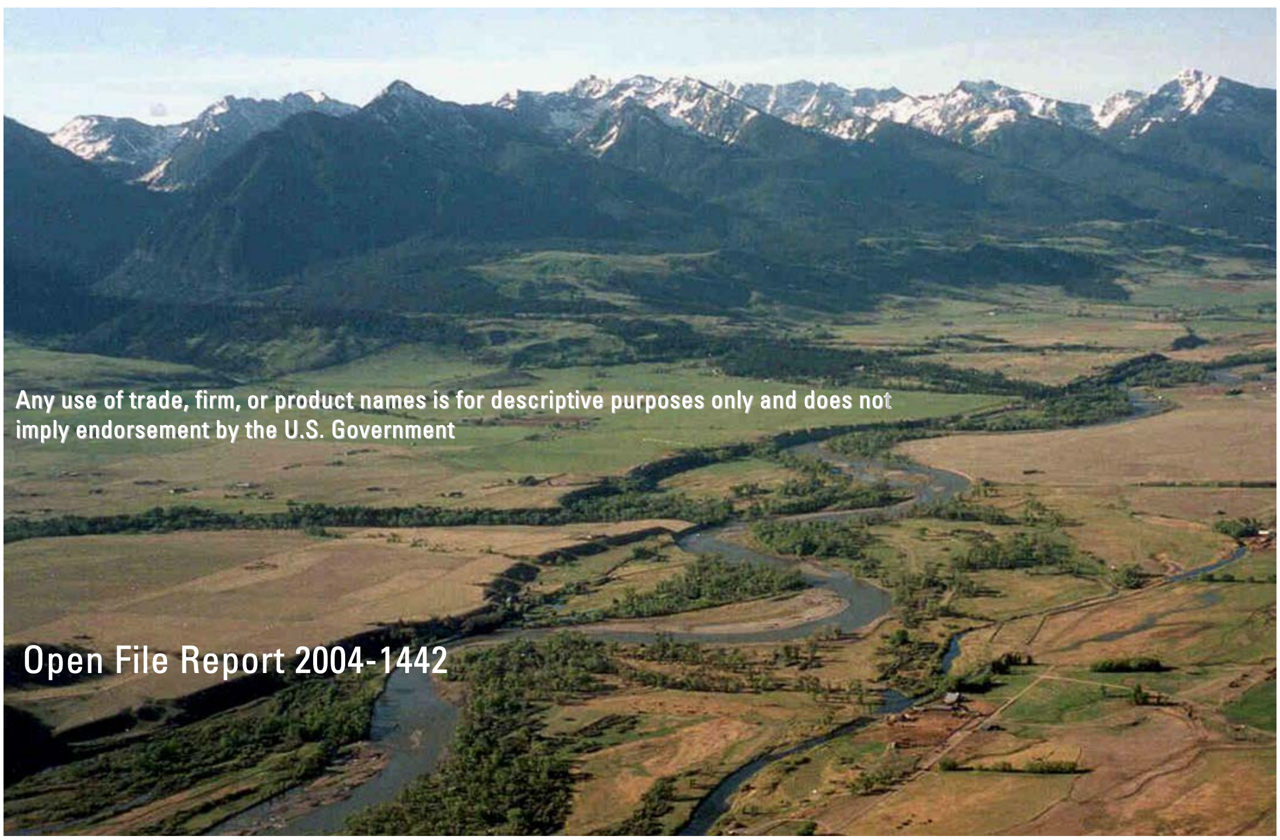
Summary of Studies Supporting Cumulative Effects Analysis of Upper Yellowstone River Channel Modifications

By Gregor T. Auble, Zachary H. Bowen, Ken D. Bovee, Adrian H. Farmer, Natalie R. Sexton, and Terry J. Waddle, U.S. Geological Survey



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Contents

Figures

Tables

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Introduction

During the last several decades, portions of the upper Yellowstone River have been modified for flood control and erosion prevention. The U.S. Army Corps of Engineers is responsible for administration of a permit program for evaluating construction activities affecting rivers, streams, and wetlands. The Corps regulates activities under the authority of Section 10 of the Rivers and Harbors Act and Section 404 of the Clean Water Act. Since assumption of jurisdiction in the mid-1970's, the Corps has processed a total of 156 permit actions for the upper Yellowstone River. Over two-thirds of the permit actions occurred during or after two consecutive large floods during 1996 and 1997. In response to concern regarding the potential environmental and ecological consequences of channel modification, the Corps, in conjunction with State and local government agencies, initiated a series of scientific studies to better understand the effects of channel modification in the upper Yellowstone River (Figure 1). These included preparation of wetland and riparian inventory maps (Bon, 2001); hydraulic modeling and flood-plain delineation; watershed land-cover assessment (Pick and Potter, 2003); historic bottomland use analysis (Brelsford and others, 2003); analysis of channel modification effects on fish habitat (Bowen and others, 2003); comparison of juvenile salmonid use of modified and unmodified habitats (Zale and Rider, 2003); analysis of riparian vegetation and flood-plain turnover (Merigliano and Polzin, 2003); study of the relations between riparian habitat and bird communities (Hansen and others, 2003); analyses of geomorphology and historical channel changes (Dalby and Robinson, 2003); socioeconomic assessment (BBC Research and Consulting, 2002); and sediment transport investigations and modeling (Holnbeck, 2003).

This report is a summary of results from the individual scientific studies as they bear on future programmatic cumulative effects analyses of channel modification of the upper Yellowstone River. We do not attempt a formal, cumulative impact assessment in the sense of evaluating alternatives or future scenarios. The first section presents major findings of the resource studies in terms of temporal comparisons, spatial comparisons, and causal relations. In this section, we present a series of conceptual models or flow diagrams of the major causal pathways of cumulative impacts from channel modification. These represent major pathways of potential impact based on knowledge from other rivers, concerns expressed about the upper Yellowstone, and results from the scientific studies. These diagrams serve to focus interpretation of study results as either supporting or not supporting the importance and magnitude of particular causal relations and to identify key linking variables appearing in multiple causal pathways. These key variables that connect channel

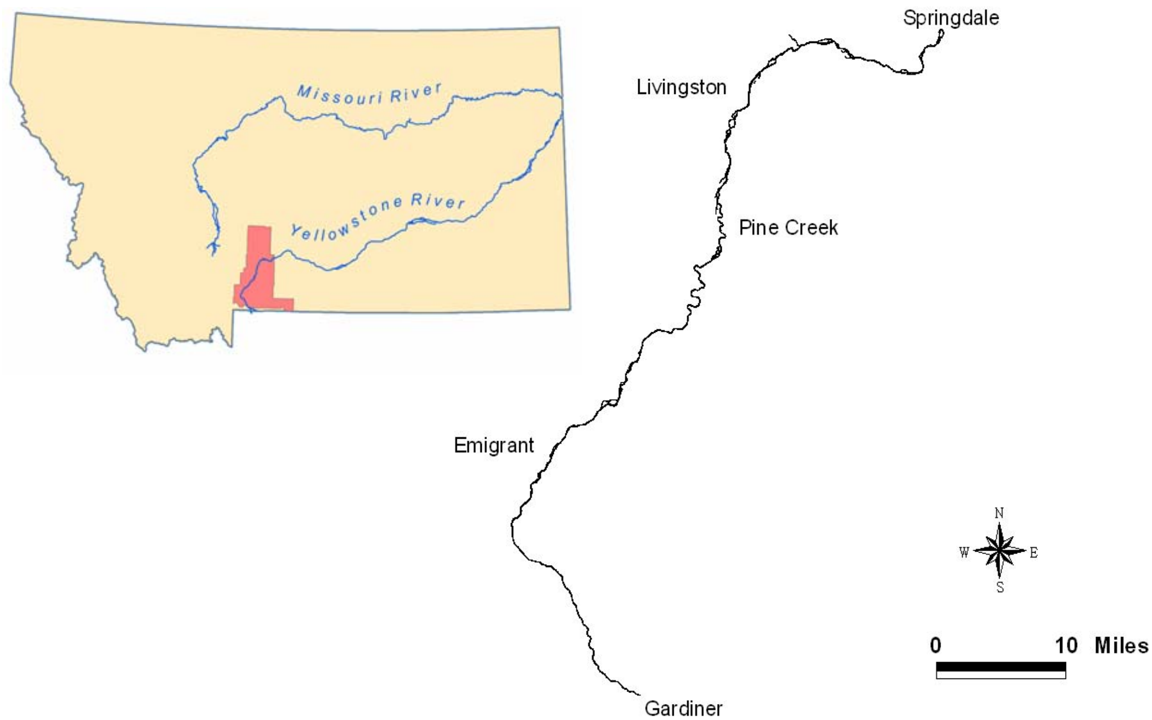


Figure 1. Upper Yellowstone River study area with Park County, Montana highlighted.

modification actions to multiple, valued environmental attributes can serve as the foundation for both projecting and monitoring future responses of the system.

A section on analytical realities outlines some of the limitations of projecting cumulative impacts from channel modification of the upper Yellowstone River on meaningful spatial and temporal scales and some of the difficulties of interpreting results from studies conducted shortly after two extreme floods and substantial increases in channel modification. A section on classification describes the two primary geomorphic classification systems of the upper Yellowstone River used in the various individual resource studies. Each of these systems has been valuable in supporting field sampling and expressing results concerning patterns of variation. Their integration or revision into a classification system to achieve some new purpose, such as a regulatory program or monitoring system, will depend on a crisp articulation of riverine management or regulatory objectives. A section on key variables identifies those that are central to the causal pathways connecting channel modification to impacts and provides a rationale for key variables as an alternative to other tools such as Proper Functioning Condition (Barrett and others, 1993), Index of Biotic Integrity (Karr, 1981), or the Synoptic Approach (Liebowitz and others, 1992). This section also explains relations among key variable to Hydrogeomorphic (HGM) assessment procedures (Hauer and Smith, 1998; Hauer and others, 2001) and outlines how these variables might be monitored to track cumulative impacts. Examples of how selected key variables can be quantified using Geographic Information System data sets developed from the resource studies are presented for one reach.

The largest portion of the document is an Appendix that summarizes each of the individual scientific studies in terms of scope and methods, findings, principal variables, and metrics used in the study or suggested by the study results, and important needs for further study.

Major Findings

At the scale of the whole river corridor, the results of individual studies indicate that the upper Yellowstone River system has not been fundamentally altered by cumulative channel modification structures. The general character of the vegetation is similar to that of a century ago, streamflow magnitudes and patterns of variation are natural, basic physical processes of overbank flooding and channel movement are still occurring, and the natural fish and wildlife habitats and communities are still present.

While the river corridor as a whole has not yet experienced a qualitative, catastrophic loss of ecological integrity, the resource studies do provide evidence for concern about cumulative impacts related to channel modification. Some reaches have been heavily modified by both channel structures and bottomland use conversions. Channel modifications by humans have increased dramatically and are producing measurable changes associated with more confined channels – 14% of the channel between Gardiner and Springdale is affected on at least one bank by channel modification structures that laterally confine the channel and another 6% is in a forced morphology due to a combination of human and natural factors (Dalby and Robinson, 2003). Although land use and cover over the watershed and the bottomland as a whole are relatively stable with large proportions of natural communities, agriculture, and ranching, there are reaches that are heavily developed such as the Livingston area, and rates of bottomland development are substantial (Brelsford and others, 2003; Hansen and others, 2003; Pick and Potter, 2003).

The common theme from the scientific studies is that the character of the upper Yellowstone River ecosystem is strongly determined by lateral channel migration and flooding. This is evident in the natural differences among geomorphic strata with different natural levels of lateral channel constraint. The channel movement and overbank flooding that cause human property damage also maintain topographic complexity and diversity of habitat conditions for fish; produce suitable sites for regeneration of cottonwood and willow; maintain a shifting mosaic of diverse riparian vegetation types; and support wildlife species dependent on spatially complex riparian vegetation communities. Overall, existing channel modifications have not yet fundamentally altered the upper Yellowstone River system as a whole because:

1. the overall extent of channel modification is still low;
2. much of the channel modification has been recent relative to the time scale of response variables such as cottonwood;
3. channel modifications have been only partially effective in reducing flooding and lateral migration (e.g., only one side of channel confined in many locations, failure of structures);
4. channel movement in much of the upper Yellowstone occurs in large events and there have been two recent large floods that have tended to offset any adverse effects of structures on channel movement; and
5. bottomland use and cover has not changed substantially at the corridor level over the last 50 years.

There are three basic approaches to analyze the cumulative impacts of a set of actions such as channel modification.

1. **Temporal comparisons** measure changes over time as the system becomes increasingly modified, attributing some or all of the changes to the modifications.
2. **Spatial comparisons** measure the differences between areas that have been highly modified and areas that have not, attributing some or all of the differences to the cumulative effects of the modifications.
3. **Causal relations** that are quantified and verified can be used to project cumulative effects. Organizing these relations in conceptual diagrams focuses the analysis on potential impact pathways. In some cases, relations can be linked as a set of predictive equations and applied as a simulation model. Projections of cumulative impacts based on causal relations are especially desirable because they can inform decisions about alternatives before the system has changed.

All of these approaches are used in varying combinations in the upper Yellowstone River studies. Their application to the upper Yellowstone is summarized below, including some conceptual diagrams of major impact pathways. These conceptual diagrams highlight the role of linkages among variables and help identify key variables that can serve as indicators of ecological integrity both from assessment and monitoring perspectives.

Temporal Comparisons

Because much of the channel modification of the upper Yellowstone River has occurred very recently relative to the time scale of forest and geomorphic response, temporal comparisons primarily serve to establish a base line of pre-modification conditions. This situation is exaggerated by the large, recent floods (1996 and 1997) that tend to over-ride and mask hydraulic and geomorphic responses to channel modification that might be occurring gradually under more moderate conditions. Historical channel analyses show that these large floods (e.g., 50-100 year recurrence interval) establish the dominant channel configuration and act as resetting events characterized by large channel migrations or avulsions – especially in braided or anabranching reaches (Dalby and Robinson, 2003).

Channel modifications have increased dramatically from 1954 to 1999. Riprap bank has increased 400% to 111,260 feet in 1999; point structures have increased 600% to 292 structures in 1999; and linear flood-plain modifications (dikes, levees) have increased 265% to 92,250 feet. These modifications tend to be concentrated in the less naturally confined geomorphic strata. Overall main channel length has remained essentially constant from 1948 to 1999, whereas the length of side channels has increased by 16% in part reflecting the influence of the 1996 and 1997 floods (Dalby and Robinson, 2003).

Overall land use has not changed substantially from 1948 to 1998, with no land uses consistently increasing or decreasing. There has been an increase in the number of homes either in or near the flood-plain. Vegetation cover types have not changed dramatically in the last 50 years and the general character of the vegetation is similar to that shown on photos from the late 1800s. There is a trend of reduction and aging of the cottonwood forest, in part reflecting the natural aging of a large area of forest established between 1850 and 1900.

Spatial Comparisons

Contrasts between heavily modified and relatively unmodified areas were possible in several of the studies. At a local scale, fish abundances did not differ greatly across bank types, with riprap having the largest abundances. At a reach scale, the shallow, slow velocity habitat important to juvenile fish was more common in less modified reaches where the overall topographic diversity, including side channels, provided more of this habitat over a range of flows.

Geomorphic strata and channel types explained much of the spatial variation in the upper Yellowstone River system. The less confined strata, including braided and anabranching channel types, had greater extents and diversity of riparian forest and greater richness of bird species dependent on riparian vegetation as habitat. To some extent, these differences among geomorphic strata can serve as a surrogate for changes that might be expected from channel modifications. Physical and biological characteristics associated with naturally constrained reaches should provide an indication of what to expect if channel modification changes a reach to a more constrained or forced morphology. For example, modifications that constrain channel movement might generally be expected to move the system in the direction of the naturally confined strata with narrower and less structurally diverse flood-plain vegetation and less diverse bird communities dependent on that vegetation. Classification of the current channel indicated that 14% of the channel length from Gardiner to Springdale fell into a class of forced morphology where the channel type was strongly influenced by human structures that laterally confined the channel – most commonly a shift of anabranching channel types to pool-riffle or plane-bed channels. Another 6% of the channel was in a forced morphology due to a combination of human and natural factors (Dalby and Robinson, 2003). Highly modified sections in the Livingston area have less of the shallow, slow water habitat conditions desirable for juvenile fish than otherwise comparable reaches nearby and experienced a loss of side channel length from 1948 to 1999 in contrast to the general increase throughout the corridor as a whole.

Causal Relations—Simulation

Several resource studies employed simulation models to examine how aspects of the system would behave. Development of maps representing the 100-year flood-plain involves application of a hydraulic simulation model predicting surface water elevations for given discharges and a flow-frequency model estimating the probability of certain discharges. Projections of current rates of change were used to estimate a no-action alternative for future land use and economic activity (BBC Research and Consulting, 2002). Bowen and others (2003) developed spatially explicit hydrodynamic simulation models for three river segments to quantify the area and location of depth-velocity combinations at different discharges. Their results demonstrated the importance of topographic diversity and side channels in maintaining the shallow, slow current velocity (SSCV) habitat known to be important for juvenile salmonids under a range of discharges.

Holnbeck (2003) quantified a moveable-bed sediment-transport model predicting vertical changes in the channel bed and sediment balance for a portion of the upper Yellowstone River near Livingston, Montana. Although this model does not incorporate lateral channel movement and bank erosion, it does provide indications of vertical channel stability. While the model has important limitations, it does quantitatively link causal relations in a structure that provides direct evaluations of channel modification alternatives. Most of the alternatives (e.g., altering bridge openings) simulated by Holnbeck (2003) are at a relatively local scale. There were two important general results. Water surface elevations simulated with a moveable bed were very similar to those simulated assuming a fixed bed. This is very reassuring for the accuracy of flood-plain delineations along the upper Yellowstone River made using fixed-bed hydraulic models. Holnbeck's (2003) simulations of baseline conditions indicated a slight tendency for aggradation. While there were some substantial differences between simulated sediment loads and loads estimated from sediment rating curves, the simulations provided no indication that the current level of channel modification in the simulated reach near Livingston, Montana, is producing widespread and substantial net channel incision.

