 1996-97 floods, suggesting that local scour or incision had taken place (Colleen Horihan, personal communication 2003). In addition, water-surface elevations in the west channel are several feet lower than in the east channel, over a range of flows. Examination of the 1948 to 1999 historic channel changes for the Livingston area indicates that lateral migration has been minimal as a result of channel confinement by bridges, revetment and bedrock along the east side of the valley. Channel response appears to include aggradation upstream of the I-90 Bridge and HWY89/RR Bridges and local channel incision. Comparison of historic channel survey data with recent data provides some insight into vertical channel changes over a 30-year period.

The USACE conducted a flood plain delineation study for the Livingston area (Carters Bridge to Shields River) in 1974 (USACE 1974). The analysis was based on thirty-two_ cross-sections were surveyed between Carter's Bridge and the confluence with the Shields River. Examination of Table 3 in the 1974

[8] The thickness of the active layer typically scales with the D_{90} of the surface particle size distribution. On the upper Yellowstone the active layer is likely 0.5 to 3 feet thick depending upon particle size and channel type

report suggested discrepancies in the streambed elevations reported and those surveyed by USGS-BRD in 2002 (e.g. indication of a 10 foot increase in bed elevation near cross-section 12, about 1000 feet upstream of I-90 Bridge). Montana District USGS-WRD conducted the 1974 channel surveys under contract to USACE in the spring and summer of 1974, and provided the original survey notes and cross-section plots supporting USACE's 1974 analysis and report. These data were compared with 2002 UWSGS-BRD data and 1998 USACE data to assess vertical changes in channel-bed elevation (Chuck Parrett, personal communication 2003).

The 1974 channel cross-sections were not precisely located (e.g. survey coordinates for end points) so locations were visually transferred from the map-photo base in the 1974 report to the 1999, 1:6000 scale orthophoto base (Figure 13a.) These locations were also compared with the locations shown on the USGS 1:24000 scale maps accompanying the original survey notes. Cross-sections 12, 13, and 14 correspond to reference points 12, 13, and 14 in the 1974 report (USACE 1974). However Cross-section 15 corresponds to the 9th Street Bridge and cross-sections 16 through 21 are mis-labeled as reference points 15 through 20 in the 1974 report's Table 3. Cross-sections transferred to the 1999 orthophoto base were examined to ensure that prominent landscape and civil features (for example, bridges, road prisms, side channels, ditches and lagoons) intersect the trace of a cross-section in accordance with its location.

The 1974 survey was referenced to the National Geodetic Vertical Datum of 1929. Survey observations by USGS-BRD (2002 data) and USACE (1998 data) were converted from NGVD 1988 to NGVD 1929, using the National Geodetic Survey's VERTCON 2.0 before comparing historic and recent data. Channel cross-section plots were inspected and 2 to 10 well-defined locations (lowest point in channel, centerline of channel, edge of main channel bank, top center of island) were selected along each cross-section for comparison. Cross-section bed-elevations were estimated for each anabranched channel through the Livingston area (West and East channels).

The comparison shows that minimum bed elevation has increased or remained stable at all locations except near cross-sections 17 and 19 (Table 15a). Cross-section12 shows about 4 feet of fill in the west channel and 6 feet in the east channel; cross section 13 shows about 1.5 feet of fill in the west channel and 3.5 feet in the east channel. Cross-section 14 shows a similar but reduced trend. Channel incision in the west channel does not appear to be the primary source of the water-surface elevation differential between the two channels. Instead, aggradation of the west channel is responsible. Future monitoring of the channel geometry will be required to establish if these are persistent trends.

Table 15a. Comparison of Vertical channel changes in Livingston Urban area: 1974 to 2002

1974 USGS Cross-Section	1974 USGS-WRD Minimum Bed Elevation (ft)[1]	1974 USGS-WRD Minimum Bed Elevation (ft)	1997 USACE Minimum Bed Elevation (ft) [2]	1997 USACE Minimum Bed Elevation (ft)	2002 USGS-BRD Minimum Bed Elevation (ft) [3]	2002 USGS-BRD Minimum Bed Elevation (ft)	Comment
	West Channel	**East Channel**	**West Channel**	**East Channel**	**West Channel**	**East Channel**	
12	4496.0	4491.0	4498.0	4496.1	4499.8	4497.2	USACE 1998 xs 63402 and 5712
13	4482.5	4487.0	4480.1	4488.5	4484.0	4490.6	I-90 Bridge (USACE xs 3832 and 4173)
14	4483.0	4490.0	4485.1	4490.6	4485.6	4492.3	USACE 1998 xs 60157 and 3439)
15 USGS (not shown on USACE 1974 map)	4482.0		4482.6		4483.5		9th Street Bridge (USACE 57979)
USGS 16 (15 on USACE 1974 map)	4481.0	4482.0	4479.5	4482.7	4482.0	4481.3	USACE xs 57592 and 1779
USGS 17 (16 on 1974 map)	4475.0		4469.6		4472.0		USACE XS 55562
USGS 18 (17 on 1974 map)	4468.0		4467.8		4470.0		USACE xs 53531/53006
USGS 19 (18 on 1974 map)	4469.0	4458.0	4464.9	none given	4464.0	4462.0	USACE xs 50833/49482
USGS 20 (19 on 1974 map)	4555.8		4452.4		4456.0		USACE XS 48703 (USACE xs below bedrock drop)
USGS 21 (20 on 1974 map)	4553.0		4450.7		4454.0		USACE xs 46754

[1]Elevation obtained from original survey notes provided by USGS-WRD, Helena, MT; all elevations given in feet NGVD 1929
[2] Elevation from Table 3. In USACE (2003) Yellowstone River near Livingston, Montana Floodplain Analyses. . USACE Omaha District
[3] Elevation obtained from x, y, z point file provided by USGS-BRD, Ft. Collins, Co.

Upper Yellowstone Side Channels

Flood control and channel stabilization projects may affect the connection to the main channel through directly reducing flow and through channel incision (i.e. downcutting), which lowers water-surface elevation, at a given flow, and thereby reduces the frequency of flow in side channels. Incision may also reduce the local water table elevation and thereby reduce surface and groundwater interaction between the channel and floodplain. Reduced side-channel flow, coupled with progressive incision, enhances sediment deposition in the side channel and eventually the channel becomes part of the flood plain and not the active channel. Although many side channels are probably reoccupied numerous times over a period of several hundred years.

Side channels are created by a variety of fluvial processes and receive flow from the main channel, alluvial groundwater, and springs (less common). Side channels within a given channel segment display a variety of bed elevations so that some channels only receive flow at relatively high main channel discharges and are dry at lower flows; other side channels receive flow at all but the lowest main channel discharges (<1200 cfs?).

Extensive lateral confinement of a given channel segment could lead to channel incision and/or inhibit lateral migration; incision would modify the stage/discharge relationship for the inlet (and outlet) channels and reduce the magnitude and duration of side channel flow for a given main channel runoff hydrograph--with significant incision, the channel would be come stranded. Inhibited lateral migration would affect erosional and depositional processes (continuous in pool-riffle channels and more episodic in anabranching channels) that form side channels. Together incision and inhibited lateral migration could lead to a reduction in abundance in side channels and modify the mixture of side channel types available for fish in the upper Yellowstone River.

Comparison of the overall length of side-channels, between Gardiner and Springdale, Montana (Table 16 and Figure 14) shows that the amount increased by about 16 percent between 1948-49 and 1999 (from 707,660 feet in 1948-49 to 838,130 feet in 1999). The higher percentage of side channels in 1999 is due to the floods of 1996-97, which rejuvenated old side channels and cut new ones -- especially in the anabranching and anabranching channel types. The increase in side-channel length occurs in the sidegbdry, sidemidgbdry, sidelatfp, and sidelatspr channel types. Since streamflow was lower in the 1999 comparison year, a larger amount of dry side channels associated with gravel bars is expected. No fish ponds were mapped in 1948-49, while a significant number were present in 1999. A larger number of spring creek side channels were mapped in 1999--many of these are old side channels that have been rejuvenated with fish habitat structures added (e.g. Jumping Rainbow). NOTE: *The side-channel category, "side lost" reflects those side channels that have been lost directly to flood plain development and is being revised to include losses prior to 1948-49 that are due primarily to transportation corridor development.*

Most of the increase in 1999 side-channel length occurred in Geographic Regions 2 (Carbella to Eight Mile Creek) and 7 (Shields River to Springdale Bridge) in the anabranching and anabranching channel types; all of the other Geographic Regions showed small increases in length (Figure 15). While all of the Geographic Regions contain side channels, Regions 1 (Gardiner to Carbella) and 5 (I-90 Bridge to Railroad Bridge) contain significantly fewer than the others (Figure 16). Region 1 consists largely of bedrock, cascade, and plane bed channel types which are typically steep and incised, lack sediment storage sites and lateral processes that create and maintain side channels. Region 5 is one of the most heavily constrained and revetted channel segments, and while the 1948-49 to 1999 comparison shows a slight increase in side-channel length, the smaller amount of side channels in this Region may be due to flood plain development that occurred prior to 1948-49 (see above note). Geographic Regions 2 and 7 contain the greatest length of lateral side channels (sidelatall). Regions 3, 4a, 4b and 6 also contain significant lengths of lateral side channels and these are associated with both the anabranching and pool-rifle channel types. Generally the areas with the largest amounts of lateral side channels also have the greatest lengths of side channels associated with active channel gravel bars (sidegball, sidemidgball). Fish ponds occur in Regions 2, 4a, 4b, 5 and 7, with the greatest amount in Regions 2 and 4a. Spring creeks occur only in Regions 2 and 4a --the latter containing over 95%.

The 1948-49 to 1999 comparison of side-channels indicates that most of the channel segments have remained laterally connected to the flood plain, and that lateral channel processes maintaining and creating side-channels have not been significantly impaired. A possible exception is Region 5 (I-90 Bridge to Railroad Bridge) -- although excessive incision does not appear to have occurred in response to bank stabilization, some side channels have been lost through flood plain development prior to 1948-49.

Table 16. Comparison of 1948-49 and 1999 Side-channel length, by Side-Channel Type and Geographic Region: upper Yellowstone River, Gardiner to Springdale, Montana

1948-49 side channels (length in feet)														
GEOGRAPHIC REGION	**Sidegb**	**Sidegbbw**	**Sidegbdry**	**Sidemidgb**	**Sidemidgbbw**	**Sidemidgbdry**	**Sidelat**	**Sidelatbw**	**Sidelatdry**	**Sidelatirr**	**Sidelatfp**	**Sidelatspr**	**Sidelost**	**Grand Total**
1	2712	3554	6285	1054	0	0	1716	0	0	0	0	0	0	**15321**
2	31833	4685	7515	4384	2378	828	32331	24848	23171	10128	0	0	0	**142102**
3	3781	2193	10336	1431	0	230	12324	885	9602	0	0	0	0	**40781**
4a	13202	11702	7958	6044	2354	3359	17126	6336	36944	1738	0	31294	1425	**139481**
4b	9578	4638	4540	520	269	1958	22044	9425	17708	3743	0	0	0	**74423**
5	5054	1879	2863	667	0	729	14855	1112	2666	0	0	0	0	**29825**
6	14471	4444	1741	6067	2619	5042	19212	12214	28745	0	0	0	0	**94555**
7	26411	7463	3373	3018	2546	2187	71919	26522	25228	2506	0	0	0	**171172**
Grand Total	**107041**	**40558**	**44611**	**23186**	**10166**	**14332**	**191527**	**81341**	**144064**	**18115**	**0**	**31294**	**1425**	**707660**

1999 side channnels (length in feet)														
GEOGRAPHIC REGION	**Sidegb**	**Sidegbbw**	**Sidegbdry**	**Sidemidgb**	**Sidemidgbbw**	**Sidemidgbdry**	**Sidelat**	**Sidelatbw**	**Sidelatdry**	**Sidelatirr**	**Sidelatfp**	**Sidelatspr**	**Sidelost**	**Grand Total**
1	5264	0	11374	0	0	0	0	0	1242	0	0	0	0	**17881**
2	19038	5775	14039	3010	1888	13600	64443	16863	25064	1873	8791	375	2993	**177752**
3	661	2314	4879	2320	1127	1318	18415	4725	20144	0	0	0	0	**55903**
4a	15759	10187	19993	5627	1079	8457	6564	7404	16557	3243	8081	52273	0	**155222**
4b	9886	2845	8262	2222	916	4631	16113	5715	20243	0	797	0	6611	**78241**
5	13842	1606	4385	0	0	0	280	3186	5289	6332	4418	0	0	**39339**
6	11767	6025	10247	1697	2692	10217	12990	20146	26897	0	0	0	0	**102677**
7	23667	10859	19902	2614	2147	11157	69633	16285	44241	7904	2736	0	0	**211145**
Grand Total	**99883**	**39611**	**91755**	**17491**	**9848**	**49380**	**188438**	**74324**	**159676**	**19351**	**24823**	**52648**	**9605**	**838160**

Lateral Channel Changes

A variety of interpretative analyses are being conducted on lateral channel change data for the various channel segments and time intervals. Changes in the lateral position of the low-water, centerline channel trace between 1948-49 and 1999 was used to identify areas of significant lateral channel change. Detailed channel mapping of bankfull and low water channel features in 1948-49 and 1999 was used to measure channel changes in portions of Geographic Regions that extend from Mallards Rest to Carters Bridge and from the I-90 Bridge to the Rail Road Bridge (work on other areas and additional historic years of coverage is in progress).