Causal Relations -- Cumulative Impact Pathways

Overview

The diagrams of causal pathways presented in this section (Figures 2–5) are intended to summarize the main sources of concern about cumulative effects of channel modification. They do not represent all possible connections in the system, nor are they all of equal importance. Furthermore, they emphasize broad-scale cumulative effects, rather than more local changes (i.e., specific channel modifications in a specific location). These local changes can, in fact, themselves be quite complex, involving "ricochet" or other offsetting changes in spatially and temporally complex patterns. Holnbeck's (2003) simulation results provide several excellent examples of how a structure can produce aggradation in one direction and degradation in another direction. However, here we are focusing on possible broad-scale changes from the cumulative results of a large number of local actions.

The general outline of causal relations underlying impacts of channel modification of the upper Yellowstone River is depicted in Figure 2. The scientific studies of the upper Yellowstone River have verified and partially quantified a number of the important causal relations connecting channel modification to environmental responses. Channel modifications in the upper Yellowstone River are motivated by protection of human land uses and activities in the bottomland from flood and erosion damage. If effective, these channel modifications alter the physical environment. Some of these alterations induce further changes in the physical environment that may interact and play out over long time scales. One of the important concerns about cumulative impacts of channel modification is that a large number of individually small actions may accumulate to cross a geomorphic threshold fundamentally altering the processes determining riverine and flood-plain morphology and habitats (Church, 2002). These changes in the physical environment at both the individual and cumulative scales are more or less suitable for various plants and animals and thus produce biological responses – changes in fish habitat and habitat use, changes in riparian vegetation, and changes in riparian-dependent wildlife such as birds.

Reduced risks of flood and erosion damage also tend to facilitate further development and use of the bottomland. This is the second area of major concern about cumulative impacts - where the effects of human land use in the bottomland (altering natural vegetation) and channel modification (reducing natural processes of flooding and channel dynamics) both accumulate and interact. The interaction between channel modification and flood-plain development could potentially proceed to a point where maintenance costs are high, damage from rare events is catastrophic, and the biological system is altered to the extent that habitat features and species are lost and environmental values that contributed to the bottomland's desirability for human use are degraded. In addition, human activities in the bottomland may impact biological communities in ways other than through channel modification. This is especially clear in the case of riparian vegetation where the communities that might naturally be produced by a different flooding or channel movement regime might be masked by direct land conversions such as urban development, housing construction, and modifications of natural plant communities by agriculture or ranching.

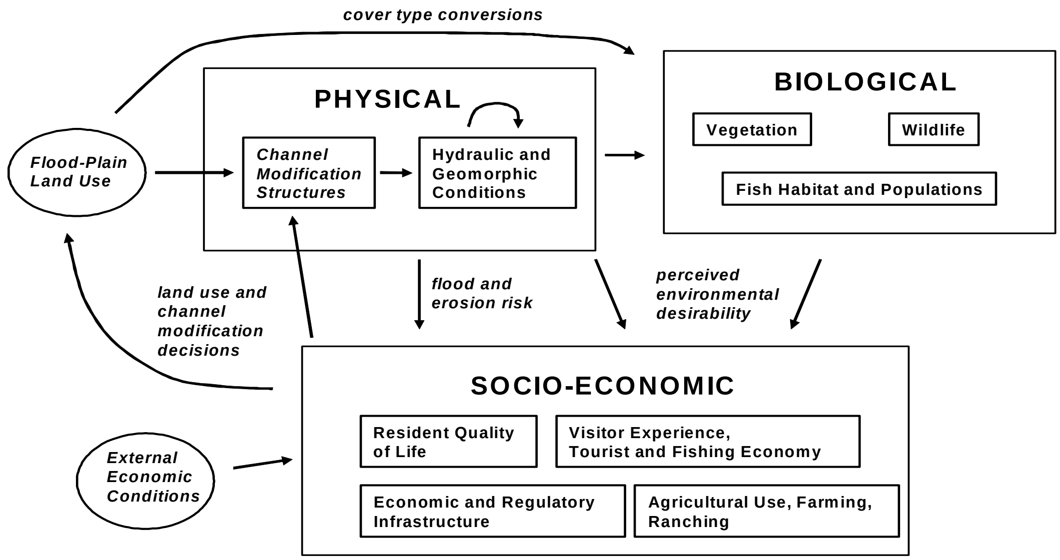


Figure 2. Overview of causal pathways.

BBC Research and Consulting (2002) provides some insight into how socioeconomic factors interact with the physical and biological environment of the upper Yellowstone River in the overall scheme depicted in Figure 2. Residents and business owners view the river as an important aspect of local quality of life and important to the economy. Residents view low water and drought as more of a problem, however, than floods. The river is an important component of the visitor experience, and tourism is currently the strongest element of the local economy. There are, however, differing views on how the river should be managed and for what purpose. Most residents and business owners prefer proactive management for flood control and erosion; however, visitors prefer a free-flowing river. Although streamside vegetation and scenery along the river are important components of visitors' positive experience, visitors do not presently feel that their experience is negatively impacted by existing channel modification structures.

Population is increasing moderately in Park County, Montana, with almost all growth occurring in rural areas and nearby, but outside, Livingston (BBC Research and Consulting, 2002). The large number of permit applications for channel modification following the floods of 1996 and 1997 indicate that land use near the river is creating a need for flood and erosion protection. Dalby and Robinson (2003) found that historic bank stabilization measures tended to be incremental and grow both at a site and within a geographic region (for example, Pine Creek to Carters Bridge and I-90 to Railroad Bridge). It appears that while there are some examples of the so called "ricochet" effect, where erosion problems are passed downstream along with the need for additional bank stabilization, the more prevalent cause is the increased need for protection that accompanies increased flood-plain development and urbanization.

Brelsford and others (2003) found no consistent trends in land use change from 1948 to 1998 in their historic analysis, and BBC Research and Consulting (2002) described current growth as moderate. However, seasonal residents account for 8% of Park County's population, non-wage income (e.g., dividends) is the fastest growing component of personal income in Park County, and high land prices and an adverse ranching economy are driving an out-migration of long-time ranchers. These trends, if combined with external economic conditions, might spur the type of additional bottomland development that would increase the pressure for additional flood and erosion control (Figure 2).

Although residents and businesses perceive overcrowding of the Yellowstone River as a problem, tourists do not (BBC Research and Consulting, 2002). Coupled with the generally very positive visitor experience, this suggests that the upper Yellowstone River is far from the condition where perceived environmental desirability reduces tourism (Figure 2). Much of this is likely due to the contrast between Paradise Valley and the places tourists and seasonal residents are coming from.

Physical Pathways

There are two primary types of channel modification structures that influence hydrologic and geomorphic conditions in the riverine system: channel stabilization and levees (Figure 3). The primary purpose of channel stabilization structures such as riprap, barbs, and jetties is to reduce the rate of lateral channel migration. In so doing, they may alter bank substrate and modify the nature and amount of sediment input through mass wasting and bank erosion. To the extent that they are effective in reducing lateral channel migration, stabilization structures tend to produce less natural bottomland disturbance that removes existing vegetation and fewer new side channels. Disturbance here is used in the ecological sense of an event that removes biomass, creating a mosaic of diverse landscape features and opening sites for early seral or successional communities such as young cottonwood and willow. The natural disturbance regime of a river largely determines and maintains the diversity of physical features and biological communities in a riverine landscape (Ward, 1998; Robinson and others, 2002; Ward and others, 2002).

The primary purpose of levees or dikes is to reduce the area inundated by high discharges by confining high flows to the main channel. To the extent that they are effective, levees reduce the area flooded and result in less connection between river and flood-plain, drier conditions in the flood-plain and bottomland, and possibly shortened or abandoned side channels. The river, however, must carry the water that levees confine to the main channel by some combination of higher velocities and greater water depths. Higher velocities and depths can incise the main channel, which will tend to further reduce the area flooded at a given discharge and may lead to abandonment of side channels. Incision does not always result from channel constriction despite generally greater mean velocities and water depths. Bed movement is most directly related to near bottom velocity, which may decrease even though the overall mean velocity increases (Carson and Griffiths, 1987). Furthermore, isolating side channels may decrease the total sediment transport capacity in a reach so that the main channel may be less able to move all of the sediment.

If the bed does not incise and the confined water cannot be accommodated by increased velocities, levees may produce higher water surface elevations at a given discharge. This response is obvious on the lower Missouri River and the lower Mississippi River where extensive levees have substantially increased the stage associated with a given discharge and lowered the effective flood protection provided by a levee of a specific height. A tendency for higher water surface elevations could actually counteract effects of bed incision or even increase the area flooded at a given discharge, at least in zones not immediately behind the dikes (indicated by dashed arrows in Figure 3).

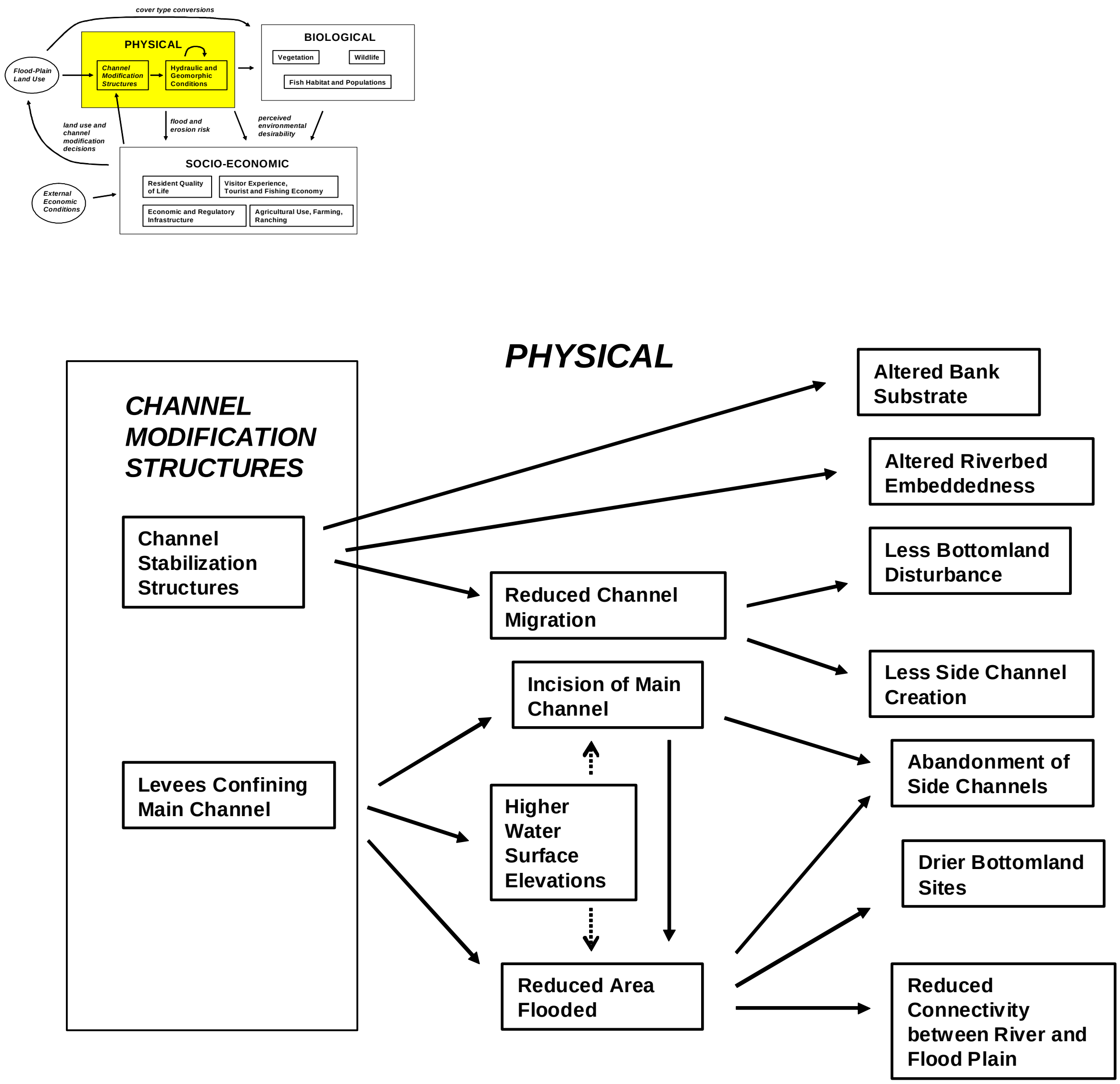


Figure 3. Causal pathways between channel modification structures and the physical environment.

Dalby and Robinson (2003) found a net increase in side-channel length of 16% and general maintenance of river-flood-plain connectivity from 1948 to 1999. However, the Livingston Urban area that has the highest proportion of channel riprapped or leveed on both banks did experience a decrease in side channel length. Although changes in side channel length that might be produced by recent increases in channel modification structures may have been masked by the large floods of 1996 and 1997, Dalby and Robinson's (2003) results do not provide evidence for any systematic reduction in side channel length to date.

Dalby and Robinson (2003) classified 20% of the Gardiner to Springdale section of the upper Yellowstone River channel as forced into an altered channel type either dominantly or partially by human activities. The majority of the upper Yellowstone River continues to function mostly as it has since 1948. Even in the segments forced to a new channel class by channel modification structures, there is little evidence to suggest that the system has experienced or is close to a threshold of dramatic or catastrophic geomorphic change such as rapid incision or wholesale destabilization of reaches. Rather, the effects are more likely composed of subtle differences in hydraulic and geomorphic attributes. This is probably for several reasons:

1. the very coarse bed of the upper Yellowstone River appears to effectively resist large-scale degradation at many locations;
2. most areas are confined on only one bank which allows some freedom to adjust laterally; and
3. in anabranched areas large floods cause the river to avulse, bypass revetments, and create new channels (the Livingston Urban area is the most notable exception and somewhat an endpoint of channel stabilization).

Biological Pathways – Fish

Given the Yellowstone River's economic importance as a trout fishery, significant concern about cumulative effects of channel modification is focused on fish responses. Changes in the hydraulic characteristics of the river produced by channel modification can change the availability of physical habitat conditions suitable for fish (Figure 4). Shallow, slow current velocity conditions (SSCV) are especially important for young salmonids and can be a limiting factor for the overall fish population. Reduced connectivity between river and flood-plain, less side channel creation, and abandonment of side channels could lead to reduced or more erratic availability of the SSCV habitat. Less bottomland disturbance and reduced connectivity between river and flood-plain could also result in less input to the aquatic food chain and less recruitment of large woody debris (LWD), which is an important component of woodland river systems (Gurnell and others, 2002). Finally, direct alteration of the bank substrate by structures such as riprap can alter both the physical suitability of bank habitat for fish and the food provided to fish by primary and secondary production in bank habitats.

Zale and Rider (2003) found similar local usage among different bank types, with riprap having the highest abundances of juvenile salmonids. The boulders used as part of channel modification structures such as ripraps generally increase particle size along the bank and decrease mean velocities (Figure 4). Thus, boulders serve to increase the volume of habitat usable by juvenile salmonids in locations where they replace an eroding cutbank made of smaller particles by providing visual and velocity shelters. Boulders also provide colonization surfaces for algae and invertebrates, which might serve to increase local primary and secondary production. At the scale of the structure (about ½ channel width upstream and downstream from the structure), barbs and jetties alter flow fields, which can change local patterns of deposition and scour. The value of the resulting habitat depends strongly on the type and condition of natural bank that was replaced, but there is little evidence from Zale and Rider (2003) that channel stabilization structures along the upper Yellowstone River are altering bank substrate in a way that is substantially detrimental to fish. Furthermore, they found that juvenile abundances along main channel banks of the upper Yellowstone were relatively low compared to abundances in other river systems, suggesting that this habitat is not of critical importance to fish populations in the upper Yellowstone.

Zale and Rider (2003) verified the importance of side channels by showing that ephemeral side channels were colonized rapidly by juvenile salmonids during runoff and that densities of fish increased with increasing duration of inundation. Bowen and others (2003) found that main channel locations (regardless of their state of modification) were substantially smaller sources of SSCV habitat during runoff, compared to off-channel areas. Bowen and others (2003) also demonstrated how the shallow, slow velocity conditions known to be important to juvenile salmonids are

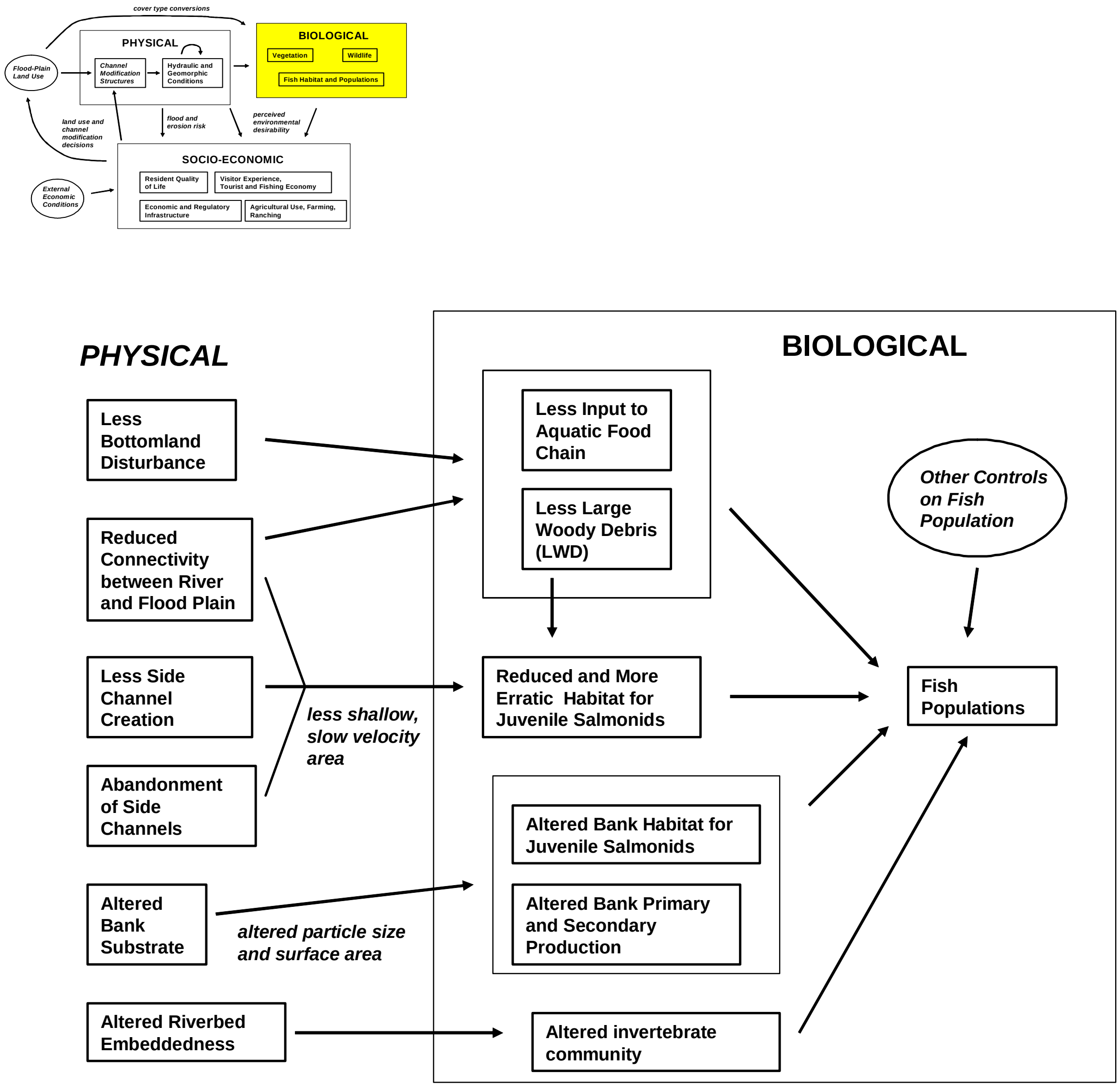


Figure 4. Causal pathways between fish and changes in the physical environment produced by channel modification.

produced over a range of flows by the existence of a diversity of channel features, including side channels. They found that the amount of shallow, slow velocity habitat was strongly dependent on overall topographic diversity and complexity of channel features, especially side channels. Locations of shallow, slow velocity conditions shifted substantially as flow changed. Channel modifications that simplify the topographic complexity, isolate side channels, or diminish the processes maintaining this diversity would reduce the amount of this important habitat type.

It is unlikely that channel modification, even carried to an extreme, would result in a complete collapse of the trout populations of the upper Yellowstone River. Incremental additions of channel modifications, however, may eventually reduce the topographic diversity of the river, resulting in habitat dynamics and fish populations more characteristic of a confined river. Channel modifications that result in reduced availability of side channel and overbank habitats, especially during runoff, will probably cause local reductions in juvenile abundance during the runoff period. The effect of local reductions during runoff on adult numbers later in the year will depend on the extent of channel modification, patterns of fish displacement and movement, and longitudinal connectivity between reaches that contain refugia and those that do not. In confined channels, the only place that SSCV can occur is in the main channel, where the amount of habitat is inversely related to discharge (Nehring and Anderson, 1993). Therefore, it is common for strong year classes to occur only in drought years, when the spring runoff is relatively low. In normal and wet years, year classes are typically weak and sometimes absent.

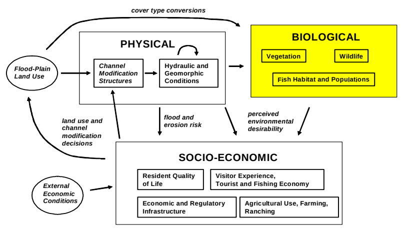
Although the studies of Bowen and others (2003) and Zale and Rider (2003) established some causal relations between channel modification and juvenile salmonid habitat and use, the importance of juvenile habitat relative to other habitat needs or population controls is largely unknown. Overall limitations on the fish populations need to be better determined before clear predictions about the relations between channel modification and adult fish in the river can be made.

Biological Pathways – Vegetation and Wildlife

Rivers control riparian vegetation by two primary mechanisms: (a) increased moisture associated with overbank flooding or elevated alluvial groundwater; and (b) physical disturbance associated with channel change and destructive flooding (Figure 5). Structures that alter these processes (Figure 3) will have effects on riparian vegetation and wildlife dependent on that vegetation. The relation of riparian vegetation communities to disturbance from channel change is complex, but is fundamental to an assessment of how the riparian vegetation will respond to channel stabilization measures over the long term. Seed regeneration of riparian cottonwood and willow is disturbance-dependent, requiring bare, moist sites produced by fluvial disturbance. In the absence of such disturbance – for example, if all flows were confined to a fixed, concrete-lined canal – recruitment of new stands by seed would cease, and existing cottonwood and willow stands would likely age and eventually disappear with consequent effects on bird and other wildlife communities utilizing riparian vegetation. Reduced connectivity between the river and flood-plain influences the movement of organisms, organic material, and nutrients in ways that may impact both aquatic and terrestrial food chains, as well as the physical habitat available for aquatic and semi-aquatic organisms. These linkages have been well established in many riverine ecosystems (Tabacchi and others, 2002; Ward and others, 2002).

Merigliano and Polzin (2003) found that the extent of cottonwood and willow is greater in less confined geomorphic settings where the river moves more freely over a broader flood-plain. Overall richness and diversity of riparian vegetation communities are also greater in these geomorphic strata. Long-term maintenance of cottonwood and willow is strongly dependent on riverine disturbances of channel movement and flooding that create bare, moist sites suitable for new seedlings of these species. Structures that limit channel movement and flooding (Figure 3) will thus have the greatest potential impact in the geomorphic settings that are relatively unconfined where extensive forests are naturally maintained by channel movement and flooding over broad areas (Church, 2002; Richards and others, 2002).

The turnover analysis conducted by Merigliano and Polzin (2003) based on age structure of the existing forest provides a solid baseline for the unmodified river. Furthermore, it shows that a disproportionally large area of current cottonwood dates to the period 1850 to 1900, presumably reflecting more channel movement in an earlier hydrologic regime. As a result, the cottonwood



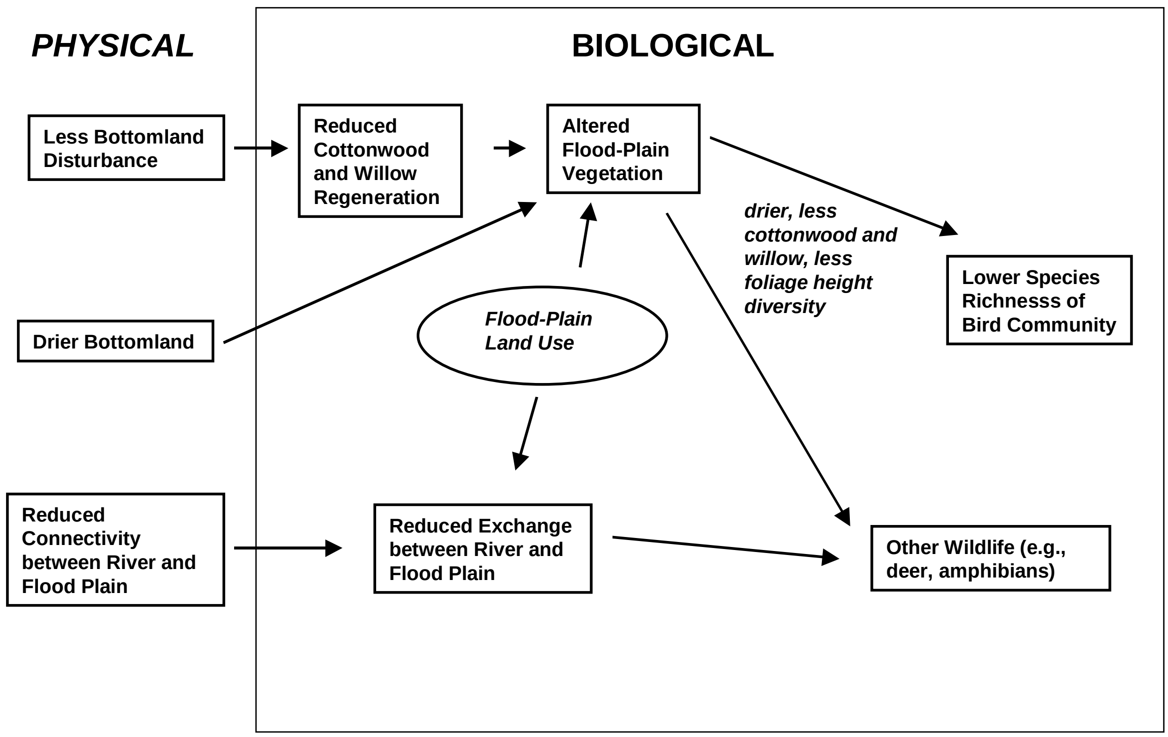


Figure 5. Causal pathways between vegetation and wildlife and changes in the physical environment produced by channel modification.

forest is aging and diminishing under the current hydrologic regime. Because of the long time scale of riparian forest response, no clear effects of the recent increase in channel stabilization structures could be observed in the distribution and age structure of the current forest. The Urbanized reach around Livingston might have provided some such evidence, but the riparian vegetation was not analyzed in this reach in part because the large amount of direct land conversion made it difficult to sample forest responses adequately.

The significance of effects of channel modification structures on riparian vegetation will depend on the spatial and temporal scales on which those structures are effective in reducing channel movement and flooding by the physical linkages depicted in Figure 3. Structures that affect those processes only locally will have only local effects on vegetation. Likewise, structures that are effective for only short periods of time relative to the life span of trees (100–300 years for cottonwood), or that fail in the more extreme events and allow channel movement, will have limited long-term impact on the forest.

Hansen and others (2003) established that maintenance and regeneration of a diversely structured cottonwood-willow riparian forest are important to bird communities. This is consistent with similar studies by Saab (1999) on the Snake River and Scott and others (2003) on the upper Missouri River in Montana. Hansen and others (2003) found that vegetation community type (successional stage) explained 51% of the variation in bird species richness. Bird species richness and diversity were higher in mature cottonwood stages. Shrub stages had intermediate bird species richness and diversity, and the lowest values occurred in meadow and gravel bar habitats. Hansen and others (2003) also found that bird species richness varied among river reach types. More bird species were seen in the less confined geomorphic classes that had more extensive and diverse cottonwood-willow forests.

The ultimate vegetation and wildlife responses to structures that limit channel movement and flooding may be mediated by other human activities and land use changes. A natural response of riparian vegetation would likely involve succession to shrubland and meadow. Human activities of livestock grazing, agriculture, and residential development could alter these natural vegetation responses and the consequent wildlife responses.

Analytical Realities

Consideration of cumulative effects in the management of complex environmental systems would be a difficult institutional and political challenge even if reliable and precise predictions of future effects were available. Reliable and precise predictions about the long-term future behavior of ecological systems, and the upper Yellowstone River in particular, are not generally available. It is thus important to consider the practical limits to prediction and the extent to which those limits can be approached by further scientific study.

The precision of predictions about changes in the upper Yellowstone River ecosystem is limited by the precision with which driving variables of the system can be specified. Predicting condition of streamflow-dependent attributes is to a large extent dependent on the precision of future streamflow – exactly what the channel will look like 20 years from now depends on exactly what streamflow will be, especially the timing and magnitude of extreme events that are generally beyond our ability to predict. Likewise the nature of land use changes will depend in part on external economic conditions that are difficult to predict. These realities generally constrain predictions to the realm of probabilities given assumptions about the driving variables.

The state of scientific understanding introduces another level of uncertainty. Detailed prediction of complex responses over long time scales and broad areas is not currently possible in areas such as fluvial geomorphology, plant ecology, and fisheries population ecology. Prediction in these fields generally involves a number of assumptions that “unconsidered variables are not important” or that “all other things remain constant” – assumptions that are unlikely to be accurate over any long time period. Because precise prediction of complex responses is not possible, consideration of cumulative effects entails making inferences about likely future trends based on scientific observations and our general understanding of how river ecosystems function.

Finally, there are specific aspects of the upper Yellowstone River situation that complicate analysis. There are several time scale problems. Many of the important response variables, such as channel migration and forest composition, respond on time scales of decades to centuries and are heavily determined by episodic phenomena such as extreme floods. However, the bulk of the channel modification in the system has occurred very recently relative to the time scale of response variables. Thus, it is very difficult to observe how channel modification has influenced these response variables. On time scales of forest response, assumptions about the long-term maintenance, effectiveness, and failure of channel modification structures become as important as the analysis of their immediate effects as built. Furthermore, the recent individual resource studies were conducted shortly after two near 100-year flood events. These extreme events may have over-ridden or masked longer-term trends. In particular, the length of side channels has increased in ways that may be an artifact of measuring shortly after some large resetting events.

The resource studies conducted specifically on the upper Yellowstone River, in combination with general understanding of riverine ecosystems, provide a tremendous amount of information to support analysis of how the upper Yellowstone has responded and would respond to different scenarios of channel modification. The emphasis of the resource studies summarized here on developing data and results as compatible geographic information system (GIS) data layers further facilitates analysis and portrayal of system response over multiple variables and large areas. Specific subject areas where increased ecological understanding of the upper Yellowstone River is needed include fish population dynamics and limiting factors, effects of potential habitat changes on wildlife species other than birds, and subsurface hydrology. The fish work has focused on juvenile fish and their habitats. Additional work is needed to generate a firm understanding of what factors or life stages are limiting and controlling overall fish numbers and production. Wildlife work has focused on bird communities. Skagen and others (2001) have, however, provided a literature summary of other potentially impacted wildlife.

All of the resource studies concentrated on surface waters, and a better understanding of subsurface hydrology and surface-groundwater interactions is needed. The subject of subsurface hydrology is of particular importance locally because many of the channel modification structures not associated with development are intended to protect spring creeks. More broadly, much recent work in riverine ecology has emphasized the importance of subsurface flows, defining a hyporheic zone of subsurface water closely connected to surface water with a distinctive fauna and complex spatial pattern of vertical and lateral flow vectors of water, nutrients, and organisms (Stanford, 1998; Huggenberger and others, 1998; Malard and others, 2002; Ward, 1989; Ward and others, 1998). The resource studies conducted on the upper Yellowstone do not provide much information on this aspect of the river corridor, including the importance of subsurface connections to the spring creek features that are important to fish.

Geomorphic Classification

Geomorphic classification of rivers provides a framework for describing: (a) the form and condition of the river, (b) the physical and biological process that shape and respond to the river, and (c) the different modes of likely response to alterations. It can thus support efficient sampling, assessing channel stability and channel changes, forecasting effects of channel modification, and decision making for a variety of channel management actions (e.g. permitting, monitoring design).

Two geomorphic classification schemes were used in the upper Yellowstone River resource studies. The first system (referred to as the Flood-Plain Classification) is based on the channel and bottomland system with level of confinement of the river within the bottomland as a primary characteristic. The primary goal of this system was to organize stratified random sampling of the bottomland and flood-plain. Merigliano and Polzin (2003) used the Flood-Plain Classification for sampling riparian vegetation and estimating flood-plain turnover rates. Hansen and others (2003) used a simplified version of the Flood-Plain Classification for their sampling and analysis of bird communities in relation to vegetation.

The Flood-Plain Classification is based largely on Nansen and Croke (1992). It comprises six classes: (a) Wandering Gravel Bed (Nansen and Croke, 1992); (b) Confined Wandering Gravel Bed (a modification to Nansen and Croke, 1992); (c) Confined Coarse Textured (Nansen and Croke, 1992); (d) Entrenched (Rosgen, 1994); (e) Canyon; and (f) Urbanized, which is defined by land use rather than channel characteristics. Wandering Gravel Bed (Nansen and Croke, 1992) is a subset of braided rivers that exhibit irregularly sinuous channels with stable, well-vegetated and sometimes naturally-leveed islands, anastomosing channels, braid bars, and one dominant channel.

Merigliano and Polzin (2003) distinguished a Confined Wandering Gravel Bed class to address their focus on channel migration. The Canyon class is used for Yankee Jim Canyon. The Urban class around Livingston would naturally fall into the Wandering Gravel Bed class and is separated based on land use in the bottomland. Merigliano and Polzin (2003) mapped 11 individual segments on the upper Yellowstone from Gardiner to Springdale, Montana (Figure 6).

Dalby and Robinson (2003) modified the Montgomery and Buffington (1993, 1997) channel classification system for the upper Yellowstone River, referred to here as the Channel c\Classification. The Montgomery and Buffington (1993) system is process-based and focuses on channel characteristics of bed-material size, bedform and channel pattern, dominant roughness elements and sediment sources, sediment storage, confinement, and relative pool spacing. An anabranching channel type was added to modify the system for the upper Yellowstone. Forced channel types represent segments where either human or natural forcings had altered the channel type.

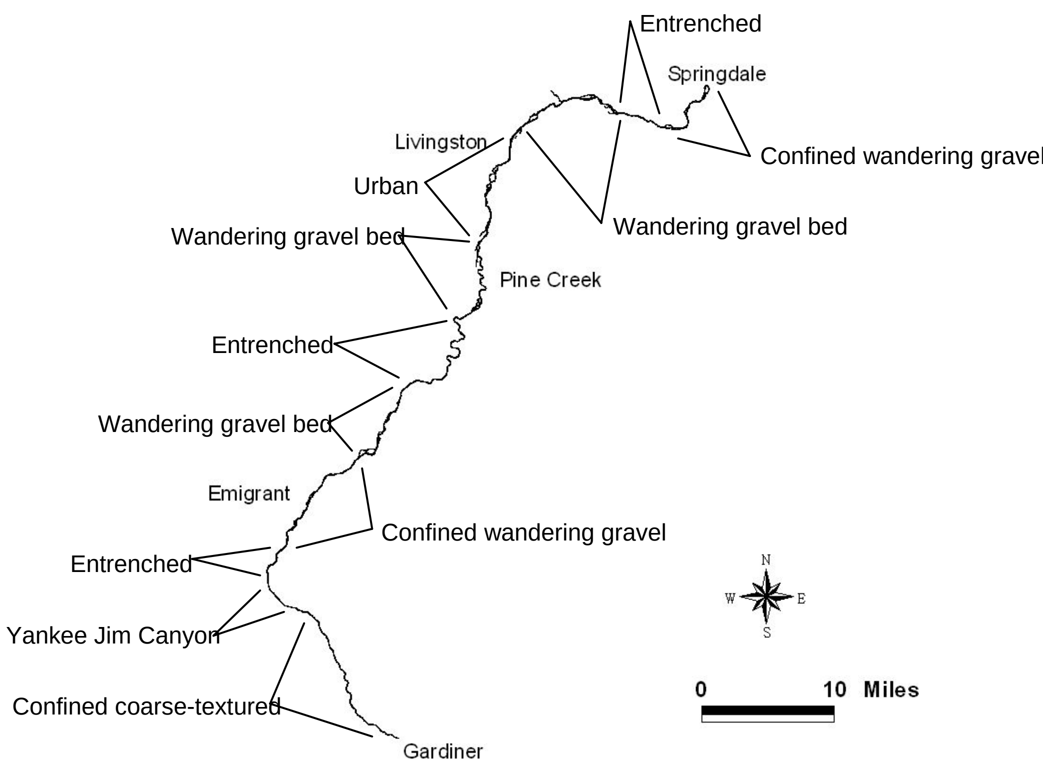


Figure 6. Flood-plain geomorphic classification of Merigliano and Polzin (2003).

the basic types in the Channel Classification are: (a) bedrock, (b) cascade, (c) anabranching-braided, (d) anabranching, (e) plane bed, (f) pool-riffle, and (g) forced. Additional detail is represented by mixed classes, designated by a slash between the primary and secondary class, and by describing forcing in terms of source (human or natural) and effects (what channel type is converted to what other channel type). Dalby and Robinson (2003) mapped 58 individual segments on the upper Yellowstone from Gardiner to Springdale, Montana. Their map is not presented here because the level of detail is not well represented in a small figure.