Other geomorphic measures of plan channel geometry are being be compiled and compared over the time intervals selected for analysis. These include: sinuosity and other measures of meander geometry (wavelength, radius of curvature etc); the areal extent, frequency, and spatial distribution of gravel bars, by bar type, and their general vegetation cover (bare, shrub, wooded).

Reconnaissance-Level:
Lateral channel changes (1948/49 to 1999) were estimated by digitizing the centerline trace of the low-water channel on the partially rectified channel mosaics for those years (Plate 14). Accuracy of the digitized centerline trace, limits detection of lateral changes to a range of about ± 20 feet to ± 50 feet. The digitized channel traces were overlaid in a GIS and areas of low (or no) change were identified by the close agreement of the two lines. Channel locations where the lines diverged greater than 50 feet were identified for further data collection and analysis. Significant lateral channel changes occurred in pool riffle and anabranching channel types located between Point of Rocks and Mill Creek, Mallards Rest and Livingston (Figure 17) and between the Shields River confluence and Mission Creek (Figure 18). *NOTE: We have identified 12 channel modification study areas where case histories of historic channel change and channel modification are being developed (see Plates 5 to 12).*

The length of the low-water channel trace was also compared between 1948-49 and 1999 (Table 17). The comparison of 1948-49 with the 1999 channel centerline length shows a very small overall change in mainstem channel length. The largest change occurred in region 2 -- a reduction in channel length of about 2%. (Note: the Yellowstone River Mile Index (DNRC 1976) shows a mainstem length of 437,184 feet; this value is inaccurate and reflects the use of 1:62,500 scale maps for much of the upper Yellowstone drainage).

Table 17. Comparison of main channel length*: 1948-49 to 1999, Upper Yellowstone River, Gardiner to Springdale, Montana.

Geographic Region	1948-49 River Distance (ft)	1999 River Distance (ft)	Difference
1.Gardiner to Carbella	91279	91199	-80
2. Carbella to Eight Mile Cr	103847	101738	-2109
3. Eight Mile Cr to Pine Creek Br	72385	72626	241
4a.Pine Cr. Br to Carters Br	40330	41215	885
4b.Carters Br. To I-90 Bridge	20180	20706	526
5. I -90 Bridge to RR Br	15717	15235	-482
6. RR Br to Shields R	31657	31119	-538
7. Shields R to Springdale Br.	77501	78661	1160
Totals	**452896**	**452499**	**-397**

*low-water, channel centerline trace digitized from 1999 orthophotos and 1948-49 photo mosaic

Detailed Channel Changes

Bankfull channel features (e.g. bankline, bankfull islands) and low water channel features (e.g. waters edge, islands, gravel bars) were mapped for Geosegments 6,7, 8, and 9/10[9] using the 1948-49 and 1999 aerial photos and channel mosaics. Channel features were mapped into a GIS as attributed polyline and polygon data to facilitate subsequent analysis of changes in fluvial features over the 1948-49 to 1999 time period. Figure 19 shows the 1948 and 1999 channel features mapped for the downstream portion of Geosegment 6 (Mallard's Rest to Pine Creek Bridge). Changes were assessed by overlaying similar features for the two time periods and calculating change polygons for subsequent classification . Areas of channel change were classified as erosional, depositional or stable (no change). Figure 20 shows an example of classified channel changes that occurred for the 1948-49 to 1999 time period; changes highlighted in yellow represent the area of bank or island erosion that occurred.

Figure 21 shows channel changes near the head of the Nelson and Armstrong Spring Creeks. Volumes of bank -material eroded at each site are given in Table 20. At the Armstrong site, the maximum (axis of bend) distance of lateral erosion was about 900 feet and the average, 630 feet. At the Nelson site the erosion was distributed more uniformly with about 100 feet of lateral bank loss.

The Yellowstone River in the Livingston Urban area (Figure 22) is constrained by rip-rap along most of the western bank of the west channel, and along both banks for much of the west channel north of the I-90 Bridge. Although lateral erosion has occurred at several locations, revetment and bedrock controls have limited lateral movement over the 50-year comparison period. Deposition has occurred upstream from the I-90 Bridge and HWY89/RR Bridge as is indicated by the changes in gravel bar occurrence and size. Deposition shown between cross-sections 51 and 58 (north bank) is due to fill of the floodplain for domestic use. Several side channels to the east and west of the I-90 Bridge crossing were cutoff and partially filled by the bridge approaches. Other side channels in the area (for example Fleshmann Creek) have been modified and remain partially connected to the main channel through a series of diversion and outlet works.

Mapping of the energy expenditure (unit stream power) in the channel through the Livingston area (USGS-BRD 2003) shows maximums at several locations: just upstream and under the I-90 Bridge (cross-section 19) and near cross-sections 23 and 27 in the west channel where flow impinges on extensively rip-rapped channel segments; downstream (cross-section 51) from where the east and west channels join and flow impinges upon a long expanse of rip-rapped bank; and near cross-section 54 where bedrock outcrops in the channel. These areas represent “pressure points” in the channel network where local scour and channel incision should be anticipated as a long-term channel response,

[9] The Livingston area including the lower part of Geosegment 9 and upper portion of 10

IV. Geomorphic Analysis of Historic Channel Processes and Cumulative Effects of Channel Modification.

Summary

Several methods were (are being) used to measure and quantify the historic effects channel modification has had on the physical characteristics of the upper Yellowstone River. These include case histories of channel modification, statistical inference through hypothesis tests, sediment-budget analysis, and hydraulic modeling. Case histories are particularly important because the temporal sequence of channel change is often intertwined with channel modification and knowledge of the past history is essential to interpretation of the contemporary channels physical attributes and stability.

Hypothesis tests and other statistical methods, applicable for comparison of control and treatment populations, are being used to construct retrospective assessments of the historic effects of channel modifications. A variety of parametric (and nonparametric if appropriate) statistical methods (e.g. ANOVA; discriminant function analysis, trend analysis) are being used to make "above and below", and "before and after" comparisons of effects of historic channel modifications on physical channel attributes (e.g. hydraulic geometry) and channel stability (i.e. rates of lateral and vertical processes).

A sediment-budget analysis that quantifies flood plain and channel sediment sources and storage reservoirs is being developed for channel reaches with sufficient information. Contemporary (1999) channel morphology and stability are being analyzed using various geomorphic methods that relate channel type and physical characteristics to geomorphic change thresholds Areas of historic, existing and likely future channel instability (lateral or vertical) and potential areas of rapid future channel change (channel cutoffs and avulsions) are being identified. This analysis provides a means for defining channel reaches that may be especially sensitive to increases in coarse sediment inputs or modification of channel width or slope.

A hydraulic model developed for flood plain delineation within the detailed study segment, will also be used to evaluate historic cumulative effects of channel confinement on water-surface elevations of floods (USGS-WRD). A sediment-transport model is being developed and used to examine potential cumulative effects, of hypothetical scenarios for channel management/stabilization, on channel characteristics and stability.

Geomorphic Analysis of Contemporary Channel Processes and Problems

The current-day distribution of channel types and channel stability the Yellowstone River's channel network are the result of complex interaction between watershed scale processes that influence the supply of water and sediment to the river, and channel-scale hydraulic processes which govern the localized erosion, transport and deposition of sediment. Two of the most significant challenges presented by cumulative effects analysis are, 1) detecting change against the background of spatial and temporal natural variability, and 2) separating channel response(s) to man-induced effects from channel response to purely natural effects. These issues are widely recognized by practitioners of cumulative effects analysis as well as the public(Reid, McDonald and Bunte, etc). A description of our approach and the methods used to analyze cumulative effects of channel modification is given in Appendix C. Although the analysis is in its preliminary stages, some of the results are reported here.

Over the past three years the Upper Yellowstone River Task Force, in cooperation with the Technical Advisory Committee, has identified several natural events and processes that may have contributed to channel stability problems and potentially confound an assessment of cumulative effects of channel modification:

♦ What effect have tributaries had on channel processes of the Upper Yellowstone?
Do the tributaries contribute significant sediment to the channel?

♦ The effect(s) of the 1988 Yellowstone wildfires on water and sediment runoff to the channel.
How did the fires affect runoff (e.g. peak flow) ?
Did the 1988 fires have a lasting effect on stream flow?
Did the 1988 fires cause the 1996 and 1997 floods? Or at least make them Much larger than they would have been with out the fires?
How much coarse sediment came from YNP ?
Has the coarse sediment affected channel stability ?

♦ The effect(s) of the 1996 and 1997 floods on channel stability.
What channel segments were the most effected ? Why ?
What were the primary sources of sediment in the floods—
Bank erosion ? Mass wasting ? Tributary sources ?
What is the fate of coarse sediment supplied to the channel ?

♦ The effect(s) of natural sediment sources (e.g. material eroded from high banks— Weeping Wall) on downstream channel processes and stability.
What influence do natural sediment sources play in determining local and downstream channel stability ?

These are important questions -- to provide answers several geomorphic analyses were conducted and preliminary results of these are reported here.

Tributary Influences on Channel Processes

Tributary affects on main stem channel processes and stability were qualitatively assessed based on geomorphic interpretation of channel morphology and historic changes near tributary confluences. Interpretation of historic stereo air photos was used to assess the relative importance of tributaries as sources of coarse sediment to the channel network. Information on the geomorphic stability of tributary streams and the likely fate of coarse material, as it transits the floodplain to be supplied to the main channel, was used to identify streams which may supply coarse sediment to the channel network. Similar examination of the main channel attributes (e.g. gravel bar type, abundance and change over time) above and below tributary junctions was used to estimate the effects of tributary sediment supply on the main channel. The analysis indicates that none of the tributaries between Gardiner and Springdale were sufficiently large contributors of coarse sediment to have measurably affected contemporary channel processes. The largest tributaries between Gardiner and Livingston are Miner Creek and Mill Creek, and these along with smaller tributaries show no evidence of significant change in deltaic sediments or gravel bar type and frequency above or below their confluences over the 1948/49 to 1999 period. Downstream from Livingston, the Shields River is a possible exception, however the Yellowstone River gravel flux at that point may overwhelm the Shields River's coarse sediment contribution (the Shields River drains Cretaceous sediments that tend to produce more fines than gravel when weathered and sediment contributions may be more of a water-quality concern).

While tributary stream contributions of water and sediment to the main channel were significant during Pleistocene de-glaciation, contemporary effects are small due to the generally small drainage size and correspondingly small water and sediment contributions to the main channel. Landscape changes in tributary attributes affecting water and sediment runoff (e.g. forest-practices, fire) could alter their importance as water-sediment sources to the Yellowstone River.

Hydrologic and Geomorphic Effects of 1988 Yellowstone Fires

The Yellowstone wildfires of 1988 covered an extensive portion of Yellowstone National Park that contributes runoff to the downstream study area. Wildfire can significantly increase runoff and affect sediment yields for several years following a fire (Tiedeman et al. 1979; Brown 1989). The amount of the increase in water yield and the temporal distribution and duration of increased runoff is highly dependent upon the geography (e.g. topographic, soil and vegetation characteristics) of the area burned and the characteristics of the fire (e.g. areal extent within various elevation zones, type of forest affected, intensity of burn). The effect of wildfire on sediment yields depends upon the same factors.

Research (Ewing 1996) indicates that the effects of the 1988 fires on runoff and were localized and did not produce measurable changes in flow characteristics of the Yellowstone River at Corwin Springs, MT. Analysis of the effects of the 1988 fires on Yellowstone River runoff has been done by Farnes (2002) and others. In May 2000, the Task Force sponsored a "Fire Effects Workshop" to discuss results of post-fire research. The general conclusion was that the 1988 fires might have lead to a small increase (~5 to 7%) in the 1997 flood peak at Livingston for duration of one day—the corresponding geomorphic effect of this increase is not significant.

The post-fire effects of the 1988 fires on suspended-sediment loads and turbidity is an important water-quality consideration. The fires did increase suspended-sediment concentration and loads for the Yellowstone River at Corwin Springs and in the Lamar basin (Ewing 1996). Bed-material discharge was not measured so it is not known, by direct means, if the increase in suspended-sediment load was accompanied by increased bed load transport. However, except in extreme situations, fine sediment (sand size and smaller in modest quantities) that is transported as suspended load has a minimal affect on channel morphology in gravel-cobble-boulder bed channels (Leopold 1992).