There are strong correspondences between the classification systems. Canyon in the Flood-Plain Classification corresponds to bedrock in the Channel Classification; Wandering Gravel Bed in the Flood-Plain Classification is a combination of anabranching and anabranching-braided in the Channel Classification; and Confined Wandering Gravel Bed (Flood-Plain Classification) is a combination of anabranching and pool-riffle (Channel Classification). Plane bed in the Channel Classification is a combination of Confined Coarse Textured and Entrenched in the Flood-Plain Classification; and cascade (Channel Classification) is a subset of Confined Coarse Textured in the Flood-Plain Classification. Most of the Urban class in the Flood-Plain Classification falls into the forced type of the Channel Classification.

Any classification scheme represents a specific decision about scale, simplicity, detail, and the relative importance of different attributes. The Flood-Plain and channel geomorphic classifications for the upper Yellowstone River were developed for somewhat different objectives and have both advanced the understanding of that system in terms of structuring sampling and describing important variation. Integrating or modifying those systems to support future monitoring or management would be best accomplished by sharply defining the objectives for the modification (especially in terms of the level of detail and spatial scale desired).

Measuring Ecosystem Integrity: Key Variables

Measures of ecological integrity at the landscape level are needed for: (a) a retrospective assessment of cumulative impacts to date, (b) monitoring system condition in the future, (c) evaluating alternative potential future scenarios, and (d) informing a regulatory program that incorporates cumulative effects in decisions about individual actions. A number of approaches have been used for measuring system integrity, including indicator organisms and multivariate indices defined to represent variation among systems, sensitivity to actions, or relations to valued attributes or functions. Assessment tools used in wetland, riparian, and aquatic systems include proper functioning condition (Barrett and others, 1993), index of biotic integrity (Karr, 1981), the synoptic approach (Liebowitz and others, 1992), and the hydrogeomorphic (HGM) approach (Hauer and Smith, 1998). Though developed for different applications, these tools all use measures that are referenced to some combination of historical or unaltered conditions in the ecosystem, or values observed in other systems. Choice of ecological integrity measures is ultimately a political and institutional decision reflecting a compromise among programmatic aspects of institutions making decisions regarding actions; society values and concerns about different aspects of system structure and function; and practicalities of measurement and estimation. Use of judgment and inference in selecting and interpreting indicators is unavoidable because of time and funding limitations and our often incomplete understanding of the complex interactions of driving variables (Abbruzzese and Liebowitz, 1997).

The hydrogeomorphic approach was developed specifically to evaluate the functions of riparian wetlands in the context of regulating and mitigating actions such as channel modification under the Clean Water Act. Although HGM is primarily focused on site-level evaluations, Hauer and others (2001) applied a version of the approach to evaluate cumulative effects along the upper

Yellowstone River. Their assessment was based on functional capacity indices for eight functions (Table 1). For each of these functions, an index combined values of variables (Table 2) logically reflecting the capacity of the system to perform that function. The indices were scaled by the range of variation exhibited by a set of reference rivers in the Northern Rocky Mountains (Hauer and others, 2001). Quantification of the variables included both scores assigned to narrative criteria (e.g., for VGEOMOD or degree of anthropogenic modification of the flood-plain geomorphic properties) and direct measures (e.g., V_{HERB} as percent cover) scaled relative to comparable measurements at the reference sites. Values of the indices were calculated for homogeneous polygons and then aggregated to larger areas by the area-weighted averages of the polygons. The variables V_{GEOMOD}, $V_{COMPLEX}$, V_{HABCON}, and $V_{LANDUSE}$ (Table 2) were the most sensitive to human impact. Hauer and others (2001), using substantial estimation, were able to use this approach to produce both a retrospective comparison of cumulative impacts to date and a comparative analysis of two future scenarios of reduced and increased channel confinement.

The HGM approach employed by Hauer and others (2001) for the riparian wetland components of selected areas of the upper Yellowstone River corridor could be extended to encompass aquatic functions of the main channel (including acquisition of appropriate reference site data from other rivers) and employed for cumulative impact analysis on the whole corridor. The principal advantage of this approach is that it is complete in the sense of actually providing a scoring of specific functions under both historical and alternative future conditions. The principal limitations are: (a) coarse, and arguable, estimation of the values of variables; (b) coarse, and arguable, models for how variables combine to determine the capacity for higher-level functions; and (c) the multi-variable (or multi-index) nature of the ultimate output. Multi-variate output is almost unavoidable, but in this case a very large number of arguable assumptions are necessary to produce endpoints that still provide little direct indication of how much change in which of multiple dimensions is significant or should trigger specific decisions. To provide an alternative method for assessing effects of channel modification, we sought to identify key variables that were directly measurable and broadly important. Our general approach was to: (1) combine primary results from the upper Yellowstone River technical studies with what is known from the literature to develop causal diagrams; (2) use the causal diagrams to help identify variables that are critical to multiple resources; and (3) provide specific descriptions of key variables to measure based on relevant spatial and temporal scales.

The causal diagrams presented here in a preceding section represent general models of how variables might interact to produce important cumulative impacts from channel modification of the upper Yellowstone River corridor. Some of these variables occupy critical positions in the causal pathways in the sense that they have multiple linkages to valued attributes of the ecosystem. Table 3 identifies a core set of metrics that: (a) reflect key variables in the causal diagrams of Figures 2–5; and (b) are amenable to practical, efficient measurement in straightforward units using a combination of remote sensing, geographic information system analysis, and field sampling. Direct use of such key variables as the measurement system for monitoring and assessing cumulative impacts on ecosystem integrity is an alternative to complex, synthetic indices. The principal advantages are that both the units and definition of each metric are straightforward. The importance of the variables is established through qualitative, causal models rather than numerical combinations. This is not as accurate as a validated simulation model, but also does not impart the kind of false precision implicit in the coarse, but complex, numerical algorithms employed in many index calculations. As with HGM functional capacity indices, use of directly measured key variables does not directly inform a decision about the significance or acceptability of a given difference. However, summary statistics for key variables from different geomorphic channel types

Table 1. List of functions evaluated in HGM application to upper Yellowstone River (Hauer and others, 2001).

Function	Variable (Table 2) Used in Index
Surface-groundwater storage and flow	$V_{SURFREQ}$, $V_{SUBFREQ}$, V_{MACRO}, V_{GEOMOD}
Nutrient cycling	V_{HERB}, V_{SHRUB}, V_{DTREE}, $V_{COMPLEX}$, $V_{ORGDECOMP}$
Retention of organic and inorganic particles	$V_{SURFREQ}$, V_{MACRO}, $V_{COMPLEX}$, V_{LWD}
Generation and export of organic carbon	$V_{SURFREQ}$, V_{MACRO}, V_{HERB}, V_{SHRUB}, V_{DTREE}
Characteristic plant community	$V_{SURFREQ}$, $V_{SUBFREQ}$, V_{MACRO}, $V_{COMPLEX}$
Characteristic aquatic invertebrate habitats	$V_{SURFREQ}$, $V_{SUBFREQ}$, V_{MACRO}, $V_{COMPLEX}$
Characteristic vertebrate habitats	V_{HERB}, V_{SHRUB}, V_{DTREE}, $V_{NPCOVER}$, $V_{SURFREQ}$, V_{MACRO}, $V_{COMPLEX}$, V_{HABCON}
Flood-plain interspersion and connectivity	$V_{LANDUSE}$, V_{HABCON}, $V_{COMPLEX}$, V_{MACRO}, $V_{SURFREQ}$, $V_{SUBFREQ}$, V_{GEOMOD}

Table 2. Variables used in HGM application to upper Yellowstone River (Hauer and others, 2001).

Variable	Description
$V_{COMPLEX}$	Proportionality of landscape features
V_{HABCON}	Flood-plain habitat connectivity
V_{GEOMOD}	Geomorphic modifications affecting hydrologic flow
$V_{LANDUSE}$	Proportional land use within assessment area
V_{MACRO}	Macrotopographic complexity
$V_{SURFREQ}$	Frequency of overbank flooding
$V_{SUBFREQ}$	Frequency of flooding from subsurface input
$V_{ORGDECOMP}$	Microbial decomposition of organic matter
V_{DTREE}	Tree density
V_{SHRUB}	Shrub and sapling density
V_{HERB}	Herbaceous plant density
V_{LWD}	Large woody debris
V_{NPCOV}	Percent coverage of native plants

could be used to quantify natural ranges within geomorphic classes and as a baseline for detecting changes in key measures over time.

The driving forces of upper Yellowstone River corridor cumulative impacts depicted in Figure 2 are decisions about channel modification and land use. This is certainly a restricted domain of cumulative impact assessment, focusing on flood-plain development and channel modification, and ignoring sources of impact such as global climate change, species introductions, and wildlife disease patterns. The simplest metrics of impact on ecological integrity are: (a) the extent of modified bottomland use in terms of non-natural cover types, and (b) the extent of channel modifications. The implications of channel modification and anthropogenic cover-type conversions vary according to the specific types of changes (e.g., a bank stabilization that does not stop lateral channel migration has little impact, and vegetation alteration from light grazing has less impact than conversion of a forest to a parking lot). Nonetheless, the overall extent and magnitude of channel modification and the overall extent and magnitude of non-natural bottomland cover types are powerful, simple measures of the overall loss

Table 3. Directly measured metrics of upper Yellowstone River corridor ecological integrity.

Metric	Data source	Time scale
Physical and biological		
Area of vegetation types inundated at reference flows (current 2-year, 10-year and 100-year flood magnitudes)	Aerial mapping at high flow	Decadal and opportunistic based on events
Length of wet channel >5 m wide at reference flow (current 2-year flood magnitude)	Aerial mapping at high flow	Decadal and opportunistic based on events
Channel migration rate	Aerial mapping	Decadal and opportunistic based on events
Location and type of channel modification	Aerial mapping	Decadal
Channel cross section topography, vegetation, and stage at selected locations	Field measurement	2 to 5 years and opportunistic based on events
Fish year class strength as catch per unit effort	Field measurement	Annual
Socioeconomic		
Immigration and emigration	Census data	Decadal
Demography	Census data	Decadal
Employment by job category	Census data	Decadal
Building related permits	County	Decadal
Fishing guide revenues	State/Federal	Annual
Flood damage claims	FEMA or insurance industry	Decadal and opportunistic based on events
Social attitudes	Survey or focus group	Decadal

of ecological integrity. The area and nature of vegetation types inundated by reference flows are a direct measure of both the extent of cover-type conversion and the loss of flood-plain connectivity due to levees or channel incision. Reference flows are most easily defined with respect to specific discharge magnitudes. Extension of the reference to a flow recurrence interval (e.g., 10-year flood) adds the possibility of impacts associated with flow depletion that might change the magnitude of the 10-year flood.

The resource studies on the upper Yellowstone River and current scientific understanding of riverine landscapes in general emphasize the importance of natural fluvial disturbance in maintaining the diversity of physical features and a shifting mosaic of habitats that support characteristic levels of biodiversity (Figures 3–5). Channel migration rate (Table 3) is a direct measure of this variable, although there are several alternatives for both expressing and measuring migration rates.

Side channels are important fish habitat features that also reflect overall physical heterogeneity of the river corridor and riverflood-plain connectivity (Figures 3 and 4). Length of side channels at a reference flow (Table 3) is easily measured from aerial photography and also represents a sensitive indicator of channel incision that might isolate side channels (Figure 3).

Although they are substantially more expensive to obtain in a long-term monitoring effort, field measurements of selected permanent cross sections and actual fish populations by some standard sampling method (Table 3) would provide the detail required to better understand the specific changes going on in the system. In the case of age class strength of fish, this measurement would highlight an especially valued attribute of the system (Figure 2) as well as help to understand the relative long-term importance of different potential habitat factors controlling fish populations.

The socioeconomic variables listed in Table 3 are easily obtained statistics that partially reflect the population and economic forces driving channel modification and human land use in the bottomland, as well as the quality and extent of resident and visitor use of the river corridor.

Ideally, measurement of ecological integrity within the upper Yellowstone River corridor would be stratified by geomorphic reach types. There are obvious differences in variables such as the width of the 100-year flood-plain between unconfined Wandering Gravel Bed reaches and the strongly confined Yankee Jim Canyon. To be most useful, such analysis will require acceptance and use of a consistent geomorphic classification system to integrate across the results of various resource studies. Comparison of different geomorphic classes might further suggest some variable especially tailored to the upper Yellowstone River system. Merigliano (written communication) has proposed metrics of patch size and age distribution, island size distribution, and flood-plain turnover rate. These metrics differ among geomorphic reach types and could serve to monitor system condition. Whether or not the specific measures recommended in this report are used, variables assessing cumulative effects of bank stabilization in the upper Yellowstone River should incorporate both channel modification and land use; focus on channel migration and flood-plain connectivity; be amenable to detecting change in meaningful units; and build from results from the upper Yellowstone technical studies.

A substantial amount of work remains in order to conduct credible analyses over the entire upper Yellowstone River corridor. This work includes: (a) refining and reconciling multiple land-cover classification systems; (b) reconciling multiple geomorphic classification systems employed by the various resource studies; (c) refining the metrics suggested in Table 3; (d) fairly and consistently estimating historical conditions for which direct data are not available; and (e) articulating meaningful and internally consistent future alternatives or scenarios.

Measuring Ecosystem Integrity: Prototype Geographic Information System Analysis of Selected Variables

The analytical power of modern geographic information systems coupled with the attention recent resource studies on the upper Yellowstone River have paid to developing data in the form of consistent geospatial coverage enables relatively comprehensive assessment and monitoring of cumulative changes in ecosystem integrity. The key variables identified in this report were selected in part because of compatibility with geographic information system analysis.

In this section we present a prototype analysis of a single Wandering Gravel Bed reach (site name TECCA), quantifying some of key variables identified in this report (Table 4) based on coverage derived from various individual resource studies. We make some estimates of changes from 1948 to 1999 and also include a hypothetical scenario of future channel modification in the reach. The goal is not a definitive analysis, but rather to illustrate how the foundations available might be used to conduct cumulative impact assessment and alternatives analysis.

Table 4. Metrics of upper Yellowstone River corridor ecological integrity used in GIS analysis.

Metric	Data sources
Physical and biological	
Land-use classes and riparian classes inundated at the current 100-year flood magnitude	Holnbeck and Parrett (2002); Pick and Potter (2003); Hansen (2003)
Physical structures (channel modifications and houses) in the river corridor (1948 and 1999)	Dalby and Robinson (2003); Brelsford and others (2003)
Large woody debris inundated at the current 100-year flood magnitude	Holnbeck and Parrett (2002); Bowen and others (2003)
Lengths of side channels (1948 and 1999)	Dalby and Robinson (2003)
Difference in channel centerline position measured perpendicular to the river valley axis (1948 and 1999).	Dalby and Robinson (2003)
Socioeconomic	
Employment by job category (1971 and 2001)	U.S. Census Bureau
Rates of population change for Montana and Park County	U.S. Census Bureau

The study reach for this analysis is depicted in Figure 7, with the actual location of dikes in 1999 and a shaded area that would hypothetically be removed from the 100-year flood-plain by connecting all existing dikes along the west side of the main channel. Figure 8 depicts the current area and vegetation types inundated at the reference flow corresponding to the current 100-year flood in terms of the cover classes of Pick and Potter (2003). Figure 9 illustrates implementation of the hypothetical alternative by depicting the polygons of different cover types that would be excluded from the 100-year flood-plain by the hypothetical construction of a connecting dike.

A large part of the power of geographic information systems lies beyond the ability to generate maps and in the capability of generating quantitative analyses of spatially referenced data. Figure 10 depicts historical changes in the number and extent of channel modification structures (one of the key metrics from Table 3) and the number of houses in the study area (a measure of land use and anthropogenic bottomland cover-type conversion). Figure 11 compares cover types (Pick and Potter, 2003) connected to the river (within the 100-year flood-plain) in 1948, 1999, and under the hypothetical dike scenario. Shifts among cover types between 1948 and 1999 sum to zero because the same extent of 100-year flood-plain was assumed for these two time periods. However, total area in the 100-year flood-plain decreases in the hypothetical dike scenario, although area lost as it is disconnected from the river by diking does not come proportionally from all the cover types. Figure 12 is a parallel analysis of 1948, 1999, and the dike scenario using the cover-type classification of Hansen and others (2003) rather than Pick and Potter (2003). Figure 13 compares the current (1999) extent of large woody debris in the study reach with the hypothetical dike scenario based on detailed mapping of large woody debris (Bowen and others, 2003) and exclusion of diked area from the connected flood-plain.

Figure 7. Actual locations of dikes in 1999 (bold line) and hypothetical area affected (shaded) by connecting all existing dikes along the west side of the main channel in the TECCA site.