Of greater interest to this project is the affect of the fires on coarse-sediment supply to the Upper Yellowstone River. Within YNP it has been established that fire (and climatic controls on fire occurrence) plays a key role in determining coarse sediment supply to headwater channels (e.g. Lamar River, Soda Butte Creek) and in the subsequent evolution of the local channel network (Meyer et al. 1995). However, there has been no systematic analysis of the post-fire effects on coarse sediment loads outside the Park boundaries. Research by Meyer and Wells (1997) indicates that most coarse sediment produced by fires in the Park are stored in alluvial fans in small headwater basins and that the residence time for sediments is high (100's to 1000's of years). It is unlikely that coarse sediments capable of affecting downstream channel processes have yet exited the Park boundary.

Potential affects of the 1988 fires on coarse-sediment supply to the downstream channel network were further evaluated by indirect means. First, interpretation of pre (1983, 1987) and post (1991, 1999) fire aerial photos was used to examine changes in downstream channel characteristics (e.g. gravel bar morphology, type) of the upper Yellowstone River between Gardiner and Corwin Springs, MT. Aerial photos were examined for periods prior to the 1988 fires, within a few years of the fires, and following the 1996 and 1997 floods. This examination showed that no significant changes in existing channel characteristics occurred in that time period. Second, contemporary sediment deposits in the river channel between Gardiner and Corwin Springs were field examined for evidence of accelerated sedimentation and the presence of fire related debris -- none was found. Third, long-term stream gauging records for the USGS station at Corwin Springs were examined (e.g. sequential cross-sections over time, specific gauge height plot) to assess channel stability prior to and subsequent to the 1988 wildfires) and the discharge rating and channel section was found to be fairly stable over the above time periods spanning the 1988 fire (and the 1996-97 floods).

Effect of Floods of 1996 and 1997

Historic Channel Forming Floods, Channel Response and Channel Changes

Upper Yellowstone Hydrology and Flood History

The present day morphology of the Upper Yellowstone River channel/floodplain complex is a mosaic that has been created by a variety of historic flood influences. The glacially influenced paleohydrology of the ancestral river has created the basic valley/channel configuration and may impose slope constraints as well as influence the characteristics and availability of sediment to the channel and the degree of confinement of flood flows. In more recent time, the flood history of the basin over the last 100 years has affected the temporal distribution of channel changes. In some channel segments, these floods had significant effects on channel characteristics and stability, while in others little lasting effect is evident.

Pertinent streamflow characteristics of the U.S. Geological Survey streamflow gaging stations located near Livingston (06192500) and at Corwin Springs, MT are summarized in Table 18. Drainage area increases downstream from Corwin Springs to Livingston, by about 35%, while mean annual discharge increases by about 20 %.

Table 18. Runoff Characteristics for Upper Yellowstone River Stream Gaging Stations

Station	Drainage Area (mi^2)	Mean Annual Discharge[1] (acre-feet)	Lowest Minimum Daily Mean flow (cfs)	Highest Maximum Daily Peak flow (cfs)
Corwin Springs	2,623	2,264,000	380 (2-2-1989)	32,220 (6-10-1996)
Livingston	3,551	2,72,0000	540 (2-4-1989)	38,000 (6-6-1997)

[1] Period of record varies for stations.

Average annual runoff and monthly mean discharge for the Livingston station are summarized in Figures 23 and 24). Means and extremes of the 1897-2002 are indicated on the graphs --Note that Figure 24 shows the study years of 1999, 2000 and 2001. The year 1999 was an above average year, 2000 was approximately an average year for the months Jan-May and below normal for the remainder of the year, and 2001 was a below average year.)

Historic annual peak flows at the Livingston gage are given in Figure (Figure 25). A portion of the missing record at the site was estimated by Merigliano (2001) and is included. Significant floods of record (~100 year)[10] R.I.) occurred in 1918, 1974, 1996 and 1997. The largest flood of record may have occurred in 1918 (approximately 40,000 cfs), however 1996 (37,100 cfs) and 1997 (38,000 cfs) floods closely approach this value and are probably within the uncertainty of the 1918 flood estimate.

Floods and Channel Forming Discharge

The role of floods in sediment transport and channel maintenance has been examined extensively over the past 40 years. Wolman and Miller (1960) first hypothesized that frequently occurring floods of modest size accomplished more geomorphic work than large, infrequent floods; a corollaries of this are that frequent floods are responsible for maintaining the average bankfull hydraulic geometry of the channel, and that frequent flooding is an intrinsic characteristic of self-formed, alluvial channels. Subsequent investigations have supported this hypothesis and linked the effective discharge (i.e. the peak flow range that transports the most bed-material sediment over the long-term) with the bankfull discharge (i.e. the flow that ideally corresponds to floodplain elevation adjacent to the channel) (Andrews 1980; Andrews and Nankervis 1995; Whiting et al. 1999; Emmett and Wolman 2001).

Typically in gravel-bed channels most of the sediment transport that shapes and maintains the channel occurs at flows that approach or just exceed bankfull stage. Investigations of bankfull stage in diverse rivers has established that in most instances the recurrence interval ranges from about 1.5 to 2 years on the annual maximum series (Emmett 1975; Williams 1978; Carling 1988; Whiting et al. 1999; Emmett and Wolman 2001). In general there is a consensus that in most rivers the more frequent floods shape the channel and are the dominant flows responsible for maintenance of average channel properties. Although larger less frequent floods are capable of much erosion, over the long term (~>25 years), the frequent floods that occur every other year move much more sediment.

There are several situations where deviations can be expected from this general model of channel maintenance. First, although there appears to be consistency between the recurrence interval of effective and bankfull discharges, across lowland and upland channels, there is evidence that as channel slope and erosional resistance of bed-material increases, the recurrence interval of effective discharge increases (Andrews 1980; Pitlick 1988) and larger flows assume a greater role in maintaining the average channel dimensions. Although flows in the range of the 2-year flood may maintain the average channel characteristics over the long-term, large infrequent floods may significantly modify channel and flood plain attributes over the short-term, and in some cases leave a lasting imprint.

Geomorphic Effectiveness of 1996-1997 Floods

The 1996 and 1997 floods caused significant property damage both through inundation and flood plain erosion and deposition, however significant parts of the channel network were not measurably affected; it is expected that the bedrock channel type would be little affected, however the cascade and plane-bed channel types were similarly relatively unaffected.

In the channel types (pool-riffle, anabranching and anabranching/braided) significantly affected by the 1996 and 1997 floods, several factors may have contributed to the erosion and sedimentation caused:

(1) historic channel modifications, such as diking and manipulation of channel position, may have "solved" a problem at one location, only to pass it downstream,
(2) natural contributions of coarse (gravel, cobble, boulder) sediment from high cut banks, may have introduced large amounts of material that accumulated locally in the channel and forced

[10] 100- year recurrence intervals on the annual maximum flood series as determined with the Log Pearson Type-III frequency distribution

water to seek another path (avulsion),
(3) the lack of riparian vegetation at some locations may have encouraged excessive bank erosion and flood plain stripping, and
(4) the combination of "back-to-back" floods of record, with the 1997 flood having a nearly three week duration above the National Weather Services flood stage.

The geomorphic effectiveness of large floods in the Upper Yellowstone drainage is also influenced by the effects of complex valley morphology and boundary conditions on flood confinement and energy expenditure in the channel network. In general, other factors being equal, large floods may be more likely to cause lasting channel changes in narrow steep valleys, than in broad, low-gradient valleys (Miller 1995)[11]. Baker and Costa (1987) incorporated magnitude-frequency concepts, thresholds, and geomorphic effectiveness into the concept of critical flood power. They concluded that fluvial systems could be destabilized when input forces exceed resistance forces. Input forces or flood power, are determined by flood magnitude and duration, channel and valley morphology, and stream gradient (Baker and Costa 1987; Magilligan 1992; Miller 1995). Resistance forces are controlled by geology, sediment and soil type, and vegetation cover (Baker and Costa 1987; Costa and O'Connor ,1995; Magilligan et al. 1998).

The upper Yellowstone River appears to deviate from the general model of channel response to large floods, in several ways. Significant portions of the channel network in the plane-bed and cascade channel classification, showed little or no change in response to the 1974 and 1996-97 floods. These channel types are dominant in the upper basin (Gardiner to Mill Creek) where the channel is the most confined by fluvio-glacial terraces. Under the previously discussed model of geomorphic effectiveness, one might assume that these areas should have experienced the greatest change. A likely explanation for this apparent deviation is that in spite of the lateral confinement, the resisting forces (e.g. very coarse bed material) in the channel bed and banks remained dominant.

Channel changes in the 1974 and 1996-1997 floods occurred primarily through lateral erosion in pool-riffle channel segments and through avulsion and lateral erosion in anabranching channel segments. It appears that a channel response model for these segments of the upper Yellowstone includes relatively rapid lateral changes through avulsion in large events (e.g. 50? to 100 year floods) which establish the dominant lateral channel configuration. Between these events, more frequent flows with return periods close to the conventional "bankfull" discharge (e.g. 2 to 10? year floods) shape and maintain the average characteristics of the individual anabranches.

Effects of Natural Sediment Sources on Channel Processes

Seven large (long and high) eroding banks were selected for analysis of historic erosion rates (Table 6). A mapping contractor used photogrammetric methods to develop digital terrain models of the banks for four successive time periods: 1948/49, 1973, 1976 and 1991. Results are presented here for two of the banks (Mallards Rest and the Weeping Wall) over the 1948/49 to 1999-time period.

The volumes of erosion from the two banks, were estimated by creating a triangular irregular network (TIN) for each of the years and subtracting the 1999 TIN from the 1948/49 TIN using a composite/exact method for creating the surface of difference. Volumes were estimated, adjusted for the fine fraction, and converted to Tons. Uncertainty estimates account for accuracy of the method (Table 19).

[11] The Upper Yellowstone River appears to deviate from this generalization with the most lasting effects of the 1996 and 1997 floods evident in the broad, low-gradient valley and the least effects in the terrace confined upper reaches.

Table 19. Estimates of the Bedload Contribution from Mallards Rest and Weeping Wall: 1948/49 to 1999

Location	Time Period	Lateral Retreat (feet)	Volume (cu.yd.)	Weight (Tons)*	Bedload Contribution (Tons)
Mallards Rest	1948/49 to 1999	60	160,000 ±40,000	350,000±88,000	280,000 ±70,000
Weeping Wall	1948/40 to 1999	80	350,000±120,000	790,000±280,000	630,000 ±220,000

*Volume converted to weight using specific weight of 165lb/ft^3

These amounts of sediment appear to be significant, at least within the channel segments that contain them. Significance is being further evaluated by estimating erosion rates for the intermediate years to estimate the relative contributions from the 1974 and 1996-97 floods. Sediment contributions will then be compared with typical bedload transport rates measured and modeled by USGS-WRD.

Preliminary estimates of the volume of sediment contributed from the seven banks are given in Table 20. With the exception of the Armstrong/Nelson Spring Creek banks, each of the seven has the appearance of being a potentially large source of sediment. However, this is not always the case -- and one of the banks with the lowest vertical relief (Armstrong) had one of the largest areas of lateral erosion and contributed significant coarse sediment to the channel.

Table 20. Estimates of Sediment Contributions from Large Eroding Banks: 1948 to 1999

Eroding Bank Location	Av. Bank Retreat (Ft)	Total Volume (cu.yd.)
Corwin Springs (north of bridge)	31	56,400
Mallard's Rest (downstream l.bank	60	160,000
Pine Creek (Upstream from bridge)	24	20,800
Weeping Wall	80	350,000
Deep Creek Area	125	175,000
Armstrong//Nelson Spring Creek Area	630 (Armstrong) 96 (Nelson)	250,000 54,000
Trail Creek Area	380	93,000

Geomorphic Analysis of Cumulative Effects of Historic Channel Modification.

Retrospective Statistical Analysis of Cumulative Effects of Historic Channel Modifications

Cumulative effects of historic channel modifications are being analyzed empirically using case histories and statistical methods (Appendix C.). Emphasis is placed on comparison of various physical channel attributes measured above and below channel reaches affected by channel modifications and comparison of attributes before and after channel modification. Information on Upper Yellowstone River channel morphology and historic channel changes is being examined for several types of potential cumulative effects:

1. Cumulative increases in the spatial extent of bank revetments within or proximate to channel segments that have been progressively modified over time.

2. Cumulative upstream or downstream changes in channel dimensions (channel width, slope) and physical attributes (gravel bars) resulting from (1) above,

3. Geomorphic thresholds that may have been exceeded, wholly or due in part to cumulative increases in bank revetment, and resulted in major changes in channel pattern, and channel stability -- these changes should also be reflected in changes in channel type.

Data are being organized and stratified so that comparisons can be made that isolate the affects of the 1996 and 1997 floods in channel reaches directly affected by channel stabilization measures and unaffected channel reaches.

Extensive research on the effects of channel modification on rivers has been conducted over the past 40 years. This work suggests that channels in rivers with significant bank revetment and/or lateral confinement by dikes and levees are generally steeper and narrower than their purely alluvial counterparts, may be incised, and that the channels may contain coarser substrate and fewer gravel bars (Kerr 1971; Carling et al. 1996; Galay et al 1998; Brookes 1988; Schmetterling et al. 2001; Wyzga 2001a; 2001b; Piegay et al. 1997; Steiger et al. 1998; Liebault and Piegay 2002; Petts et al 1989).

Preliminary case history comparisons for the Livingston area suggest that this may also be the case on the Upper Yellowstone. Comparison of the anabranched channels in the vicinity of the I-90 Bridge, over the time period 1954-1999 suggests that channels have become somewhat narrower (after correction for effects discharge variation in the photos) and steeper. However the effect is not as dramatic as might be expected given the level of channel confinement. For example, discharge on the 1999 photos is the lowest of the years examined, yet all of the principal anabranched channels appear to have retained flow--something not expected if the channels were experiencing significant incision and degradation.

Hydraulic analyses by USACE (1999) indicate that channel incision has occurred in the channel reach near the City of Livingston water intake, just upstream of the Ninth Street Bridge. Water-surface elevations measured near the water intake showed that although the 1996 flood had a lower discharge than the 1997 flood, the water-surface elevation measured at the intake was actually higher. This discrepancy was attributed to debris clearing post 1996 flood and channel incision that occurred during the flood.

Examination of changes in 1948-49 to 1999 low-water channel length indicates that the channel has not been significantly shortened over its course between Gardiner and Springdale, MT, and that overall channel slope has not been significantly modified (local and reach scale effects are currently being analyzed for). A similar comparison of changes in side-channel distribution over that time period indicates a net increase in side-channel length (in spite of a lower streamflow in the 1999 year of comparison) and suggests that significant channel incision has not occurred in response to bank and floodplain modification.

Effects of Bridges on Channel Processes and Attributes

Fourteen bridges cross the Yellowstone River within the Gardiner to Springdale study area. The location and date of construction of the bridges are given in Table22. Bridges may affect the river channel in several ways. The bridge opening typically constricts flow and this causes a local increase in velocity and erosive power, which results in "contraction" scour. If the constriction is significant a backwater may form that reduces the sediment transport capacity of the upstream channel, and aggradation of the channel occurs. Aggradation at bridges is relatively common in arid regions and the Midwest (Johnson et al 2001), and in gravel-bed rivers in the Canadian northwest (Church et al____, Kellerhals and Galay ______)

The effects of upper Yellowstone bridges on channel processes and attributes were qualitatively assessed based on comparative examination of the 1948 and 1999 channel mosaics and examination of historic channel changes at the site (Figures B1 to B7). Bridge sites, within the portion of the study area that has a delineated 100-year floodplain and floodway (USGS-WRD and USACE, 2003), were further examined and the degree of constriction of the floodplain and floodway was noted. The relative effect of the bridges on upstream and downstream channel processes was ranked from none to high depending upon the degree of floodway constriction and observed channel changes between 1948 and 1999. Due to the consistently steep slope of the upper Yellowstone, the primary zone of influence of the bridges is likely limited to a relatively short distance up and downstream (~10bankfullchannelwidths).

Table 21. Geomorphic Effects of Upper Yellowstone River Bridges

ID	BRIDGE	LOCATION	YEAR CONSTRUCTED	Relative Physical Effects	Upstream	Downstream
1	GARDINER	Near GARDINER	1930	None	---	----
2	CORWIN SPRINGS	Near CORWIN SPRINGS	1908	Low	Slight aggradation	----
3	CARBELLA	15M S EMMIGRANT	1918	None	---	----
4	POINT OF ROCKS	11M SW EMIGRANT	1958	Low	---	Slight aggradation
5	EMIGRANT	E EMMIGRANT	1949	Moderate	Aggradation[1]	----
6	MILL CREEK	3M NE PRAY	1960	None	-----	----
7	PINE CREEK	1MW PINE CREEK	1990	Low	Aggradation[2]	-----
8	CARTERS	4M S LIVINGSTON	1921	Moderate	Aggradation[3]	Aggradation
9	I-90	Near LIVINGSTON	1962	High	Aggradation/[4] Incision	Incision
10	I-90	Near LIVINGSTON	1962	High	Aggradation/[4] Incision	Incision
11	9th STREET	LIVINGSTON-9TH ST	1964	Low	Incision[5]	Slight Aggradation
12	OLD HWY/RR Bridge	NE LIVINGSTON	1934	High	Aggradation[6]	Aggradation
13	near SHIELDS R./RR Bridge	6M NE LIVINGSTON	1955	High	Aggradaton/ Incision	Aggradation/ Incision
14	SPRINGDALE	1M N SPRINGDALE	1980	Moderate	Aggradation	-----

[1 Upstream] mid-channel bar affecting channel capacity and alignment

[2] Upstream aggradation likely due to increased upstream sediment supply; bridge opening only slightly affects floodway

[3] Significant approach and abutment contraction and expansion contribute to upstream and downstream mid-channel gravel bar formation

[4] Bridge significantly constricts channel narrows and approach restricts access to former side channels; upstream aggradation effects partly offset by gravel mining; local (i.e. at site) channel incision and scour in relation to abutment and approach protection.

[5] Local contraction scour; expansion effects downstream enhance natural lateral bar formation on left bank.

[6] Significant constriction of floodway by bridge and railroad bridge approaches contribute to upstream backwater and lateral/mid-channel bar growth

Sediment Budget

A sediment-budget is a quantitative statement of the mass flux of sediment through a drainage basin, river channel or some other landscape unit. Sediment budgets account for the sources of sediment and its disposition as it travels from its origin to its eventual exit from the drainage basin (Reid and Dunne 1996) Sediment budgets can be assessed for any specified time interval ranging from geologic time to intervals of weeks or days (Roberts and Church 1986; Church and McLean 1994; Slaymaker 1993; Lane et al. 1995a; Reid and Dunne 1996).

In its complete form, a sediment budget accounts for rates and processes of erosion and sediment transport from hill slopes and in channels, and for temporary storage of sediment in gravel bars and other storage sites, and for the weathering and breakdown of sediments while in transport or storage (Dietrich et al. 1982). Complete sediment budgets are of academic interest, but are more detailed than is necessary to address contemporary channel-scale problems in the upper Yellowstone River. The principal concern of this investigation is the cumulative effect of historic river-channel modifications on channel form and stability. To construct an appropriate sediment-budget it will be necessary to analyze erosion and deposition rates in the river channel and evaluate changes in sediment storage over time (Ham and Church 2000).

NOTE: Sediment budgets are being attempted for selected channel reaches within the channel segment extending from Mallard's Rest and Carters Bridge. The primary sources of information used to construct the sediment budgets are the contemporary (1999) topographic maps and orthophotos, planimetric maps of channel change, geomorphic field observations, channel erosion information from large banks, and detailed hydrography provided by USGS-BRD (June 2003). Two significant limitations constrain the sediment-budget analysis: 1) inherent error associated with partially rectified historic channel mosaics from source photography at scales of 1:15480 to 1:40,000, limits the ability to accurately resolve lateral channel changes and the areal extent of erosion and deposition, and 2) irregular topography on dissected (ridge-and-swale) bankfull islands and gravel bars limits the accuracy of estimates of the average thickness (and thus volume) of erosional and depositional areas. Preliminary error propagation analysis indicates that with available information, 2-D morphology-based sediment budgets may only be possible for channel segments showing large lateral changes (e.g. several 100 feet). In addition, propagation of errors across several years with varying accuracy may limit the reliability of the final cumulative volume (e.g. sediment balance)-- it may be better to select the earliest year, with the most accurate historic mosaic and compare that directly with 1999 data to estimate volumetric changes and a long-term budget.

Modeling Analysis of Cumulative Effects of Historic Channel Modifications

Methods:

A one-dimensional, step-backwater hydraulic model was developed (USGS-WRD) for flood plain delineation and can also be used to evaluate historic effects of channel confinement on water-surface elevations of floods (USGS-WRD). A sediment-transport model developed by USGS-WRD can be used to examine potential cumulative effects, of different channel hypothetical stabilization scenarios, on channel hydraulic characteristics. The USGS-BRD has developed a 2-D hydraulic, fish-habitat model for selected channel segments and this can also be used as part of an integrated analysis of channel modification effects on channel hydraulics and morphology.

Monitoring Channel and Floodplain Changes:

Monitoring of the physical channel changes associated with channel modifications and revetments should be an ongoing effort with data collection protocols developed for channel segments based on contemporary channel stability (e.g. aggrading, degrading, relative stable) and geomorphic channel type. Frequency of measurement should be tied to recurrence interval of annual peak flow. All annual peak flow events with recurrence intervals greater than ~ 5 years should trigger some level of coordinated monitoring at strategic sites.

Using the detailed channel profile (compiled by DNRC from our field survey and USGS-WRD and BRD surveys) as a baseline, the elevations of all key channel controls (including the elevations of the inlet and outlet channels of key side channels) should be measured with the above frequency. 3-D channel topography data should be collected for priority channel segments (e.g. those that show incising trends) between Mallard's Rest and Livingston. These measurements provide direct useful information on channel response and potential problems (e.g. scour near Nelsons Spring Creek), provide a basis for developing 3-D sediment budgets for selected channel segments, and hydraulic information for fish habitat evaluation. Developing 3-D morphology based sediment budgets of priority channel segments is probably the most important geomorphic study need.

1:6000 black and white aerial photography should acquired for key channel segments after floods with R.I. >5 to 10 years. Photos should be controlled (aerial targets) and flown under leaf off low flow conditions in the spring (other resource areas may require photos flown under leaf on maximum canopy conditions). Alternatively LIDAR and uncontrolled stereo aerial photos could be acquired.

Future data required for permit applications, and subsequent monitoring data from river projects, should be added to the channel survey and mapping information produced by the upper Yellowstone River studies. This provides a means of updating information and making it accessible for effective use.

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APPENDIX A.
Channel Mapping Methods

Orthophotography and Topographic Mapping

1:12000 scale, black and white 1999 orthophotos

These orthophotos were created as part of a multi-agency study of the Upper Yellowstone River, extending along approximately 80 miles of the river. Partners included the Upper Yellowstone River task Force, Park Conservation District, US Army Corps of Engineers, USDA Forest Service Northern Region and Montana Department of Natural Resources and Conservation.

1: 24000 scale black and white photography was flown specifically for this project on April 11, 1999. Six strips of aerial photographs were flown parallel to the river course for a total of 91 images, using a Jena LMK 15/2323 camera with a calibrated focal length of 152.258mm. Film diapositives were scanned at 21 microns on a Zeiss/Intergraphprecision image scanner and delivered as JPEG encoded 8 bit raster files. Eighty-five film diapositives were bridged on a Wild BC3 Stereo Analytical Plotter in the Montana State Plane South Zone (2503), National Geodetic Vertical Datum of 1929 and (Horizontal) 1927 North American Datum. Map control was transferred to three plugged passpoints per photo oriented in the standard aerotriangulation passpoint configuration. DTM collection on seventy seven JPEG encoded models occurred on an Intergraph CLIX 6887 ImageStation using a combination of automatic data collection and manual point collection within Intergraph's ImageStation DTM Collection (ISDC) software. The DTMs were collected on a 100 foot grid without breaklines. Individual model DTMs were merged to create a single strip DTM and output to a triangulated irregular network (*.TTN) file. The TTN file, in concert with projected Intergraph design (*.dgn) files, were used to orthorectify selected 8 bit images, typically every other image in a strip. We used the Cubic Convolution interpolation Method to resample the images and output was as JPEG, tiled, compressed files. Orthophotos were visually matched for color and brightness and individual orthophotos were mosaicked together. The JPEG files were then converted to Tagged Image File Format (TIFF) files. All sheet collars, created in design file format, were output as DWG files and also imported into ARC for conversion to ARC coverages. The TIFF files were then registered to their corresponding ARC coverages and world files created. Spot elevations along the Yellowstone River, selected by the Montana Department of Natural Resources and Conservation (DNRC), were collected in the design files to provide a profile of water elevation as of the date of photography. These files were also output as DWG files and converted to ARC coverages. 1000 scale negatives have been produced from all TIFFs and sheet collars.

1:8000 (black and white) and 1:6000 (color) scale orthophotos and topographic mapping

This data set was prepared for the Omaha Corp. of Engineers by Surdex Corporation. The data set contains black & white and color digital orthos for the Yellowstone River in Montana . Also, included in the data set is topographic and hydrographic planimetric GIS data for the same geographic area. Project deliverables were provided in Microstation and ARC/INFO formats. The digital topographic maps prepared under this Scope of a) as a base map for hydraulic flood plain delineation, b) as a base map for mapping riverine geomorphology and flood plain attributes, and c) as a base map for monitoring long-term channel changes. This work was performed in support of the Upper Yellowstone River Cumulative Effects Investigation and in cooperation with the Montana Department of Natural Resources and Conservation (Water Management Bureau) and the Montana District U.S. Geological Survey (Water Resources Division).