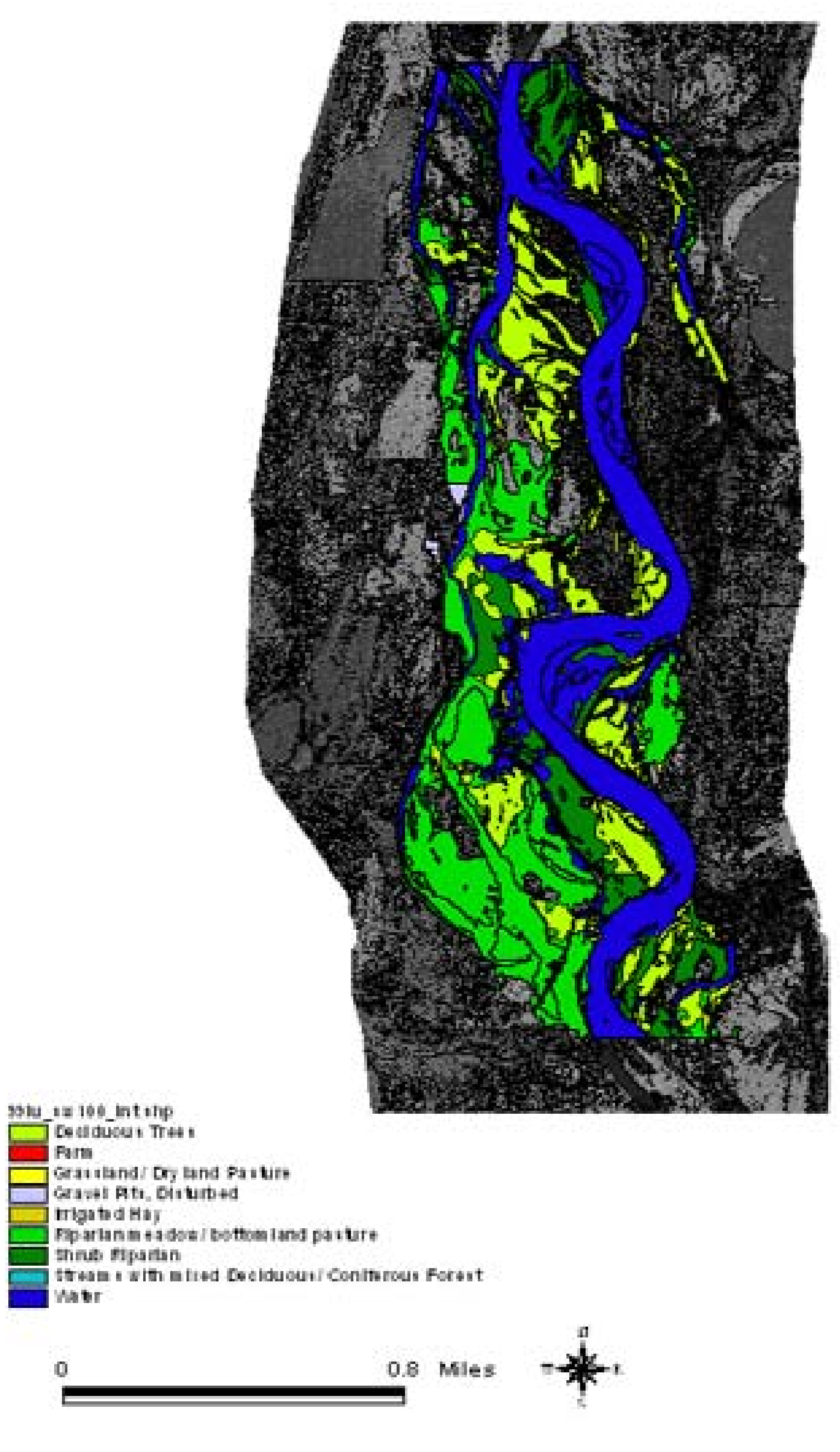


Figure 8. Area of different land-use classifications inundated by the 100-year flood in the TECCA site.

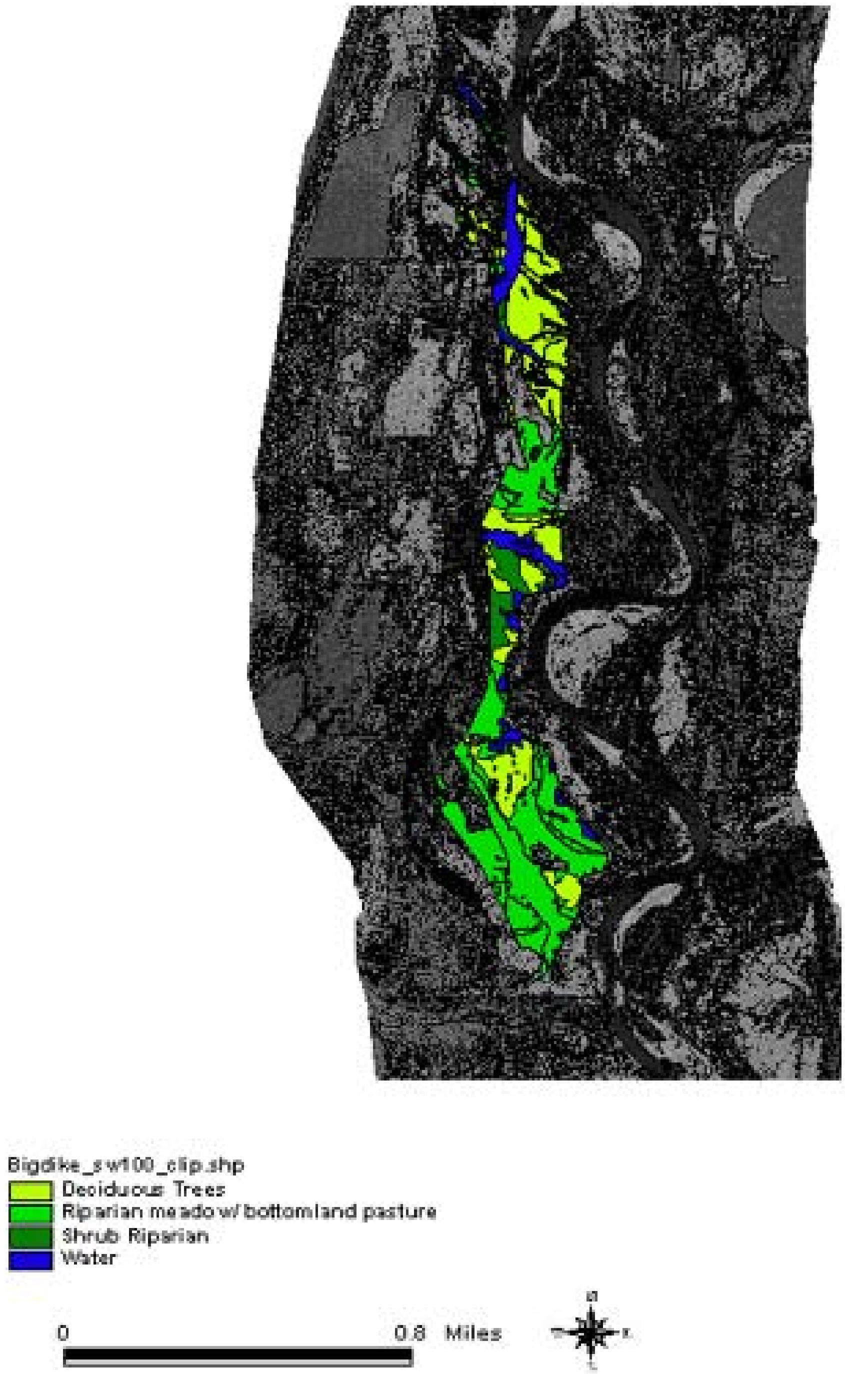


Figure 9. Hypothetical area of different land-use classifications affected during the 100-year flood after connecting dikes along the west side of the main channel in the TECCA site.

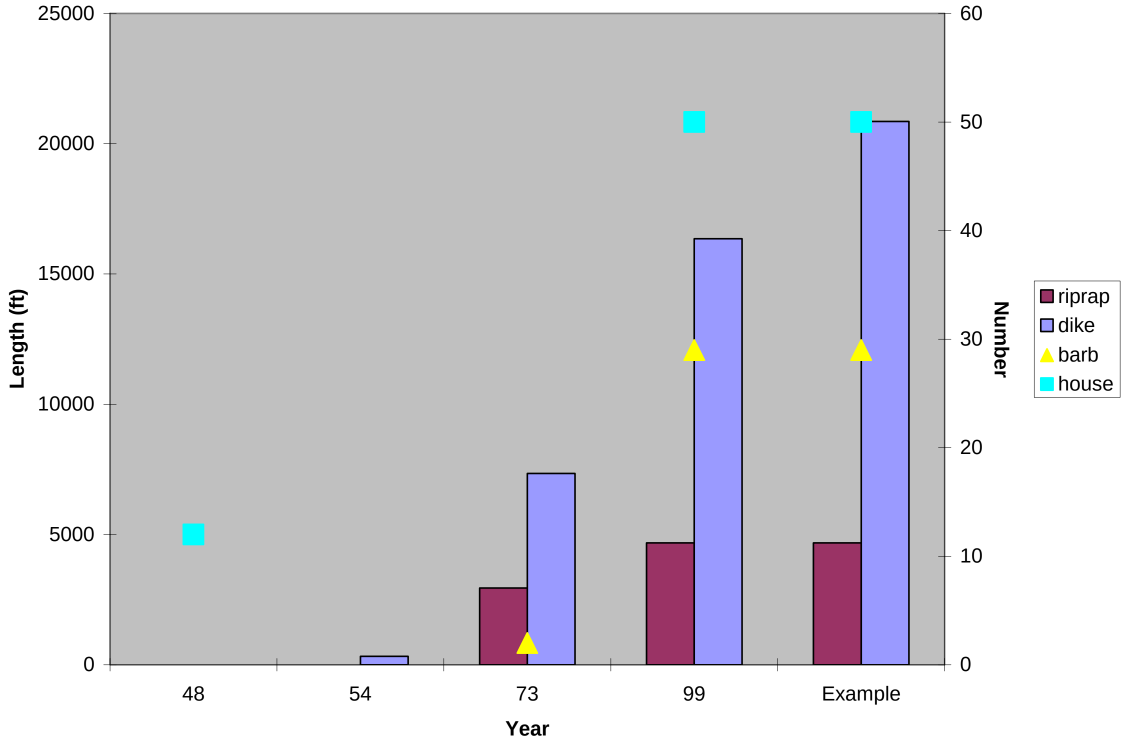


Figure 10. Physical structures including length of riprap and dikes (bars, left y-axis) and number of barbs and houses (symbols, right y-axis) in the TECCA site.

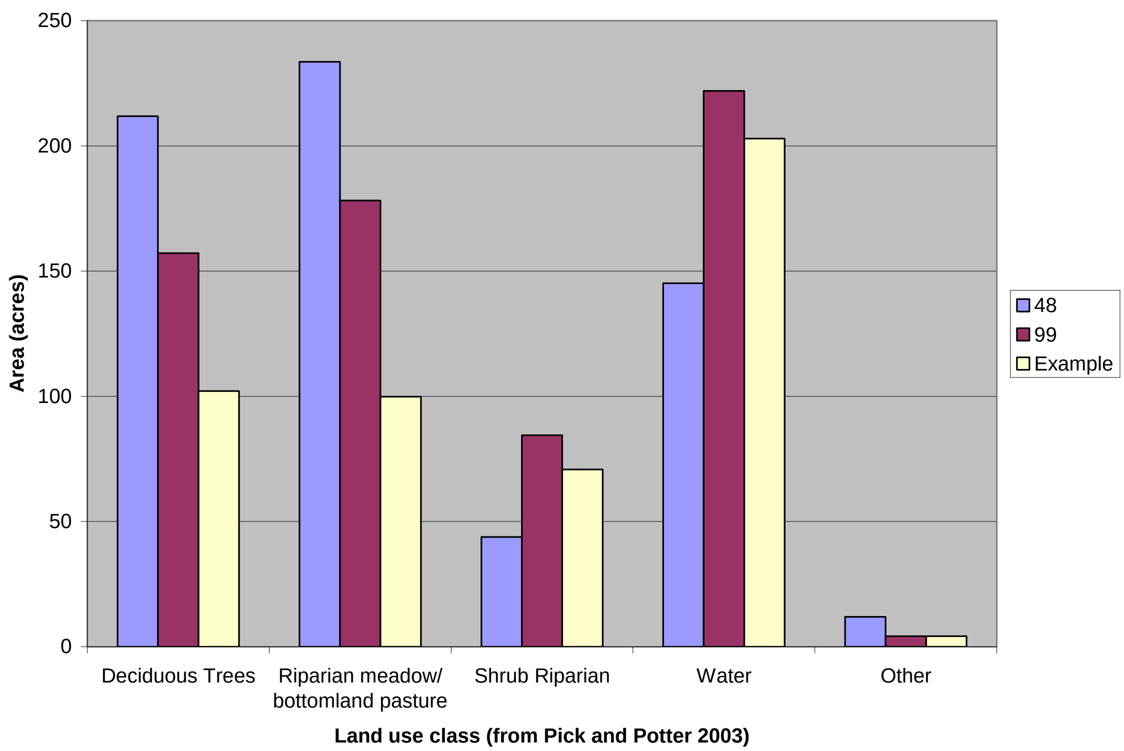


Figure 11. Area inundated at the 100-year flood for different land-use classifications in the TECCA site.

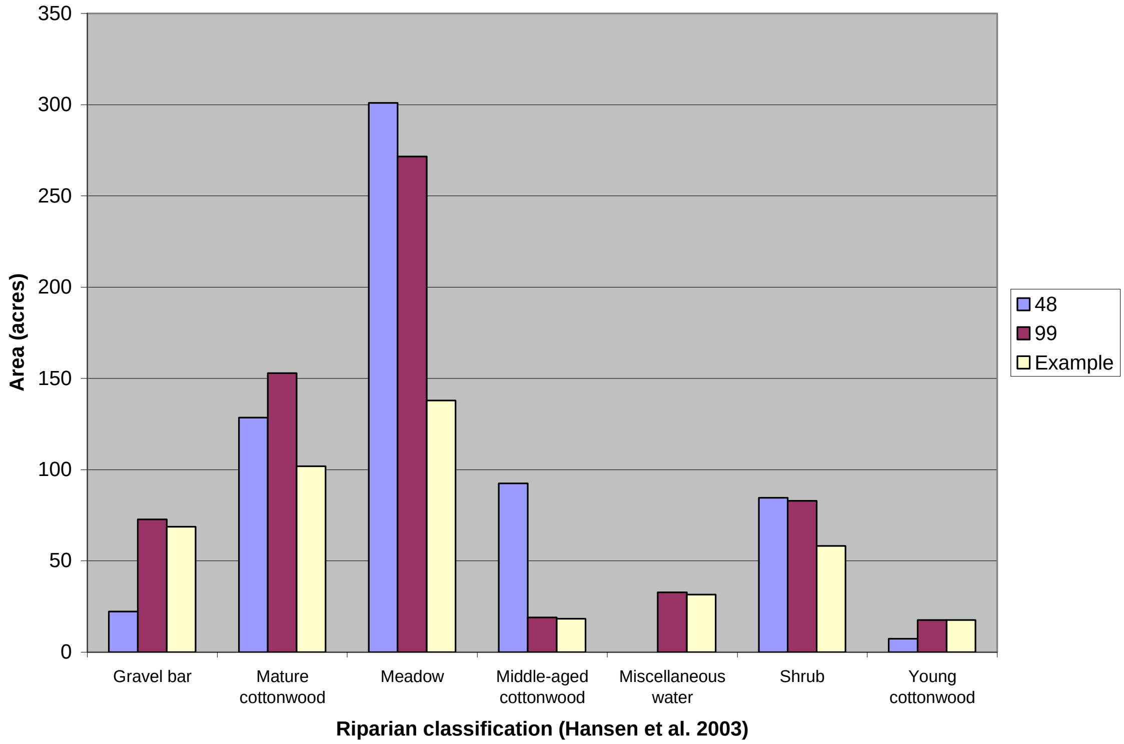


Figure 12. Area inundated at the 100-year flood for riparian land-cover types in the TECCA site.

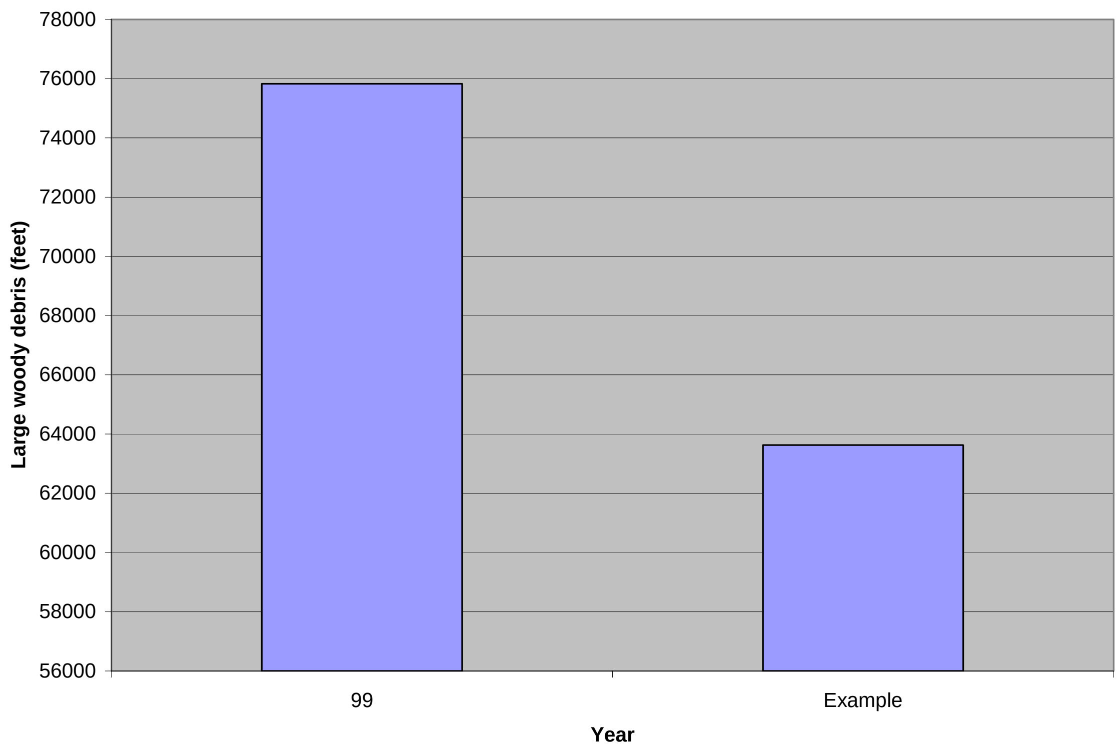


Figure 13. Amount of large woody debris inundated at the 100-year flood, measured as length of stems and branches greater than one foot diameter in the TECCA site.