The aerial photography was flown by MAP, Inc, Missoula, MT. The photography used for this mapping effort was the BW, 1 to 8000 scale (11 lines) and the color 1: 6000 scale (3 lines) following the Yellowstone River from a 1.5 miles north of Carbella to 3 miles upstream of Sheep Mtn. The original control was planned and surveyed by USDA FS Northern Region. Additional control surveys were needed for the 2 feet contour interval area and were done by Surdex Corporation. Aerial Triangulation was done for both the 1 to 6000 and 8000 scale photography using softcopy workstations by Surdex using Albany software. DTM for the generation of 4' contours and 2' contours was collected on analytical stereoplotters and softcopy workstations The 4' contours were compiled from the 1 to 8000 BW stereomodel coverage while the 2' contours were collected from the color 1 to 6000 scale coverage over the town of Livingston (4 miles south of and 2 miles north of). Hydrographic features were collected and translated to TSSDS. DTM was delivered for the 2 and feet areas in two formats, Microstation .DTM files andArcInfo TIN models. Digital Orthophotography was delivered at .5' pixels for the BW and Color areasrespectively.

Ninety per cent of all well defined features are within +/_ 2.5' positional accuracy. The vertical positional accuracy of this data set meets NMAS for 2 feet contours from the 1 to 6000 scale photography and 4 feet contours from the 1 to 8000 scale photography for topographic mapping.

Historic Aerial Photos Mosaics

Information on historic aerial photos acquired for mapping historic channel changes is given in Table A1. A subset of these were partially rectified and merged into complete Gardiner to Springdale channel mosaics for 1948-49, 1954, 1965, 1973, 1976, 1987 (partial coverage), and 1991. This data set was prepared for the Park Conservation District (Livingston, MT) by Positive Systems, Inc.(Whitefish, MT). An excerpt from the metadata for the 1991-92 channel mosaic illustrates the method used. The data set contains partially rectified, black & white digital mosaics of historic aerial photos of the Yellowstone River corridor from Gardiner to Springdale Montana based on aerial photos acquired 1991/92. The black and white, digital mosaics of the 1991/92 channel corridor were prepared for use in mapping historic changes in planimetric channel features, riparian vegetation and land use of the Upper Yellowstone River corridor. This work was performed in support of the Upper Yellowstone River Cumulative Effects Investigation and in cooperation with the Montana Department of Natural Resources and Conservation (Water Management Bureau), University of Montana, Montana State University, U.S. Army Corps of Engineers, and U.S. Environmental Protection Agency.

Black and white, 9x9in, paper copies of the 1991/92 aerial photos were scanned (Ref to scanning contractor Image Scans) at 800 dpi (the maximum resolution supported by the imagery, due to surf ace texture). Scans were then loaded , along with base imagery (USFS 1:24,000 orthophotos and SURDEX 1:6000 and 1:8000 orthophotos) onto a Windows 2000 WorkStation ; a DIME™ project file was created and a rough mosaic layout was generated. The base imagery and subject imagery (native scans of 1991/92 photos) were inspected to identify any coverage problems, and to ensure proper relative positioning (x,y translation and rotation), and scaling. DIME™ software was then used to automatically select tie points, using proprietary feature matching algorithims, within all overlapping image areas. Tie point density was greatest in the immediate channel corridor. An iterative process was then initiated that resulted in the best fit geometric transformation (or warp) necessary to match the subject image to the base. Several successive iterations of automated and manual tie point selection and adjustment were done to provide the final output mosaic. QA/QC checks were observed throughout the process and included: assessment of linear errors, identification of gaps and breaks, visual verification of subject image match to base. Radiometric color balancing was then applied to the final mosaic. Final mosaics were delivered to the Park Conservation District on CD. Delivery includes: 6 individual mosaic tiles and a complete project mosaic in GeoTIFF and MR Sid format; photo index plots; DIME™ mosaic process logs; RMSE and QA/QC reports; and metadata. Please reference DIME_Mosaic_Process_Flow_Description.doc, found within the Metadata folder, for a more descriptive DIME™ process flow.

Table A 1. Upper Yellowstone River Historic Aerial Photos

Year	Scale	Streamflow at Livingston, MT	Source
19430909	1:20000 misc	3260 cfs	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired BW paper copies from the National Archives in College Park, MD. Original photos were obtained by the U.S. Army War Dept.
19480807 19480820 19480822	1:37,400	4390 3380 3270	Mike Merigliano (UM School of Forestry, Missoula, MT tel 406 -243-4448) acquired BW paper copies from the U.S. Geological Survey, Denver CO. Original photos were obtained by USGS in support of 1950's edition topographic mapping
19490816 19490901 19490923	1:20000	3290 2530 2030	Mike Merigliano (UM School of Forestry, Missoula, MT tel 406 -243-4448) acquired BW paper copies from the U.S. Geological Survey, Denver CO. Original photos were obtained by USGS in support of 1950's edition topographic mapping
19540909	1:15840	2700	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired BW paper copies from the National Archives in College Park, MD. Original photos were obtained by the U.S. Soil Conservation Service.
19650807 19650808 19650811 19650814 19650818 19650831 19650919	1:20000	6330 6140 5800 5560 4880 3960 3400	Mike Merigliano (UM School of Forestry, Missoula, MT tel 406 -243-4448) acquired BW paper copies from the USDA, Aerial Photography Field Office, Salt, LK City, UT.
19731004	1:15840	2160	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired BW paper copies from the Montana Department of Transportation, Photogrammetry Section, Helena, MT (Bruce Larsen, Bureau Chief, tel 406 444-6321).
19760928	1:24,000	2560	BW paper copies of the photography was obtained from the U.S. Army Corps of Engineers (Mike Gilbert, US Army Corps of Engineers Omaha District, Omaha, NE (tel 402 221-3057)
19840822	1:40000	3790	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired CIR paper copies from the EROS Data Center (Sioux Falls, SD)
19870624	1:6000	4260	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired BW paper copies from the Montana Department of Transportation, Photogrammetry Section, Helena, MT (Bruce Larsen, Bureau Chief, tel 406 444-6321).
19880930	1:40000	1110	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired CIR paper copies from the EROS Data Center (Sioux Falls, SD)
19910903 19910904 19920910 19910924	1:40,000	2250 2200 2420 2110	Chuck Dalby (DNRC Water Resources, Helena, MT -- tel 406-444-6644) acquired CIR paper copies from the EROS Data Center (Sioux Falls, SD) ;

Specific accuracy information are provided for each tile in a series of ArcView 3.2 projects that show the spatial distribution of check points and the linear error associated with each. This information was used to calculate horizontal RMSE and assess compliance with map accuracy standards where appropriate. Variations in horizontal accuracy of the base imagery used to create the mosaics limit the accuracy of the mosaic tiles. Specification of horizontal accuracy is given for the channel corridor areas of each mosaic tile based on the American Society of Photogrammetry and Remote Sensing (ASPRS) Accuracy Standards for Large-Scale Maps (ASPRS Accuracy Standards for Large-Scale Maps, 1990).

<u>Historic Topographic Mapping of Large Banks</u>

This data set was prepared for the Park Conservation District and DNRC-WRD (Livingston, MT) by Horizons Inc (Rapid City, SD), under subcontract with Positive Systems, Inc (Whitefish, MT). Funding was provided by the U.S. EPA. The data set contains topographic and planimetric GIS data for seven large eroding banks located along the Upper Yellowstone River between Corwin Springs, MT and Livingston, Montana. The data were developed using photogrammetric methods to develop digital terrain models from historic aerial photos flown in 1948/49, 1973, 1976, and 1991.

Aerial photography was obtained from a 1999 mission flown by Surdex. This mapping was originally utilized for the production of orthophoto images for the Omaha Corps of Engineers. This photography was utilized as a starting point for the manual transfer of photo identifiable control locations to be used to control several dates of photography: 1948-49, 1973, 1976 and 1991 dates of photography. There were some targets locations on this photography but not enough to support a mapping effort. Therefore additional photo identifiable points were selected and surveyed to control the photography. Through an aero-triangulation process, this photography was controlled using the original targeted locations and the additional photo identifiable locations surveyed. Through this process coordinates and elevations of other photo identifiable locations were established to provide control for the other dates of photography. Each of the sites required some aero-triangulation where the photo identifiable points that were transferred from the 1999 photography were utilized to control the sites. Aero-triangulation measurements were performed on a DSR11 analytical plotter. Once aero-triangulation solutions were obtained for each site, compilation began starting with the 1973 photography, which had the lowest altitude photography and thus the best accuracy. A map scale of 1”=200’ with 10’ contours was utilized as this was the best scale and contour interval that could be obtained from the majority of the dates of photography. A DEM was collected to support this scale and contour interval through current methodologies of stereo compilation. All collection was done on a DSR11 analytical plotter with one operator performing all the map compilation. Mass points and breaklines were collected with enough density to support the scale and contour interval specified. Once the area was collected from the 1973 photography, the subsequent dates of photography were set and the mapping from the 1973 photography was utilized as the base map. The areas of change from the 1973 photography were updated to reflect the ground conditions found in that date of photography. The 1973 mapping was utilized as the base for all the dates of photography and during compilation the areas that appeared to have not changed were checked and found to be good thus giving us confidence in our process. Once all the sites were collected from the various dates of photography, contours were generated and edited for each site and then translated to AutoCAD for final delivery to the client. Delivery consisted of 2 sets of CD-ROM with AutoCAD14 release files for each of the seven map areas. A DTM file, which contains all the 3-D data that, can be triangulated to generate a surface model and a separate file with the contours and planimetric data. Deliverables also included aero-triangulation reports for each area, a completion report that described the personnel, equipment, methods used to perform the topographic and planimetric mapping, and one set of diapositives providing coverage for each of the seven map areas.

APPENDIX B.
Channel Description Methods

Delineation of Contemporary and Historic Channel Features

Low-water and bankfull main channel features:

Channel features were mapped for low and high discharge regimes. Historic and contemporary (1999) photo mosaics were obtained at low discharges (ranging from 1500 cfs to 4400 cfs, and the waters edge and gravel bars/islands were mapped at that flow. However, features mapped at low flow do not accurately indicate the dimensions of the larger "bankfull" channel, especially the banks of the channel and islands, which may be far removed from the low flow waters edge. Accordingly, the estimated bankfull channel was delineated on the 1999 orthophoto base using stereo-photo interpretation, supported by project topographic mapping, and field GPS observations. Comparison of the estimated bankfull channel and island boundary elevations, with modeled 2 to 5 year flood flow elevations (U.S. Geological Survey, Montana District, provisional data 2003) at locations between Mallards Rest and Carters Bridge, showed close agreement at about 90% of the locations mapped.

Low-water channel features were relatively unambiguous to map. Bankfull features require careful and consistent interpretation across channel segments in a given year and between successive years. The 1999 bankfull channel banks were mapped based on a variety of criteria and the lines were assigned one of 10 attribute classes that describe the criteria (Table B1).

Table B1. 1999 Bankfull channel delineation attributes

ID	Bankfull criteria	Code
1	Base woody vegetation	bwv
2	Base of shrubs	bsh
3	Top of erosion scarp on bank	teb
4	Mid-point between top scarp on eroding bank and waters edge	meb
5	Channel laterally confined by natural features (e.g. terraces)	cnat
6	Channel bank modified by man	cman
7	Channel laterally confined by bedrock	cbrock
8	Estimated	est
9.	Estimated / shadows in trees	ests
10.	Estimated /top inset bench	tib

Most commonly the bankfull channel was demarcated by the base of permanent woody vegetation and well established shrubs, an erosion scarp, or an inset bench in some confined-incised channel reaches. Due to the confining nature of glacial and fluvial terraces, bankfull stage (water surface elevation at bankfull flow) frequently does not correspond to the elevation of the floodplain or valley flat adjacent to the channel, in these channel reaches the above criteria were used where applicable or an operational criteria was used (e.g. mid point between low water and top of sloping bank); the same was done in heavily revetted channel segments. 1999 bankfull islands were mapped using the same approach.

The 1948-49 bankfull channel features were mapped by superimposing the mapped 1999 bankfull channel features on the 1948-49 channel mosaic and then editing the 1999 coverage to reflect the differences shown on the 1948-49 mosaic. The 1948-49 bankfull channel features were mapped based on careful stereo-photo interpretation of the historic and 1999 aerial photos.

1948-49 and 1999 side channels

Side channels were digitized on the 1948-49 historic photo mosaic and 1999 orthophotos and entered into a GIS for analysis. The 1948-49 aerial photos that the project mosaic is based on varied over a discharge range of 2030 to 4390 cfs. The 1999 photos were obtained at a steady flow of 1500 cfs; stage variation over the range of 1500 cfs to 400 cfs is about 1.4 feet (Carter's Bridge USGS gage) and 2.2 feet (Corwin Springs USGS gage). These differences, if not accounted for, could significantly bias the analysis and lead to the apparent conclusion of a reduction in side channels carrying flow over time.

Lacking historic channel topographic information, we could not account for effects of differing river stages, on side-channel abundance, quantitatively. Instead we used a semi-quantitative flow descriptor (continuous flow; backwater/ponded; dry) to identify the relative state of streamflow in the side channel being digitized--this allows some level of interpretative accounting of the effect of differing flows on side-channels. For example, if the side-channel was present and has continuous flow in 48-49 at a Q of 4390 cfs and continuous flow is still present at 1500 cfs in 1999, then one can conclude that if channel incision has occurred, it has been less than 1 to 2 feet.

In the comparative analysis, the 1948-49 side channels were digitized and classified first. Next the 1999 side channels were digitized and classified and the two were overlain on the 1999 orthophoto base. The first comparison being made is to identify areas where lateral processes have significantly changed ("created" or "destroyed") side channels. Then the 1948-49 and 1999 side channels that have continuous flow were identified. Finally side channels that had continuous flow in 48-49 , but were dry in 1999 were examined (stereo photos) to determine if the channel was still connected at higher flows, (bare gravel and other evidence of recent flow), or if the channel had been abandoned, filled in, overgrown by vegetation or otherwise clearly removed from functional side-channel status.

Channel Slope and Profile

Topographic Mapping

Elevation and distance data for the channel from Gardiner to near Point of Rocks was extracted (by USFS) from the DTM developed to control preparation of 1:12000 scale orthophtos[12]. Elevation data for the channel from Point of Rocks to the Shields River confluence was extracted from the 2ft and 4ft contour mapping and orthophotography performed under contract to USACE..

Detailed Study Area (Mallards Rest to 9th Street Boat Ramp)

Field survey data for a detailed channel profile were collected between September 10 and 27, 2001 (Q range at Livingston 1160 to 1360 cfs). Data were collected using Sokkia survey-grade GPS equipment

[12] Each sheet in the USFS orthophoto series was independently controlled from 1:24000 scale USGS quads and edge effects are apparent in the channel profile--because vertical accuracy of control points is ±10 feet, adjacent sheets may have disparate elevations. Channel elevation data should be used in a relative sense for estimation and comparison of channel slopes.

and kinematic methods. The network of 63 aerial target points established by USFS-DNRC in April 1999 was used to control the GPS data to Montana State Plane, North American Datum of 1983 (feet) and National Geodetic Vertical Datum of 1988 (feet). GPS data presented are accurate in x and y to ± ±3 feet; elevations are accurate to at least ± 1 foot (elevations of USGS cross-section pins near bankline, where occupied were generally within ± 0.5 feet of the elevations established by USGS by leveling). Although the data has not been extensively quality checked and compared with the 2 and 4 foot contour mapping developed by Surdex, limited inspection indicates good agreement between the two commonly controlled but independently developed sources of channel profile information.

GPS observations were taken to provide information for several purposes: channel profile, bank erosion mapping, estimation of bankfull stage (usually not "bank-top"), and locating various features of interest. Data are provided in several shapefiles and include a site name column in the attribute table that provides descriptive information about each observation (usually the location as shown on the 1:6000 and 1:8000 scale orthos is explanatory).

Description of Contemporary and Historic Channel Modifications

Channel Modification and Bank Erosion Inventory (CMBEI)

Human channel modifications include a variety structural elements used primarily to: 1) inhibit bank or bed erosion, or (2) confine or divert flood flows. In addition, transportation corridors (roadways and bridge approaches) and other civil works may confine or redirect flows. Channel modifications may be applied to erosion problems occurring locally over short reaches of channel (< one bankfull channel width) or to longer channel segments (several to many channel widths) in an attempt to generally eliminate bank or bed erosion.

A Channel Modification and Bank Erosion Inventory was prepared for the upper Yellowstone River from Gardiner, MT to Springdale, MT. The NRCS Physical Features Inventory (NRCS-PFI) was used as the starting point for preparing the Channel Modification and Bank Erosion Inventory (CMBEI). The first step was to edit the NRCS-PFI features for horizontal positional accuracy; this was accomplished by selecting and moving features to the position that visibly (and most closely) agreed with the features location on the USFS or USACE orthophotos.

Using the above as a starting point, 1999 aerial photos of the channel from Gardiner to Springdale were viewed in stereo and a variety of adjustments to the NRCS-PFI were made: some features were reclassified; spatial extent of features were increased or reduced as appropriate, and new features were added (especially eroding banks). Additional information used to supplement the stereo-photo interpretation included, field notes and mapping done in August and September 2000 and 2001 , and the projects topographic mapping (2ft and 4ft contours).

As a general rule, the CMBEI was edited to include all features present on the 4-11-1999 aerial photos used for interpretation[13]. No attempt was made to update the inventory to include more recent features--. Similarly, the emergency dike constructed through Sacagawea Park is shown, although much of it has subsequently been removed.

[13] For river management and permitting purposes there is a need to maintain a current inventory of channel modifications. For the geomorphology analysis (statistical comparisons using contemporary information) of effects of channel modification, the CMBEI needs to be current as of the date of the 4-11-99 aerial photos and topographic mapping.

This inventory includes the entire population of eroding banks along the Upper Yellowstone River. No distinction is made between the level of activity (e.g. active/inactive; rate of erosion; new vs. old) or potential importance as a sediment source. Eroding banks were mapped based on several criteria: channel bank morphology and presence or absence of scarps and skewed trees, truncation of fluvial features, and hydraulic position. Many of the new eroding banks denoted are located on dissected islands in disturbance zones, and the left or right bank designation applies to the channel that dissects the island. Additional analysis of eroding bank status is being conducted using the following criteria to further stratify and classify the banks:

1. Predominant failure mode: mass wasting; fluvial entrainment; combined
2. Historic erosion rate at a bank: average linear retreat rate (area of eroded polygon/length of bank) and area of erosion over time period 1948-1999 (selected sites other years).
3. Average bank height above low water surface
4. Bank material composition and vegetation cover (very generalized)
5. Fluvial environment: channel type, alignment etc.

Historical Channel and Floodplain Modifications – 1954. 1973, 1987, 1999

To better understand the history of channel modification and its effects fluvial geomorphology, a historic inventory was compiled using information from several sources. The years 1954 and 1973 were selected based on the availability of aerial photos with appropriate scale for discerning features of interest to the geomorphic investigations – dikes, levees, barb, jetties and rip-rip. The years 1987 and 1999 were selected based on the availability of pre-existing physical feature inventories and the availability of large-scale high quality aerial photography.

Structure type and location for 1999 features was obtained first from the physical features inventory conducted in 1998 by Task Force volunteers with technical assistance from the NRCS. This inventory was later expanded as part of this work through examination of 1:6000 and 1:8000 scale electronic orthophotos combined with topographic contour maps. The topographic contour mapping allows identification of previously unmapped floodplain feature such as dikes and levees. Similarly, structure type and location for 1987 were obtained from a 1987 Physical Features Inventory sponsored by the Montana Department of Health and Environmental Sciences and conducted in cooperation with Park CD. This 1987 information was transferred from the original, marked hardcopy, photos into a geographic information system (GIS). Structure information for 1954 and 1973 were mapped directly off 1:15,840 scale hardcopy black and white aerial photos using a high-resolution, desktop stereoscope then transferred into a GIS.

Relevant information was compiled within the GIS and grouped according to pre-established reach breaks. For purposes of historical feature mapping, the entire study reach was divided into eight geographic subreaches:

1. Gardiner to Carbella Bridge
2. Carbella Bridge to Eight-Mile Creek
3. Eight-Miles Creek to Pine Creek Bridge
4a. Pine Creek Bridge to Carters Bridge
4b. Carters Bridge to I-90 Bridge
5. I-90 Bridge to Railroad Bridge
6. Railroad Bridge to Shields River
7. Shields River to Springdale

Appendix C.

Description of Bed-Material at Selected Sites Along the Upper Yellowstone River: Gardiner to Springdale, Montana

Introduction

The texture and grain-size distribution (GSD) of river-bed sediments are important variables that influence hydraulic roughness, particle entrainment, sediment transport, channel stability, distribution of riparian growing sites, and the quality of fish habitat. Accordingly, a variety of methods have been developed to describe bed-material characteristics relevant to each area of interest (Bunte and Abt 2001). The focus of sediment data collection and description for this project was to provide information for geomorphic channel description and classification, geomorphic analysis (e.g. many hydraulic comparisons use dimensionless parameters scaled to D_{50} of grain-size distributions), and data for use in sediment-transport modeling (USGS-WRD).

Information on channel-bed surface GSD was collected at about 40 sites along the Upper Yellowstone River Between Corwin Springs and Gardiner Montana (Figures 1 and 2) . Most of the quantitative information was collected within the "detail study segment" that extends from Mallards Rest to Livingston, MT. Information on subsurface, grain-size distribution was collected at 8 sites located between Mallard's Rest Fishing Access Site and Livingston (RR Bridge).

Methods

Channel-bed sediments in gravel-bed rivers commonly display great lateral and vertical variation in particle size --this variation typically occurs at three spatial scales: at a specific site or sampling location; within a channel reach (defined as an area extending several channel widths in length and encompassing a pool-riffle or alternate bar sequence) ; and at the broader watershed scale, river-bed sediments typically become finer along a downstream gradient of channel slope from the headwaters.

Spatial variation in grain size at the surface of the channel occurs in response to hydraulic sorting and spatial distribution in surface grain size, along the channel, is closely linked with the morphology and spacing of alternate gravel-bar / pool-riffle units. All of the upper Yellowstone channel types display longitudinal and vertical variation in grain-size distribution, however the range in grain size is greatest and continuity of homogeneous units tends to be smaller, in the pool-riffle, anabranching and anabranching-braided channel types.

Vertical variation in particle size occurs due to the combined effects of: 1) hydraulic sorting during bedload transport, 2) vertical stratification that results from scour and fill during snowmelt runoff, and 3) size-selective entrainment of surface particles (e.g. winnowing of fines). Typically the surface layer of the channel bed has a grain-size distribution that is significantly coarser than the subsurface -- the median grain size of the surface[14] may be several times (~2-4) greater than that of the subsurface

Longitudinal and vertical variation in channel-bed sediments present two principal challenges to the description and measurement of GSD: 1) developing a sampling strategy that allows extrapolation of essentially "point" samples at a site to the larger population or comparison of similar hydraulic strata (e.g.

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[14] The surface layer in gravel-cobble streams is operationally defined as a layer 1 particle thick and the D_{90} of the surface is used as the reference particle size to estimate the layer thickeness when measuring subsurface GSD.

upstream ends of alternate bars) , and 2) development of accurate (precise and unbiased) methods for collecting point samples. Sampling protocols were developed to address these potential problems.

Surface Sampling

Methods for measuring the GSD of surficial sediments at a site typically involve grid or areal samples collected by point counts. Surface sampling was done by particle counting ("pebble-counts") and size-distribution was determined as frequency by size. Pebble counts were accomplished using the method of Wolman (1954) as modified by others (Leopold 1970; Marcus et al. 1995; Wohl et al 1996; Kondolf 1997; Wolcott and Church 1990; Buffington and Montgomery 1999; Petrie and Diplas 2000; Rice and Church 2000; and Latulippe et al. 2001). The principle problems that are encountered in sampling and describing river-bed sediments and our approach to minimizing these are given in Table C1.

Table C 1. Approach to Minimizing Bed-material Sampling Bias and Errors: Upper Yellowstone River Geomorphology Study

Potential Problem	Solution	Comment
Hydraulic sorting, spatial variation and the need to sample homogeneous single populations (facies or "patches')	Stratify channel reach into homogeneous patches and sample preferred strata	For basin wide comparisons (e.g. downstream fining) focus sampling on single hydraulic environment—upstream end of point or lateral bars/ for sediment transport sample recently active bed-sediments .
Coarse sediments are often poorly sorted (e.g. wide variety of sizes) and small samples do not provide unbiased estimates of population parameters	In poorly sorted coarse surface sediments we typically sampled 300 particles per pebble count (representing a surface area of about 400 to 600 ft^2)/ sample subsurface using 1% criterion.	Sample sizes of 100 may be adequate to estimate D_{50} in moderately well sorted surface patches; in poorly sorted patches a larger sample size is required.
Use of the index finger to select surface particles introduces observer bias and limits the lower size of sampling to about 8mm.	Use of a laser pointer to select particles reduces observer bias and increases the sample resolution to about 2mm	Also reduces bias in bimodal distributed sediments and lowers or eliminates the need to truncate distributions
Different observers introduce different bias into sampling due largely to surface particle selection methods	Standardize particle selection methods using a grid-by-tape layout (with selection interval scaled by 2X estimated D_{90}) and use of a laser pointer to select particles for counting	Grid by tape is the most adaptable and reproducible method. Tape lines are laid out within a homogeneous patch and sampling interval is scaled to approximately 2 times the D_{90} to ensure sample independence
Different observers introduce different bias into sampling due to variation in measurement of intermediate particle diameter	Use metal template ("gravelometer) based on sieve sizes instead of pocket tape	Used the FISP, US SA-97 template with 1/2 ϕ intervals

To obtain relatively precise, unbiased estimates of surface bed-material sample parameters ($D_{10 \text{ or } 16}$; D_{50}; $D_{84 \text{ or} 90}$) in poorly sorted sediments, typical of the upper Yellowstone R, requires sample sizes of ~200 to 400 particles (Wolcott and Church 1989; Fripp and Diplas 1993; Rice and Church 1998; Ferguson and Paola 1997). This is time consuming and limits the ability to provide reasonably precise description of lateral and longitudinal variation in large gravel-bed rivers. An alternative is to use visual characterization methods that allow more rapid estimates of gravel percentiles for a larger number of sites, but at some reduced level of precision and increased bias.