Figures 14 and 15 compare the lengths of channel types, including subclasses of side channel, between 1948, 1999, and the hypothetical diking scenario, assuming side channel impacts in the diking scenario are restricted to simple loss of all the side channels in the diked-off area. Figure 16 and Table 5 illustrate one way of measuring the rate of channel movement. Distances between channel center line locations in 1948 and 1999 were calculated throughout the reach with the longitudinal pattern depicted in Figure 16 and summary statistics presented in Table 5. Average movement of the channel center line was 310 feet over this approximately 50-year time interval.

Selected socioeconomic variables derived from census data for Park County as a whole show a reduction in farm employment of almost 50% from 1971 to 2001 (Figure 17). Other substantial changes in proportional distribution of non-governmental employment from 1971 to 2001 include proportional increases in services, construction, real estate, recreational, and financial sectors and proportional decreases in retail trade, forestry, and transportation/public utilities (Figure 18). The current rate of population change (2002–2003) in Park County is slightly negative at -0.2% per year (Table 6).

The intent of this prototype analysis was to illustrate the potential of using geographic information system analysis tools and simple, key variables to represent cumulative effects. More complex analyses are also possible by: (a) calculating synthetic indices for each polygon in the Hauer and others (2001) application of HGM to the upper Yellowstone, (b) using regression models of geographic data themes such as cover types to estimate properties such as bird species richness (i.e., using models developed by Hansen and others (2003) for the upper Yellowstone River corridor), or (c) using habitat suitability models or distributional overlays to focus on specific species as illustrated by Pick and Potter (2003) for the whole drainage basin.

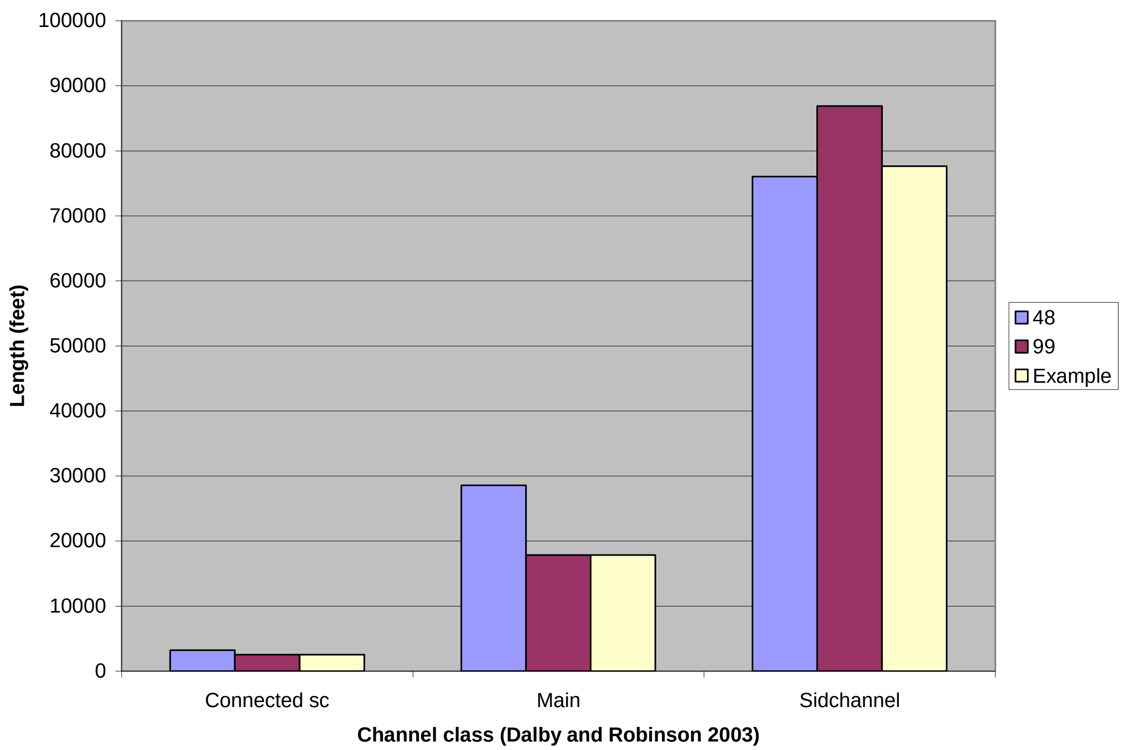


Figure 14. Lengths of channel types in the TECCA site.

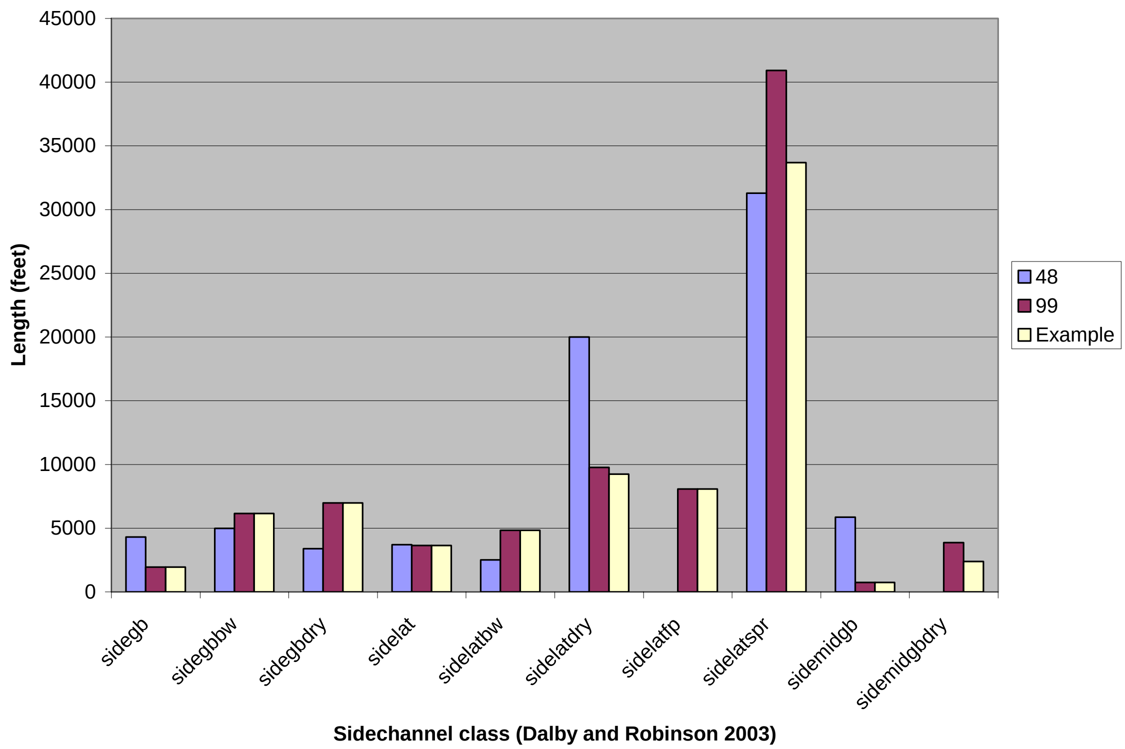


Figure 15. Lengths of side channel types in the TECCA site.

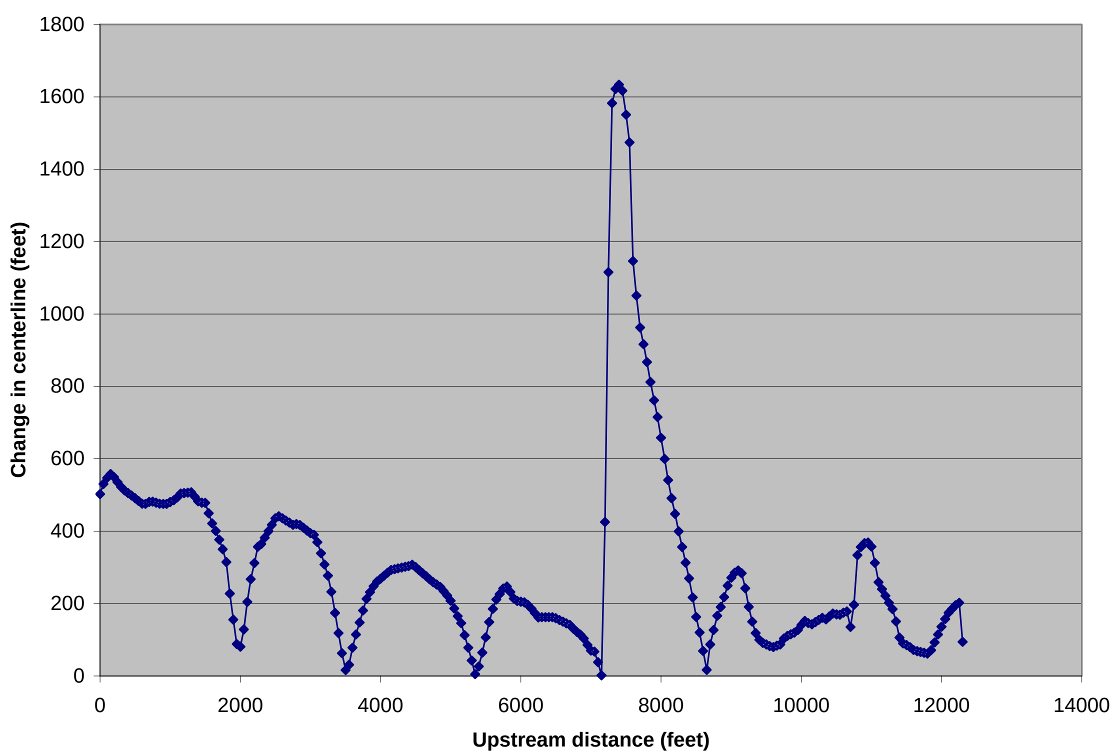
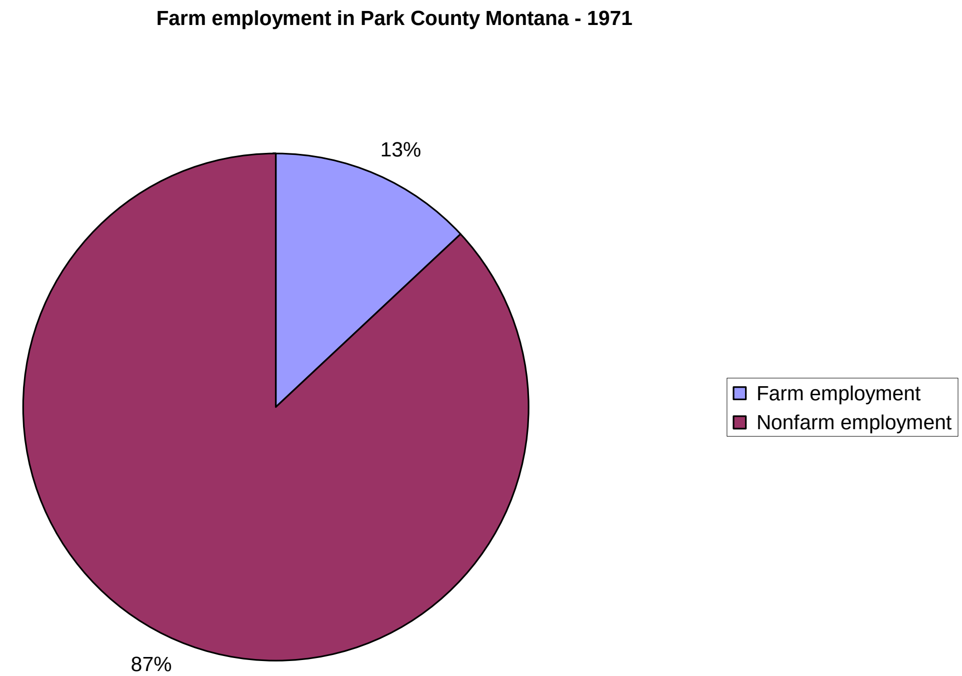


Figure 16. Difference in channel centerline position measured perpendicular to the river valley axis (1948 and 1999) in the TECCA site.

Table 5. Summary statistics for change in channel centerline measurements (1948 and 1999) in the TECCA site.

Summary statistics	
Mean	310
Standard error	18
Median	232
Mode	n/a
Standard deviation	280
Sample variance	78225
Kurtosis	9
Skewness	3
Range	1632
Minimum	1
Maximum	1633
Sum	76484
Count	247
Largest(1)	1633
Smallest(1)	1
Confidence level(95.0%)	35



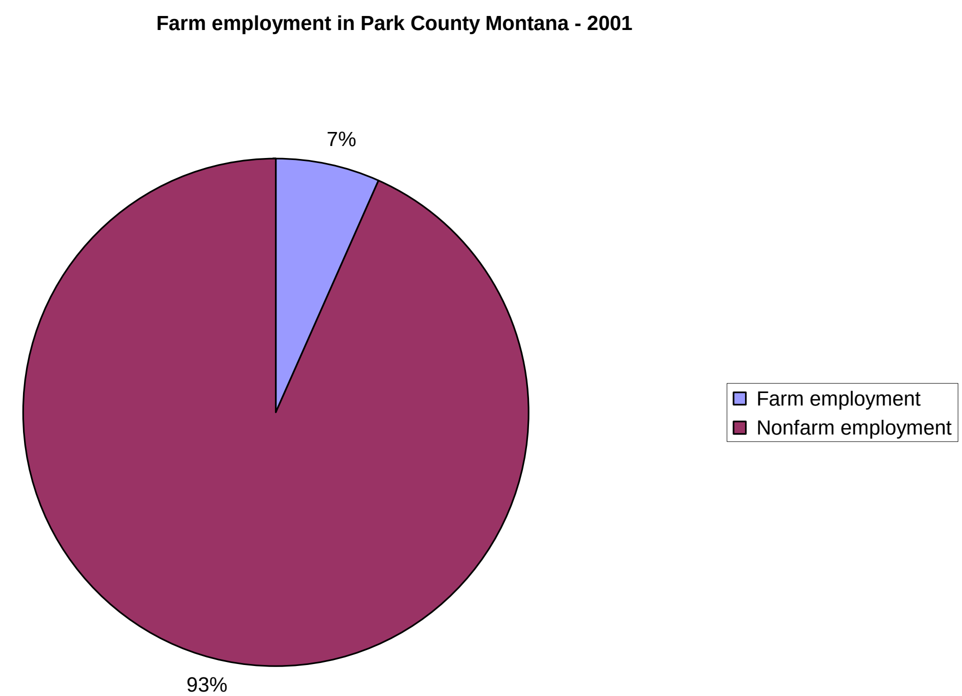
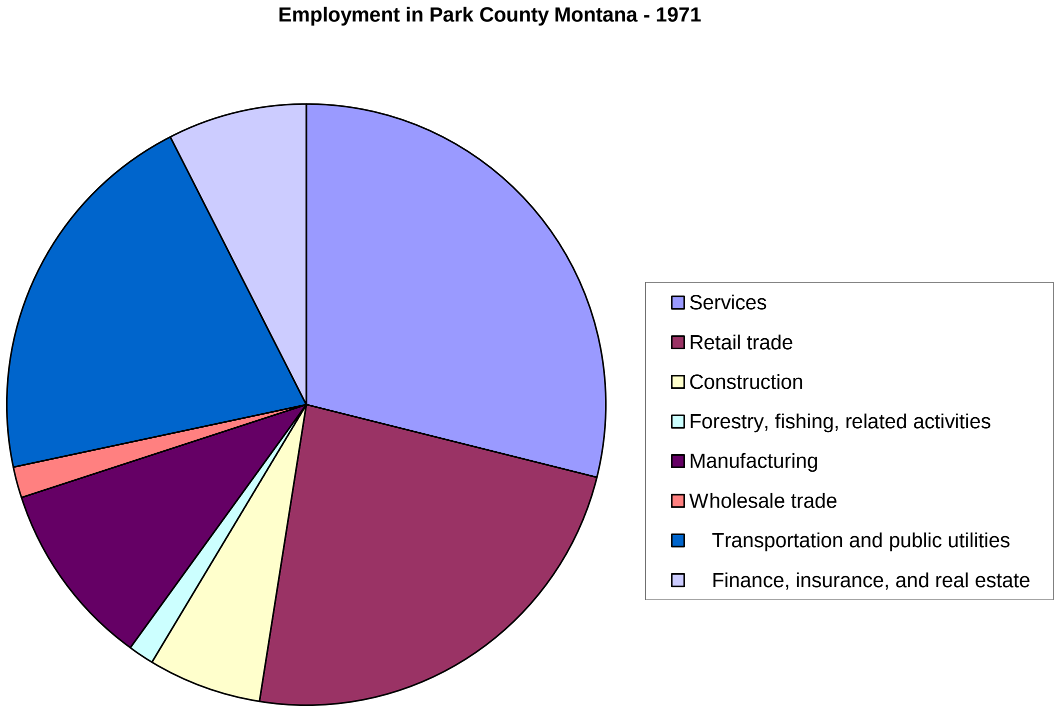


Figure 17. Total farm and non-farm employment for Park County Montana in 1971 (top) and 2001 (bottom).