A recent method for rapid visual characterization of surface GSD (Latulippe et al 2001) was tested, but found to perform poorly on the coarse, poorly sorted, bimodal sediments typical of the upper Yellowstone River (visually estimated D_{50} were ± 25 to 50% of measured values in poorly sorted gravel-cobble "patches"). Therefore a more generalized description of surficial sediments was done (in progress) using the textural classification of Buffington and Montgomery (1999).

Subsurface Sampling

Subsurface material was sampled volumetrically and GSD was determined as frequency by weight within a given size class. Samples are typically collected for bulk sieving and this presents a logistical problem for gravel with large clasts; to obtain a large enough sample for reproducible sieving, one must collect a very large sample. A variety of criteria exist for determining subsurface sample size (Church et al. 1987;Wolcott and Church 1991; Ferguson and Paola 1997; Pertie and Diplas 2000). Several guidelines are based on the criteria that the largest particle should not comprise more than 0.1 to 1% , by weight, of the total sample. This means that if the largest clast in the subsurface sample is 100mm, one needs a sample between 1300kg (0.1% criterion) and 130kg (1% criterion).

Sample sizes this large can be collected by mechanical excavation and transport to a materials lab (not practical) or by establishing a field lab onsite and processing the material on-site. Table C2. describes our method for measurement of subsurface GSD.

Table C2. Bed-material Sampling Protocol

1. **Locate sample site** on recently transported gravels representative of the currently active bed-material in the channel.

2. **Measure surface-size distribution in 2, 1-m grids** and spray paint particles for removal of surface layer and subsurface sampling.

3. **Sample sub-surface size distribution of 2, 1 meter grids**

   a. at each 1m grid determine the depth of subsurface material to remove; typically this is limited by active scour depth which usually corresponds to a depth of ≅ $2xD_{90.}$ (roughly about 0.3m); locate largest clast and scale sample weight (and volume) to ensure sample size such that largest clast is not > 1%, by weight, of total sample weight.

   b. excavate each sample, place on plastic tarp for air drying of particles >11mm size

4. **Measure surface particle size distribution** (pebble counts) in vicinity of sample grids (one 300 pebble count).

5. **Hand sieve each subsurface sample on tarps** (do as team).

   a. -hand sieve each sample (using gravelometer template) particles > 90 mm in size and place in tared buckets for weighing with certified balance or spring scale;

   -hand sieve (using ASTM sieves) particles between 90 and 11mm in size and place in buckets for weighing with certified balance or spring scale;

   -collect, sub sample and bag material < 11 mm for sieve and moisture analysis at MDT.

6. **Calculate subsurface GSD**

   a. Adjust fine material weight to dry weight using moisture content analysis from lab

   b. Combine coarse GSD and fine GSD to give total subsurface GSD.

Results

Locations and descriptions of sample sites are given in Appendix D. Data collected on surface GSD are given in Table D1 and Figures D1-D10. Data collected on subsurface GSD are given in Appendix E. and Figure E1. Surface sediments generally follow a lognormal distribution, but tend to be strongly bimodal (with fine tails) in lower energy depositional environments typical of anabranching and anabranching/braided channel types. Subsurface sediments are bimodal to polymodal and the D_{50} is typically 2 to 4 times smaller than that of the surface layer at the site.

Variation in grain size at the surface of the channel occurs in response to hydraulic sorting and spatial distribution in surface grain size, along the channel, is closely linked with the morphology and spacing of alternate gravel-bar / pool-riffle units. Throughout the Upper Yellowstone River Study Area, upstream ends of lateral (alternate) , mid-channel and point bars typically are high-energy environments with coarser sediments (boulder-cobble) which grade downstream into finer size gravels (cobble-pebble) and sand. Sand and silt are commonly deposited in minor amounts (<5-10% of exposed bar area at Q=1500 cfs), within the plane-bed and pool-riffle channel types. Surficial sediments in anabranching and anabranching braided channel types generally contain a wide range of grain sizes (boulder to sand), but with a larger percentage of pebble-size material and greater areal extent of sand and silt. Frequently the downstream end of the channel bar, corresponds with a flow-separation zone, and the eddy created, deposits fine sands and silts; areas of fine sediment deposition tend to be very limited in the bedrock, cascade and plane-bed channel types -- which lack sediment storage sites and distinct bar morphology, and are more common in the pool-riffle and anabranching/braided channel segments.

Broad-scale spatial differences in the relative abundance of different sedimentary units (i.e. coarse to fine sediments) in the channel network, depend upon position in the channel network between Gardiner and Springdale MT. Upstream from Livingston, MT, the channel flows through Pinedale age, glacial till and fluvio-glacial sediments which causes regional and local variation in sediment sources and characteristics; in addition channel entrenchment and confinement by glacial terraces, restricts depositional areas and concentrates high flows. Bed-material transport in these reaches tends to be supply limited and surface texture tends towards boulder- cobble and boulder-gravel-cobble sediments. Downstream from MallardsRest[15] the Yellowstone River becomes less confined by terraces (often bounded on one side only) and impinges on high banks containing coarse poorly sorted glacial sediments; these materials provide abundant sources of coarse and fine (primarily silt and sand) sediment and bed-material discharge is primarily transport limited.

Downstream from Livingston (reconnaissance observations only), the channel leaves the mountain front and carves through older Pleistocene terraces (and pediments), frequently exposing Paleozoic and Mesozioc bedrock. Multiple thread channels with broad flood plains are interspersed (e.g. Shields R to Mission Cr) with partially bedrock controlled plane-bed channels; extensive fine-sediment accumulations are stored within the active flood plain of the anabranching and anabranching/braided channels, in contrast to the supply-limited, plane bed reaches that display similar GSD's as upstream from Livingston. Although there are local fining trends in surface GSD between Gardiner and Springdale, there does not appear to be a significant overall reduction in particle size --likely a reflection of the relatively steep channel slope throughout the study area and continuing source areas of coarse sediment along the upper Yellowstone River[16].

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[15] And within several anabranching channel segments located between Point of Rocks and Mallards Rest.
[16] The Gardiner to Springdale study area also represents only a portion of the longitudinal channel profile and downward fining of bed material is evident at the larger basin scale.

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Appendix D.
Description of Bed-Material Sample Sites

Sample sites are listed in the following attribute table (Table D1. corresponds to ArcView attribute table). The geosite number corresponds to the site location given in the attribute table and to the GSD's shown in Figures D1-D10. Data collection sites served one or several purposes and this is denoted by the ID in the table:

PSV.	Collection of reconnaissance-level data for channel classification and visual estimation of surficial-particle size
PC.	Collection of surface particle-size data using pebble-count methods
PCT.	Tracer particle installations for post runoff assessment of particle mobility
SSP.	Collection of surface and subsurface particle size-distribution information.

Coordinate System

All polygon and point data are in the State Plane Montana coordinate system and referenced to the North American Datum of 1983 (SPNAD83) and units of feet. Point data were field located on stereo aerial photos and manually transferred to the orthophoto base. Horizontal accuracy is approximately ± 30 feet for point data located on the USFS orthophoto base and ±15 feet on the USACE (Surdex) orthophoto base.

Table D1. Description of Sample Sites

Upper Yellowstone River: Description and Location of Bed-Material Sampling Sites
PROVISIONAL DATA SUBJECT TO REVISION: Chuck Dalby, DNRC-WRD, Helena, MT 406-444-6644

ID	GEOSITENO	DATE	DESCRIPTIO	LOCATION	HYDENV	X_COORD	Y_COORD
PCT	5.0	4/6/2000	pebble counts/ tracer gravel	~900 ft u.s. C.S. Bridge/l.bnk/alt.bar	A	1635174.61	316229.34
PCT	6.0	4/6/2000	pebble count/tracer gravel	~85 ft d.s. USGS cableway	B	1634399.44	317456.75
PSV	7.0	8/12/2000	visual part size			1606986.00	353372.91
PSV	8.0	8/12/2000	visual part size			1608596.02	355231.56
PSV	9.0	8/12/2000	visual part size			1612360.19	360949.72
PSV	10.0	8/12/2000	visual part size			1614665.22	364371.31
PCT	11.0	4/5/2000	pebble counts/tracer gravel	~3330 ft d.s. Hwy Bridge/u.s.end alt-mid chan ba	A	1616567.46	369335.11
PSV	11.1	8/12/2000	visual part size			1616784.15	369455.06
PSV	12.0	8/12/2000	visual part size			1617794.98	372386.04
PSV	13.0	8/12/2000	visual part size			1621212.34	375807.63
PSV	14.0	8/13/2000	visual part size	HWY rest stop/ d.s. end mid chan bar	C	1625916.29	384052.07
PC	14.1	9/11/2001	pebble counts	HWY rest stop/u.s. end mid-chan bar	A	1625289.88	383774.72
PC	14.2	9/11/2001	pebble counts	HWY rest stop/ u.s. end mid chan bar	A	1625505.61	383754.25
PSV	15.0	8/13/2000	visual part size			1632976.30	391000.99
PSV	16.0	8/13/2000	visual part size			1643307.33	397556.22
PSV	17.0	8/13/2000	visual part size			1645830.26	399631.47
PSV	18.0	8/13/2000	visual part size			1649759.75	400784.85
PSV	19.0	8/13/2000	visual part size			1650753.36	405068.85
PSV	20.0	8/13/2000	visual part size			1653179.96	408244.40
PC	20.1	9/26/2000	pebble counts	mid chan bar/Em. fish acc/ u.s. end mid chan ba	A	1653199.28	408396.09
PC	20.2	9/26/2000	pebble counts	mid chan bar/ Em fish acc/ mid-point mid chan ba	B	1653393.94	409155.74
PC	20.3	9/26/2000	pebble counts	mid chan bar/Em fish acc/ d.s. end mid chan bar	C	1653511.63	409370.43
PSV	21.0	8/14/2000	visual part size			1653988.83	412143.93
PSV	22.0	8/14/2000	visual part size			1655381.88	414875.11
PSV	23.0	8/14/2000	visual part size			1657793.50	416193.26
PC	23.1	8/13/2001	pebble counts	d.s Grey Owl/ L. bnk/ mid chan bar	B	1658673.92	419090.24
PSV	24.0	8/14/2000	visual part size			1660308.50	423677.53
PSV	25.0	8/14/2000	visual part size			1671803.09	427213.83