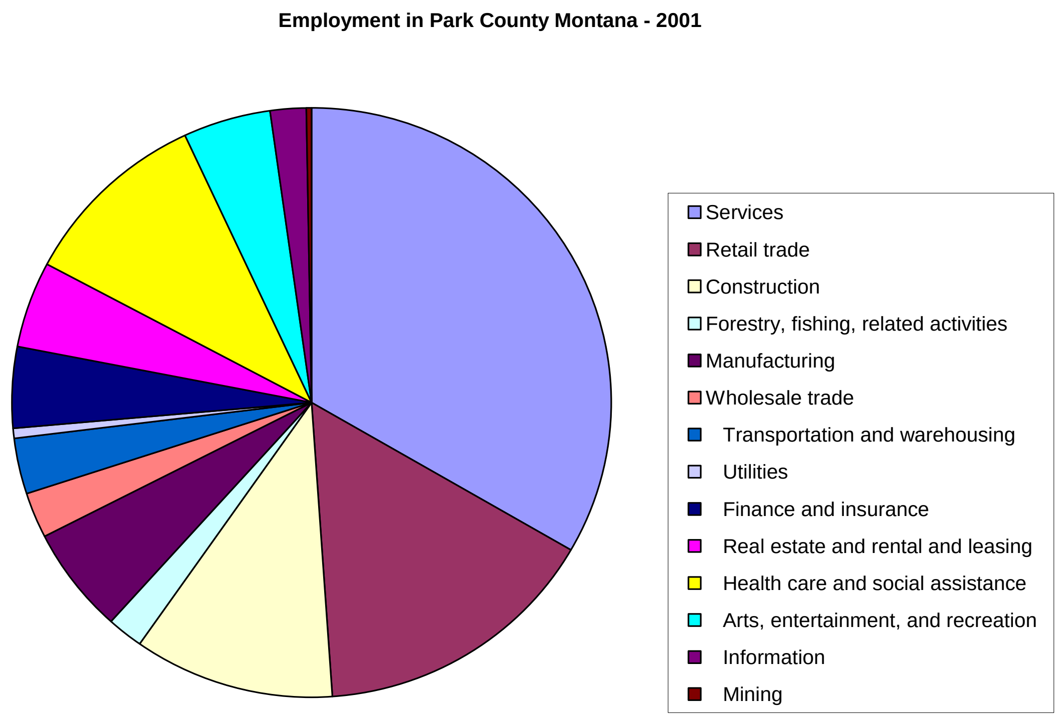


Figure 18. Total non-government employment for Park County Montana in 1971 (top) and 2001 (bottom).

Table 6. Estimates of average annual rates[a] of the components of population change for counties of Montana: July 1, 2002 to July 1, 2003.

		Natural increase			Net migration		
Geographic area	Total population change[b]	Total	Births	Deaths	Total	Net international migration	Net internal migration
Montana	**7.9**	**2.0**	**11.8**	**9.8**	**5.9**	**0.4**	**5.5**
Beaverhead County	-7.3	-0.7	9.6	10.3	-6.5	0.8	-7.3
Big Horn County	6.2	14.5	22.2	7.7	-8.2	0.2	-8.5
Blaine County	-14.9	-1.8	14.8	16.5	-13.0	0.4	-13.4
Broadwater County	7.0	-4.3	7.7	12.0	12.0	0.5	11.6
Carbon County	5.0	-1.1	9.1	10.3	6.4	0.6	5.7
Carter County	-16.4	-10.4	6.0	16.4	-5.2	0.0	-5.2
Cascade County	-0.5	1.6	12.9	11.2	-1.9	0.2	-2.2
Chouteau County	-11.2	-4.5	6.4	10.9	-6.4	0.7	-7.1
Custer County	-5.2	-0.1	11.9	12.0	-5.1	0.4	-5.5
Daniels County	-4.6	-10.3	8.2	18.5	5.7	2.1	3.6
Dawson County	4.2	-2.4	9.9	12.3	6.5	0.0	6.5
Deer Lodge County	-13.4	-7.9	11.1	19.0	-5.5	-0.1	-5.4
Fallon County	10.6	-3.3	10.2	13.5	13.5	0.0	13.5
Fergus County	2.7	-3.3	9.8	13.0	6.2	0.1	6.1
Flathead County	26.1	3.3	12.3	9.1	22.5	0.4	22.1
Gallatin County	28.7	5.4	10.9	5.6	23.0	1.3	21.7
Garfield County	-2.4	2.4	13.0	10.5	-4.9	0.0	-4.9
Glacier County	5.1	11.0	19.2	8.2	-5.8	0.3	-6.1
Golden Valley County	-25.5	0.9	9.4	8.5	-26.4	0.0	-26.4
Granite County	7.3	-6.9	5.2	12.1	13.9	0.0	13.9
Hill County	0.4	5.3	15.6	10.3	-4.8	0.0	-4.8
Jefferson County	10.5	-1.4	8.0	9.5	11.9	0.1	11.8
Judith Basin County	-23.9	-0.5	5.9	6.3	-24.3	0.0	-24.3
Lake County	7.9	0.4	11.8	11.4	7.5	0.3	7.2
Lewis and Clark County	11.7	1.7	11.1	9.4	10.0	0.5	9.5
Liberty County	13.2	2.0	11.3	9.3	11.3	0.0	11.3
Lincoln County	6.0	-1.3	9.5	10.8	7.5	0.2	7.2
McCone County	-16.4	1.1	9.3	8.2	-16.4	0.0	-16.4
Madison County	0.9	-0.1	10.8	10.9	1.3	0.1	1.1
Meagher County	17.4	5.1	9.2	4.1	12.3	0.5	11.8
Mineral County	16.6	-2.3	6.2	8.6	18.4	0.3	18.2
Missoula County	7.5	4.0	11.1	7.1	3.7	0.9	2.7
Musselshell County	1.1	-5.4	8.5	13.9	6.9	0.0	6.9

Table 6. Estimates of average annual rates[a] of the components of population change for counties of Montana–Continued.

Geographic area	Total population changeb	Natural increase: Total	Births	Deaths	Net migration: Total	Net international migration	Net internal migration
Park County	-2.1	-1.4	10.5	11.9	-0.5	0.7	-1.2
Petroleum County	6.1	-6.1	8.2	14.3	10.2	0.0	10.2
Phillips County	-21.1	-7.4	10.7	18.1	-13.9	0.5	-14.4
Pondera County	-14.5	-3.1	9.0	12.1	-11.4	0.2	-11.6
Powder River County	1.6	-2.7	8.2	10.9	4.9	0.0	4.9
Powell County	-4.3	-0.4	11.4	11.8	-3.6	0.0	-3.6
Prairie County	-27.4	-8.5	8.5	17.1	-18.8	0.0	-18.8
Ravalli County	24.4	0.4	10.2	9.8	23.5	0.2	23.4
Richland County	-11.7	-2.7	9.7	12.4	-9.0	0.2	-9.2
Roosevelt County	2.2	7.4	19.3	12.0	-5.0	0.2	-5.2
Rosebud County	3.8	9.8	16.2	6.4	-5.9	0.3	-6.2
Sanders County	2.2	-3.6	9.4	13.0	5.8	0.5	5.4
Sheridan County	-36.1	-16.1	2.1	18.2	-20.9	0.3	-21.1
Silver Bow County	-7.2	-1.3	11.8	13.0	-5.9	0.3	-6.2
Stillwater County	0.9	4.4	11.7	7.3	-3.2	0.2	-3.4
Sweet Grass County	-0.8	7.2	15.5	8.3	-7.5	1.1	-8.6
Teton County	6.9	0.2	9.9	9.8	7.1	0.5	6.6
Toole County	-16.2	1.7	11.7	10.0	-17.7	0.6	-18.2
Treasure County	-55.6	-6.6	6.6	13.2	-45.0	0.0	-45.0
Valley County	-9.1	-3.4	13.8	17.2	-5.7	0.1	-5.8
Wheatland County	-24.9	-1.4	10.8	12.2	-23.9	0.0	-23.9
Wibaux County	-18.3	-11.2	7.1	18.3	-5.1	1.0	-6.1
Yellowstone County	10.2	3.8	12.7	8.9	6.6	0.2	6.4

[a]Source: Population Division, U.S. Census Bureau. Release date: April 9, 2004.

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The data and results summarized in this report were produced by the scientists conducting and authoring individual resource studies. They are responsible for the increase in understanding of the upper Yellowstone River system. We appreciate their openness and effort in helping us understand their work. However, responsibility for the interpretations presented here is ours and those interpretations do not necessarily represent the judgments of the authors of individual studies.

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Appendix A. Resource Studies

Upper Yellowstone River Watershed Land Cover Assessment (Pick and Potter, 2003)

Scope and Methods

Original objectives of this study were to:

1. Depict present (1999) land cover/use in the upper Yellowstone River watershed.
2. Depict past land cover/use within the watershed.
3. Analyze land-use changes.
4. Provide resource evaluations related to land cover change.
5. Provide a land cover layer for the watershed.

Mapping was conducted for the upper Yellowstone River watershed as a whole above Springdale, Montana, and in a river corridor buffered for a quarter of a mile from the Yellowstone River. Satellite imagery was used for the 1999 mapping (Figure 19). The small amount of land cover/use change since the 1970's and technical difficulties processing earlier imagery limited the historical analysis, and the results focus on the 1999 classification and map. Coarse-scale resource evaluations of the 1999 land cover in the watershed were performed for hydrology, water quality, and selected upland wildlife (deer and elk).

Findings

1. The major land cover is conifer forest (52%), followed by low/moderate cover grassland (14%) and sagebrush (12%). The upper Yellowstone River watershed above Springdale, Montana, (excluding the Shields River drainage) consists of about 2.47 million acres with approximately 45% of the watershed in Montana and the remainder in Wyoming.
2. The dominant land cover in the upper Yellowstone River corridor (quarter mile buffer from river) is low/moderate cover grassland (35%) followed by agricultural lands-irrigated (18%). sagebrush and broadleaf riparian each constitute approximately 14% of the river corridor, whereas urban or developed lands are 2% of the corridor.
3. Federal agencies own 82% of the land in the watershed, 17% is in private ownership, and the remainder is in state ownership Yellowstone National Park constitutes 57% of the federally-owned land.
4. There are strong longitudinal (upstream-downstream) patterns in land cover and ownership. Federal agencies own 93% of the land above 6,000 feet whereas most (84%) of the lands below 6,000 feet are privately held. Percentages of alpine meadows, open water, and snowfields decline in the downstream direction whereas agricultural lands, sagebrush, and broadleaf riparian increase. The combination of these patterns results in strong differences in the ownership across cover types: 93% of high density and low density forest land is in federal ownership; and privately owned lands are most closely linked with broadleaf riparian, urban or developed lands, and agricultural land-irrigated. Nearly all the broadleaf riparian cover type occurs within the Yellowstone River corridor.

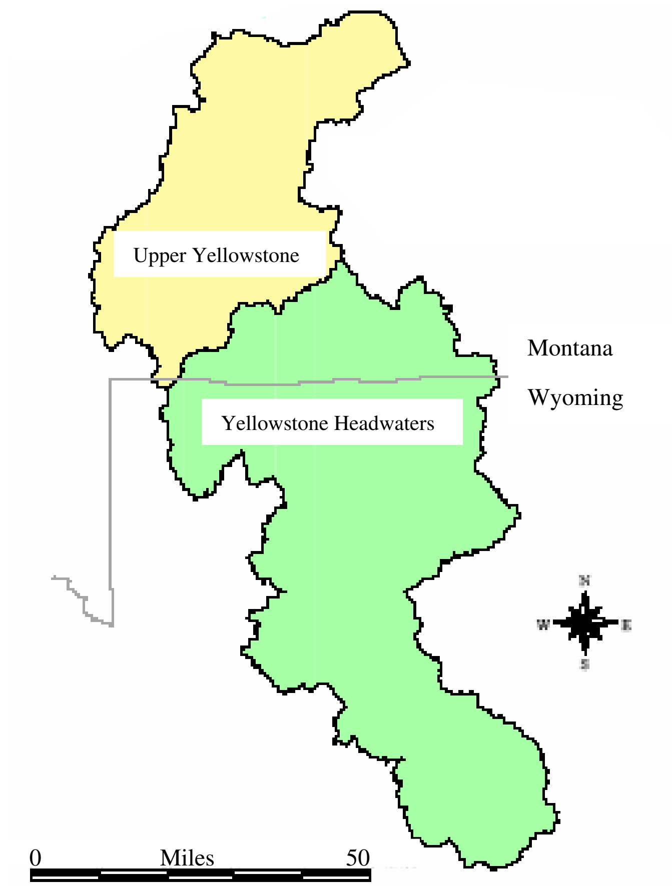

Figure 19. Spatial scope of watershed land cover study (Pick and Potter, 2003).

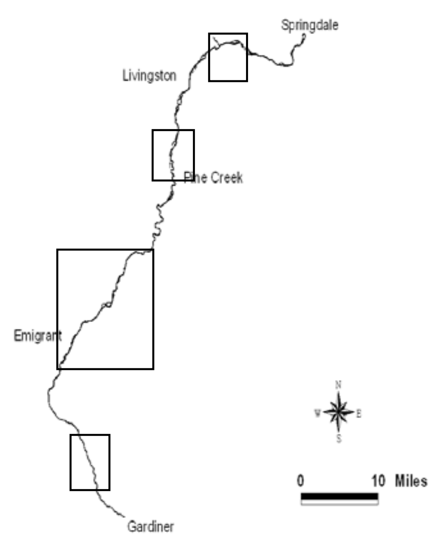

Figure 20. Spatial scope of historic watershed land use study (Brelsford and others, 2003).

5. Low moderate cover grasslands (40%) and sagebrush (28%) are the dominant cover types of mule deer winter range, with 79% of the range in private ownership. Elk winter range is about equally divided between private and U.S. Forest Service ownership, with high density conifer forest (28%), low moderate cover grasslands (28%), and sagebrush (22%) representing the dominant cover types. The majority of whitetail deer habitat is privately owned with low moderate cover grasslands (40%) and sagebrush (28%) the dominant cover types, although almost all of the agricultural lands-irrigated and broadleaf riparian that occur are part of the whitetail deer habitat.

Metrics

Pick and Potter (2003) assigned all land in the upper Yellowstone watershed to a set of cover-type classes that could be distinguished from satellite digital imagery.

Needs for Further Study

1. Continue to monitor land cover change at the corridor scale, emphasizing aerial photography and Geographic Information System (GIS) methods.
2. Identify indicators and thresholds as well as potential management scenarios for the watershed.
3. Examine the nature and extent of ground and surface water interactions.
4. Evaluate soils and soil attributes in the watershed.

Historic Watershed Land-Use Assessment of the Upper Yellowstone River Valley (Brelsford and others, 2003)

Scope and Methods

Two mapping objectives were selected to show land-use change over time as a gauge of cumulative effects for the Upper Yellowstone River:

1. Map land use/cover over three time periods (1948/1949, 1979, and 1998) and characterize historical land use change.
2. Map house locations for those three years and characterize home location in relation to land use/cover.

Four study areas were selected (Figure 20). The Mission Creek, Pine Creek, and Corwin Springs study areas are 25 square miles in area and the Emigrant area is approximately 100 square miles.

Findings

1. There were no land uses consistently increasing or decreasing through the years and across study areas. For example, looking at agricultural land use, Mission Creek area decreased in 1979, but increased in 1998; in the Pine Creek area agricultural land increased and then decreased; in the Emigrant area it increased for both time periods; and for the Corwin Springs study area agriculture remained stable. Agricultural lands

increased by 2,406 acres for all four study areas from 1948 to 1998. For separate land classification groups the majority of the land remained consistent through time. For example, 80% of the land classified as agriculture in 1948 remained in agriculture in 1998. For riparian lands, 87% remained in 1998. For grasslands classification, 89% of the grassland was still grassland in 1998. Eighty-two percent of the shrub lands remained as shrub lands in 1998.

2. The number of homes increased 555% from 1948 to 1998, with a 99% increase between 1948 and 1979 and a 229% increase from 1979 to 1998. The Emigrant study area (moderately confined river reach) had the largest increase in homes, and the Pine Creek area (braided river reach) had the smallest increase. Seventeen homes were located within the 100-year flood-plain and an additional 121 homes were located within 100 meters of the 100-year flood-plain.
3. Although it was not mapped as a separate land use/cover type, residential impact zones compose 4.7% of the total area in the four study areas. Assuming an impact radius of 100 meters around each home reduced the agricultural land-use type by 1,404 acres, grassland by 2,684 acres, and riparian land-use type by 846 acres.

Metrics

1. Changes in land use/cover by reach and channel classification type.
2. Changes in number of homes in or near flood-plain and changes in residential impact zone associated with those homes.

Needs for Further Study

1. What are the meaningful changes in land use and residential development over the last 5 years (since 1998) both from a biological and socioeconomic perspective?
2. What are the social and economic implications of these land use changes (is there a feasible way for this information to be mapped and overlaid)?
3. What are the land use changes predicted from possible changes in channel modifications (using existing geographic data and maps to visualize this)?
4. How do changes in residential use affect changes in (requests for) channel modifications?
5. Existing river alterations could be overlain on the land-use maps to better understand spatially the patterns of development and river alteration requests.

Historical Channel Changes and Geomorphology of the Upper Yellowstone River (Dalby and Robinson, 2003)

Scope and Methods

Objectives accomplished by this investigation were to:

1. Map the contemporary (1999) fluvial geomorphology of the upper Yellowstone River from Gardiner to Springdale, Montana, and historic channel changes (1948–1999).
2. Develop a process-based geomorphic channel classification (stability and morphology) of the 1999 channel.

3. Map contemporary and historic (1954, 1973, 1999) channel modifications and revetments.
4. Measure and analyze retrospective geomorphic effects of channel modifications on channel geometry and hydraulic characteristics.

Contemporary data on physical channel attributes were collected using stereo interpretation of 1999 aerial photos, field surveys, and GIS-mapping. Contemporary data included: low-water and bankfull-channel hydraulics, 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. Information was collected at reconnaissance-level throughout the Gardiner to Springdale study area, with more detailed information collected in the Pine Creek to Livingston segment. Information on physical channel attributes was used, along with mapping of 1948–1999 channel changes, to develop a modified version of the Montgomery-Buffington channel classification for the Gardiner to Springdale study area (Figure 1). The channel classification recognizes seven distinct channel types, and the spatial distribution is largely controlled by Paradise Valley glacial history.

Findings

This summary is based on a draft version of the report (Dalby and Robinson, 2003) and is subject to revision.