PCT	26.0	4/5/2000	pebble counts/tracer gravel	d.s. Mill Cr. Br/R. bnk/cobble-boulder bank	A	1675489.29	428541.86
PSV	27.0	8/14/2000	visual part size			1678868.89	434001.18
PSV	28.0	8/14/2000	visual part size			1678368.42	437334.55
PSV	29.0	8/15/2000	visual part size			1683515.47	444374.31
PC	29.1	9/26/2000	pebble counts	~1500 ft u.s. Mall. Rest/ u.s. end alt. bar, Lb	A	1682129.40	451013.81
PC	29.2	9/26/2000	pebble counts	~1500 ft u.s. Mall. Rest/ u.s. end alt. bar, Lb	B	1681949.62	451113.83
PSV	30.0	9/28/1999	visual part size			1681280.34	452645.46
PC	30.1	8/14/2001	pebble counts	~300 ft d.s. Mall Rest/ u.s. end pt bar, Rbnk	A	1681331.34	452779.30
PC	31.0	9/28/1999	pebble counts	~1700 ft d.s. Mall Rest/ u.s. end alt bar/ Lbnk	A	1682112.51	453505.93
PSV	32.0	8/15/2000	visual part size			1684915.66	453262.26
PSV	32.1	9/28/1999	visual part size			1685036.72	453379.49
PC	33.0	9/28/1999	pebble counts	d.s. AA barbs/ u.s. ende/mid-chan bar/barb infl	A/C	1688467.75	455896.06
PC	34.0	8/14/2001	pebble counts	d.s. end mid-chan-lat bar/	C	1688839.48	457008.75
PC	35.0	8/15/2000	pebble counts	u.s. end mid-chan bar/island/	A	1689904.20	457743.31
SSP	36.0	8/14/2001	surface/subsurface part size	d.s. end mid-chan bar	C	1690524.50	457868.34
SSP	37.0	8/15/2001	surface/subsurface part size	middle/ mid chan bar	B/C	1690845.94	459488.55
SSP	38.0	8/15/2001	surface/subsurface part size	~1000 ft u.s. Pine Cr. Br/ d.s end mid chan bar-	C	1691593.99	460787.63
PCT	39.0	4/4/2000	pebble counts/tracer gravel	~250 ft d.s. Pine Cr Br/ u.s. end alt,bar	A	1690999.04	462021.32
PC	39.1	9/28/1999	pebble counts	~350 ft d.s. Pine Cr. Br/ u.s. end alt. bar/ LBn	A	1690988.96	462161.61
PC	39.2	4/12/2001	surface part size est/grid p.c.	~425 ft d.s. Pine Cr. Br/ u.s. end alt. bar/ LBn	A	1690974.15	462230.11
SSP	40.0	8/16/2001	surface/subsurface part size	~500 ft u.s. Weep WL/ d.s. end pt bar	C	1692639.95	464004.01
PSV	41.0	9/13/2000	visual part size			1693254.34	464266.03
PC	42.0	9/13/2000	pebble counts	u.s. end mid chan bar	A	1691445.23	467126.23
PC	42.1	9/13/2000	pebble counts	d.s. end mid chan bar	C	1691486.72	467358.01
PC	43.0	9/9/1999	pebble counts	d.s. end point bar	C	1692024.21	468564.89
PC	44.0	9/13/2000	pebble counts	d.s. end point bar	C	1692061.35	469648.10
SSP	45.0	8/16/2001	surface/subsurface part size	d.s end alt bar/ Bbnk	C	1691185.92	470465.50
PC	46.0	9/13/2000	pebble counts	pt bar east or Ohair/Rosgen prj/ mid-point bar /	A	1690648.13	471570.10
PC	46.1	9/28/1999	pebble counts	pt bar east or Ohair/Rosgen prj/ mid-point bar /	B	1690857.81	471977.02
PC	46.2	9/28/1999	pebble counts	pt bar east or Ohair/Rosgen prj/ mid-point bar /	B/C	1690958.81	471936.15
PSV	47.0	9/30/1999	visual part size			1691557.67	474307.77
PC	47.1	9/13/2000	pebble counts	alt. bar-point bar/ u.s. end	A	1691477.00	474367.19
PC	48.0	9/30/1999	pebble counts	u.s. end point bar/	A	1691717.36	476144.62
PC	48.1	9/30/1999	pebble counts	d.s end point bar	C	1691669.73	476613.42

PC	49.0	9/13/2000	pebble counts	middle of point bar/ RBnk	B	1690380.90	477781.07
PC	49.1	9/13/2000	pebble count	u.s. end mid-chan bar-island	A	1690463.57	479669.66
PSV	50.0	9/13/2000	visual part size			1689955.40	480363.69
PC	50.1	9/30/1999	visual part size			1689958.90	480721.58
PC	51.0	9/14/2000	pebble counts	u.s. end mid c. bar/ near Dana/Nelson barbs	A	1691339.62	483396.04
PCT	52.0	4/4/2000	pebble counts/tracer gravel	middle, alternate bar/incised reach	AB	1693100.39	485173.97
PSV	52.1	9/30/1999	visual part size			1693613.37	485715.28
PSV	53.0	9/30/1999	visual part size			1694039.77	488406.38
PC	53.1	9/14/2000	pebble counts	d.s. end medial/point bar	C	1694256.17	488747.10
PCT	54.0	4/3/2000	pebble counts/tracer gravel	u.s. end alternate bar	A	1694385.56	489166.16
PC	54.1	9/14/2000	pebble count	middle alterante bar/affected by barb eddy	B	1694935.39	490272.48
PC	55.0	9/24/2001	pebble counts	u.s. Carters Bridge/ u.s. end mid chan bar	A	1695539.71	492642.18
PC	55.1	4/3/2000	pebble count	u.s. Carters Bridge/Rbnk u.s. end mid chan bar	A	1695515.64	492730.31
PC	55.2	4/3/2000	pebble count	u.s. Carters Bridge/ Lbnk mid point bar	B	1695570.49	492874.75
PCT	56.0	4/4/2000	pebble counts/tracer gravel	d.s. Carters Bridge/ Rbnk/ u.s. end alt. bar	A	1695680.38	493192.51
PC	57.0	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/coa	B	1695704.73	493329.58
PC	57.1	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/coa		1695700.21	493330.08
PC	57.2	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/coa		1695694.71	493330.58
PC	57.3	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/coa	BA	1695689.01	493331.49
PC	57.4	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/fin	B	1695717.98	493327.96
PC	57.5	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/fin	B	1695724.47	493328.09
PC	57.6	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/coa	BA	1695752.51	493327.56
PC	57.7	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar/coa	BA	1695748.33	493286.11
PC	57.8	9/29/1999	pebble counts	d.s. Carters Bridge/ Rbnk/ mid point alt bar	BA	1695692.68	493317.61
SSP	58.0	4/9/2001	surface/subusrface part size	d.s. Carters Bridge/ Rbnk/ d.s. end alt bar	CA	1695725.62	493467.66
SSP	58.1	4/10/2001	surface/subsurface part size	d.s. Carters Bridge/ Rbnk/ d.s. end alt bar	CA	1695719.77	493439.34
SSP	58.2	4/10/2001	surface/subsurface part size	d.s. Carters Bridge/ Rbnk/ d.s. end alt bar	CA	1695729.34	493409.77
SSP	58.3	4/10/2001	surface/subsurface part size	d.s. Carters Bridge/ Rbnk/ d.s. end alt bar	CA	1695728.61	493389.77
PC	59.0	9/12/2000	pebble counts	d.s. Carters Bridge/u.s. end mid chan bar	A	1695615.64	493602.18
PC	59.1	9/12/1999	pebble counts	d.s. Carters Bridge/ u.s. end mid.chann. bar./fi	A	1695534.02	493639.03
PC	59.2	9/12/2000	pebble counts	d.s. Carters Bridge/ d.s. end mid.chann. bar./fi	C	1695685.66	494379.16
PC	59.4	9/12/2000	pebble count	mid point of large alternate bar/coarse bank	B	1694090.39	497294.38
PC	59.3	9/12/1999	pebble counts	d.s. Carters Bridge/ d.s. end mid.chann. bar./fi	B	1695519.44	494430.22
PSV	60.0	9/11/2000	pebble counts	u.s. end large medial bar	A	1693884.10	498642.38

PC	60.1	9/11/2000	pebble count	d.s. end large medial bar	C	1694016.84	499203.48
PC	60.2	9/11/2000	pebble count	mid point , mid channel/diagonal bar/LWD fines	B	1694214.72	502919.67
PC	61.0	9/11/2000	pebble counts	u.s. I-90 Bridge/ u.s end alt bar	A	1696263.43	510044.23
PC	61.1	9/11/2000	pebble counts	u.s. I-90 Bridge/ u.s end alt bar	A	1696262.58	510031.37
PC	61.2	9/11/2000	pebble counts	u.s. I-90 Bridge/ u.s end alt bar	A	1696262.89	510017.48
PC	61.3	9/11/2000	pebble counts	u.s. I-90 Bridge/ u.s end alt bar	A	1696259.58	510001.34
PC	61.4	9/11/2000	pebble counts	u.s. I-90 Bridge/ u.s end alt bar	A	1696258.14	509985.95
PC	61.5	9/11/2000	pebble counts/95%< 2mm	u.s. I-90 Bridge/ d.s. end alt bar/ fine eddy de	C	1696779.59	510026.29
PC	62.0	9/11/2000	pebble counts	d.s 9th st bridge/ u.s. end alt bar	A	1697100.39	512446.55
PC	62.1	9/11/2000	pebble counts	d.s 9th st bridge/ u.s. end alt bar	A	1697107.73	512436.53
PC	62.2	9/11/2000	pebble counts	d.s 9th st bridge/ u.s. end alt bar	A	1697118.37	512428.45
PC	62.3	4/12/2001	surface part size est/grid p.c.	d.s 9th st bridge/ u.s. end alt bar	A	1697140.05	512471.46
PC	62.4	4/12/2001	surface part size est/grid p.c.	d.s 9th st bridge/ u.s. end alt bar	A	1697156.84	512502.24
PC	63.0	9/25/2000	pebble counts	u.s. ladfill/ u.s.end, lalt. bar	A	1702896.19	519099.80
PC	63.1	9/25/2000	pebble counts	u.s. ladfill/ u.s.end, lalt. bar	A	1702968.71	519165.82
PC	64.0	9/25/2000	pebble counts	u.s. RR BR/ u.s. end mid channel bar	A	1703304.55	520735.29
SSP	64.1	4/11/2001	surface/subsurface part size	u.s. RR BR/ d.s. end mid channel bar	C	1703144.14	520752.87
SSP	64.2	4/11/2001	surface/subsurface part size	u.s. RR BR/ d.s. end mid channel bar	C	1703153.78	520771.26
SSP	64.3	4/11/2001	surface/subsurface part size	u.s. RR BR/ mid point of mid channel bar	B	1703288.64	520802.79
PC	64.4	4/11/2001	surface	u.s. RR BR/ mid point of mid channel bar	B	1703291.27	520852.71
PSV	65.0	9/27/2000	visual part size			1703431.26	522192.93
PSV	66.0	9/27/2000	visual part size			1704164.87	524687.77
PSV	67.0	9/27/2000	visual part size			1706588.35	527214.02
PSV	68.0	9/27/2000	visual part size			1707715.88	528081.79
PSV	69.0	9/27/2000	visual part size			1713587.62	533336.95
PSV	70.0	9/27/2000	visual part size			1722022.71	536922.22
PSV	71.0	9/28/2000	visual part size			1739208.69	538020.97
PSV	72.0	9/28/2000	visual part size			1744135.05	535065.15
PSV	73.0	9/28/2000	visual part size			1745755.77	533898.32

Appendix E.
Subsurface Bed-Material Size Distributions

(on file Park Conservation District, Livingston MT and
Water Resources Division, DNRC Helena, MT).

Appendix F.
Historic Channel Modifications in 1954, 1973 and 1999

(on file Park Conservation District, Livingston MT and Water Resources Division, DNRC Helena, MT).

Appendix G.

Methods for Analysis of Cumulative Geomorphic Effects of Channel Modification

Methods

Three principal types of analytical methods are being used evaluate geomorphic cumulative effects of channel modification: statistical hypothesis and trend tests; sediment budgets; and predictive hydraulic models. Before presenting the selected methods, geomorphic factors affecting the analytical design are briefly discussed. Table G1 shows various geomorphic attributes, quantitative measures of the attributes, and potential indicators of fluvial change.

Table G1. Geomorphic Attributes, Measures and Indicators.

A) Contemporary Fluvial Attributes	B) Historic Fluvial Features	C) Derivative Measures (potential indicator)	E) Process Based Measures (potential indicator)
Planimetric or 3-D Channel Geometry			
(orthophotos and topography) -water surface width and area (low flow) -channel slope (low flow) -bankfull channel width -bankfull depth (est.) -side-channels -channel pattern and sinuosity Channel Survey -bankfull channel width, depth, slope -channel profile -3-D channel geometry	(orthophotos and plan maps) -water surface width (low flow) -channel slope (low flow) -bankfull channel width -side-channels -channel pattern and sinuosity Channel Survey -limited information/selected sites	-Stream power / unit width -critical shear stress -Active channel width / channel length -Braid Index -Side channel number and area by channel class and valley length -Width/Depth Ratio -Entrenchment Ratio -Pool and riffle number,spacing and frequency Hydraulic geometry -width, depth, slope vs. Q -habitat structure	-Rate of bank erosion/ deposition -Rate of lateral channel migration -Frequency and location of cutoff and avulsion -Locational plots (e.g. axial) of 1948-1999 changes in channel width, bare gravel and
Gravel Bars and Islands			
--Type -Surface area -Vegetation cover	-Type -Surface area -Vegetation cover	Island and Gravel bar frequency -by type (number and surface area) -spacing and autocorrelation	-Rate of downstream migration of bars and islands -Rate or frequency of conversion from flood plain to channel to island
Bed and Bank Material			
-Texture (particle size distribution) -Vegetation cover	-Texture (general) -Vegetation cover	-particle size statistics -Veg. bank cover (relative erosion resistance)	-Qualitative change in bed texture over time -Change in vegetation cover over time
Sediment Sources			
-Eroding banks/type -Mass wasting -Tributary deltas	-Eroding banks/type -Mass wasting -Tributary deltas	-Bank type by channel class -Thornes activity classification -Bank stability index -Unit amount (amount/channel length)	-Activity and spatial distribution of sed. sources -Net aggradation / degradation by reach -Volume of sediment eroded or deposited over time / by reach
Large Woody Debris			
-Species -Amount (number) -Spatial distribution (reach and longitudinal)	-Amount (number) -Spatial distribution	-LWD amount by channel class. -unit amount (amount/channel length)	-Change in location and abundance over time
Channel Modifications			
-type, linear amount or number	-type, linear amount or number	-Overbank Flooding Index -Flood Peak Index -Geomod (HGM)	-Reach specific rates of modification over time -Potential project effect on sediment budget/balance