1. 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). Pool-riffle and anabranching (multiple-thread) channels occur throughout the downstream drainage (40% of length), are somewhat dynamic, and locally show significant change in response to the 1974 and 1996–1997 floods. 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).
2. 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 confined to pool-riffle or plane-bed channels (e.g., main channel near head of Armstrong and Nelson's Spring Creek; Livingston area).
3. 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 compose 50% of the study area.
4. Channel length has remained essentially constant between 1948–1949 and 1999, although lateral channel position has changed remarkably in some areas (especially anabranching/braided channels) — an indication 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.

5. The total length of side channels between Gardiner and Springdale has increased by about 16% from 1948–1949 and 1999.
6. 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 channel response in 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.
7. Within the 20 km of channel affected primarily by man, local channel response includes channel incision (Livingston area), aggradation, 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 confined the channel in large events.

Metrics

1. Measurements used in Dalby and Robinson (2003) include: (a) channel features at low and bankfull flow; (b) unit stream power; (c) channel type and pattern; (c) side channel length by side channel type; (d) gravel-bar type and abundance; (e) sediment texture; (f) LWD abundance and spatial distribution by channel type; and (g) channel modifications.
2. Indicators of vertical channel incision include: (a) reduction in side channel length and number; (b) change in side channel types; (c) reduced width/depth ratio; (d) reduced channel width; (e) change in area and type of gravel bar/islands; (f) channel-bed coarsening; and (g) increased stream power.
3. Indicators of vertical channel aggradation include: (a) increase in side channel length and number; (b) change in side channel types; (c) increased width/depth ratio; (d) increased channel width; (e) increase in area of gravel-bars and islands; (f) channel-bed fining; and (g) reduced stream power.
4. Indicators of altered channel stability include: (a) changes in rates of lateral migration, incision, or aggradation; (b) changes in channel type; and (c) changes in fluvial attributes listed above.

Needs for Further Study

1. Some channel segments (especially anabranching and anabranching-braided) were in the process of adjusting to the post-flood hydraulic regimen when geomorphic data were collected. It would be useful to document geomorphic channel conditions within key channel segments (Emigrant to Chicory, Mallard's Rest to Carter's Bridge, Fairgrounds to Ferry Creek) through large-scale (~1:8000) stereo aerial photography and field survey of representative locations.
2. Monitoring of changes in physical attributes (e.g., bankfull and low-water: bankline, gravel-bar, island, and side-channel characteristics), primarily through acquisition of large-scale (~1:8000) stereo aerial photography, should be done for representative

channel segments approximately every 10 years or following annual peak flows exceeding a 5-year recurrence interval. Channel segments should be selected based on channel type, amount of channel modification, and availability of pre-existing information.

3. A detailed longitudinal channel profile should be surveyed at low-water approximately every 10-years or following annual peak flows exceeding a 5-year recurrence interval. At minimum, the profile should extend from Mallard's Rest through Livingston.
4. Developing 3-D, morphology-based sediment budgets of priority channel segments is the most important geomorphic study need. Priority segments include those that show aggrading or incising trends and contain significant channel modifications (e.g., segments between Mallard's Rest and Livingston).

Sediment Transport Investigations in the Upper Yellowstone River, Montana, 1999 through 2001: Data Collection, Analysis, and Application of a Sediment-Transport Model (Holnbeck, 2003)

Scope and Methods

Suspended- and bed-load sediment transport, bed sediment composition, and channel geometry (40 cross sections) data were collected from a 13.5-mile intensive study reach near Livingston, Montana (Figure 21). Sediment data were used to develop overall suspended- and bedload-sediment transport curves as a function of discharge. Transport equations of seven size classes of sediment were also estimated as functions of stream velocity for use in a moveable-bed, quasi-two-dimensional (stream tubes) simulation model of hydraulics and sediment transport, BRI-STARS (Molinas, 2000). This model incorporates aspects of WSPRO (Shearman, 1990) to provide more detailed calculations around bridges. Holnbeck (2003) applies this simulation model to examine several scenarios related to channel modification. The simulation model can be operated in a fixed-bed mode to approximate a standard step-backwater hydraulic model, or in a moveable-bed mode to simulate sediment movement by channel segment and vertical changes at cross sections. The model does not, however, incorporate lateral channel movement or sediment input from lateral erosion or mass wasting of banks.

Findings

This summary is based on a draft version of the report (Holnbeck, 2003) and is subject to revision[1].

1. Three-part sediment transport curves represented both bedload- and suspended-sediment transport as functions of discharge over the range of sampled discharges from 2,220 to 25,100 cfs. Phase 1 below 3,850 cfs occurred at 20% of bank-full and involved no transport larger than coarse gravel. Phase 2 ranged from 3,850 cfs to 18,500 cfs. Phase 3 above 18,500 cfs, with flatter slopes than the Phase 2 curves, is intended to minimize overestimation from extrapolating Phase 2 to higher discharges. The highest discharge used to construct Phase 3 was, however, 25,100 cfs, well below the 35,500 and 38,300 cfs of the 50- and 100-year floods, respectively.

[1] In addition to the report summarized here, USGS-WRD is finalizing a draft report on development of a HEC-RAS model used for floodplain delineation.

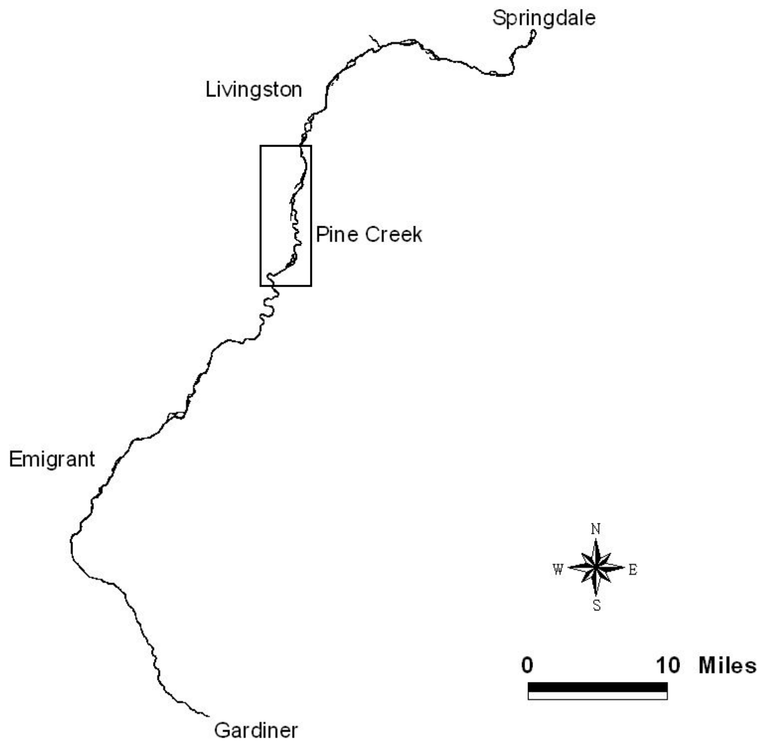

Figure 21. Spatial scope of sediment transport study (Holnbeck, 2003).

2. A reasonably good calibration of the BRI-STARS hydraulic and sediment transport model was achieved suggesting that the model is capable of simulating relative changes in vertical channel geometry and sediment transport under different conditions or management alternatives. Model calibration and verification suggested that the model represented overall patterns of aggradation and degradation in the main channel with deviations less than 2.5 feet. BRI-STARS simulated considerably smaller total sediment loads than those predicted by the simple sediment rating curves. Possible explanations are: (a) failure of BRI-STARS to account for streambank erosion, and (b) overestimation of sediment load by the rating curves by applying them to all portions (ascending and descending) of the hydrograph.
3. Differences in water surface elevation between the fixed-bed and moveable-bed modes were relatively small. Moveable-bed water surfaces were slightly smaller overall, with a median difference of 0.1 feet and 95% of all differences between -0.8 feet smaller to 1.9 feet larger. This is reassuring for the use of flood-plain estimations normally made with a fixed-bed hydraulic model.
4. Simulation of baseline conditions through seasonal hydrographs for the 2-, 50-, 100-, and 500-year floods indicated a slight overall trend for aggradation through the study reach. Aggradation and degradation daily within the hydrograph were generally substantially larger than net changes at the end of the period.

5. Simulated sedimentation effects of the Carter Bridge are substantial near the bridge, especially during large floods, but do not extend very far in either the upstream or downstream direction. The bridges produces aggradation, including net accretion upstream, and scour, though little net degradation, through the bridge subreach. Simulation of bridge removal substantially reduced both upstream aggradation and scour in the bridge reach.
6. Simulated effects of the Pine Creek Bridge were substantially less than those of the Carter Bridge because of its location relative to a natural flow constriction. Simulated narrowing of the Pine Creek Bridge by 30% was required to produce a substantial effect.
7. Simulation of a hypothetical levee in the Carter Bridge area increased the range of aggradation and degradation within the hydrograph. Results of channel narrowing and widening in an area of multiple channels were complex, suggesting complicated interactions among multiple channels and subreaches. Narrowing did tend to produce greater scour depths.

Metrics

1. Bed particle size distributions and sediment loads.
2. Vertical changes in channel geometry (aggradation and degradation) at cross sections.
3. Changes in water surface elevation at a given discharge.

Needs for Further Research

Collection of additional sediment data at higher discharges would reduce uncertainty associated with extrapolation.

1. Resurvey cross sectional elevations over time.
2. The biggest limitation of a sediment transport model like BRI-STARS for the upper Yellowstone is the incorporation of lateral migration and bank erosion. Comparison of BRI-STARS results with sediment-transport and channel dynamics models that do incorporate bank erosion, at least for smaller study reaches, would be a meaningful, though likely expensive, research topic.

Effects of Channel Modification on Fish Habitat in the Upper Yellowstone River (Bowen and others, 2003)

Scope and Methods

The goal of the fish habitat study was to evaluate the effects of channel modification on shallow depth, slow current velocity (SSCV) habitat. Shallow and slow water habitats have been demonstrated repeatedly as important growth and survival factors for young fish (Welcomme, 1979; Sedell and others, 1984; Kwak, 1988; Nehring and Anderson, 1993; Bovee and others, 1994; Scheidegger and Bain, 1995; Copp, 1997; Bowen and others, 1998; Freeman and others, 2001; Zale and Rider, 2003) that are important determinants of subsequent adult fish populations in many river systems. The fish habitat study was designed and implemented to be complimentary to the fish population study conducted by Zale and Rider (2003). Specifically, the fish habitat study investigated four aspects of the possible effects of channel modification:

1. Do different levels of channel modification change the amount or distribution of SSCV habitat at different sites?
2. Does availability of SSCV habitat vary among sections of river with different types of modified and unmodified banks?
3. How important is large woody debris in creating SSCV habitat?
4. What is the relative importance of main channel SSCV habitats compared to side channels and other areas?

Two-dimensional hydrodynamic simulation models were developed at three intensive study reaches (Figure 22) using data acquired by a combination of aerial photogrammetry, ground surveys with survey-grade Global Positioning System (GPS), and boat-mounted echo sounder. The River-2D two-dimensional (depth-averaged) model of Ghanem and others (1995, 1996) was used to simulate depth and velocity distributions at unmeasured discharges with output displayed in a Geographic Information System (GIS).

Findings

1. The amount of SSCV habitat was inversely related to the density or intensity of channel modification, measured as the percent of inundated shoreline occupied by riprap, barbs, jetties, or levees. Although the small sample size prevented testing the statistical significance of the relationship, the study indicated that as the percent of the site classified as modified decreased, the amount of SSCV habitat increased. This tendency was most apparent at higher discharges (e.g., bankfull and above).

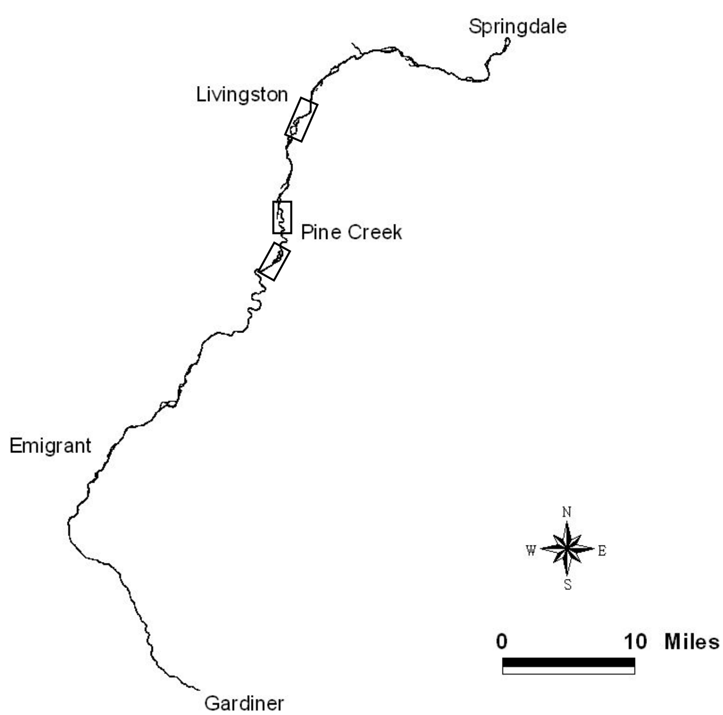

Figure 22. Spatial scope of fish habitat study (Bowen and others, 2003).

2. The spatial distribution of SSCV habitat tended to follow a consistent movement pattern from runoff to base flow. During runoff, SSCV habitat was almost exclusively associated with off-channel areas, such as side channels and inundated riparian areas. As the runoff receded, SSCV habitat was almost evenly divided among main channel and off channel areas, and at base flow, was predominantly associated with unmodified main channel locations and in side channels. In all time periods, the relative contribution of modified channel areas to the total area of SSCV habitat was small compared to unmodified areas.
3. Large woody debris and willow thickets (LWD) were relatively ineffective in creating SSCV habitat at low flows but provided modest increments at higher discharges. This phenomenon occurred because LWD was concentrated on point bars and overbank areas, inundated only at relatively high discharges (e.g., above 5,000 cfs). The largest contribution of SSCV attributable to the influence of LWD occurred in the site having most channel modification, even though the total amount of LWD was lower at this site. This phenomenon was attributable to very large amounts of SSCV occurring in side channels and riparian areas in the less modified sites. The contribution of SSCV by LWD was appreciable in these areas, but overwhelmed by the large amounts of SSCV occurring in the off channel areas.
4. During runoff, the vast majority of SSCV habitat occurred in off channel areas. During runoff, the largest areas of SSCV habitat were available in side channels and overbank locations. Large amounts of SSCV habitat occurred in side channels and overbank areas at flows ranging from bankfull to as low as 5,000 cfs. This suggests that the availability of SSCV habitat during runoff periods is persistent. That is, large, contiguous, and widely dispersed areas of SSCV habitat are likely to be available for colonization by young salmonids, regardless of the discharge during the critical runoff period. This persistence can be attributed in large measure to a diversity of elevations that is characteristic of braided portions of the Yellowstone River. As discharge increases, some areas of the channel become too fast or deep to be suitable for young salmonids. However, as one area of the channel becomes unusable, another appears at a higher elevation.

Metrics

1. Change in the proportion of SSCV habitat associated with main channel relative to that associated with side channels and riparian areas.
2. Increase in the proportion of SSCV associated with LWD, especially if accompanied by a reduction of LWD deposits.
3. Density of channels having flowing water at bankfull. This is an indicator of side channel abandonment due to incision of main channel or reduced channel migration. Bankfull flow should be established as a reference discharge (for example, 24,000 cfs) rather than a reference stage. If the channel degrades, the reference stage will be associated with a higher discharge.
4. Density of rootwads in active channel(s). This is a short-term indicator of channel mobility. As the channel is simplified and stabilized, fewer trees are undercut by eroding banks, and more snags are removed during high flows. Rootwad density is also a long-term indicator of flood-plain isolation and declining recruitment of riparian vegetation, especially cottonwoods.

5. Surface-connected inundation area at 5- to 10-year interval flood events. This is a short-term indicator of flood-plain isolation and side channel abandonment. It is important to ascertain surface connection to the main channel because some low-lying areas may become flooded as a result of groundwater intrusion. The reference flood-frequency discharge should be indexed to a specific flow, rather than a recurrence interval, for the same reason as indexing bankfull flow.

Needs for Further Study

Needs for further study are integrated with needs associated with fish use study of Zale and Rider (2003) and described in following section.

Comparative Use of Modified and Natural Habitats of the Upper Yellowstone River by Juvenile Salmonids (Zale and Rider, 2003)

Scope and Methods

Objectives of this study were to compare juvenile salmonid use of modified bank habitats and natural, unmodified bank habitats, and evaluate juvenile salmonid use of ephemeral side-channel habitats during periods of high run-off.

The study area was in and near the town of Livingston, Montana, where a variety of modified and unmodified bank types as well as side channels were present (Figure 23). All sampling occurred in the Wandering Gravel Bed type of the Merigliano geomorphic classification system (see previous Classification section). For the comparative use objective, a stratified random sampling design was used to select 50-m long sampling locations with six bank types (e.g., inside bend, riprap) serving as strata. Fish were sampled seasonally along main channel banks using a hand-held mobile electrode and fish abundances were compared by bank type, season, reach, and year. Juvenile salmonid use of side channels was assessed by backpack electrofishing opportunistically in ephemeral side channels during runoff to estimate fish densities. All fish sampling occurred during 2001 and 2002, which were both dry water years.

Findings

1. Juvenile salmonid abundances were similar between modified and unmodified bank types. Similar juvenile salmonid abundances between modified and unmodified bank types suggest that bank stabilization does not directly decrease recruitment from main channel banks. Boulders associated with channel modification structures were used as habitat by juvenile salmonids during periods of low discharge. This is consistent with findings from other rivers where large riprap supported higher abundances of juvenile salmonids than smaller substrates (Lister and others, 1995).
2. Juvenile abundances along main channel banks of the Upper Yellowstone were relatively low compared to abundances in other river systems. Generally low juvenile abundances along main channel banks in the upper Yellowstone River compared to other rivers suggest that the main channel banks of the Yellowstone might be poor or unimportant habitat.
3. Ephemeral side channels were colonized rapidly by juvenile salmonids during runoff and densities of fish increased with increasing duration of inundation. Rapid colonization of side channels during runoff is evidence that juvenile salmonids use

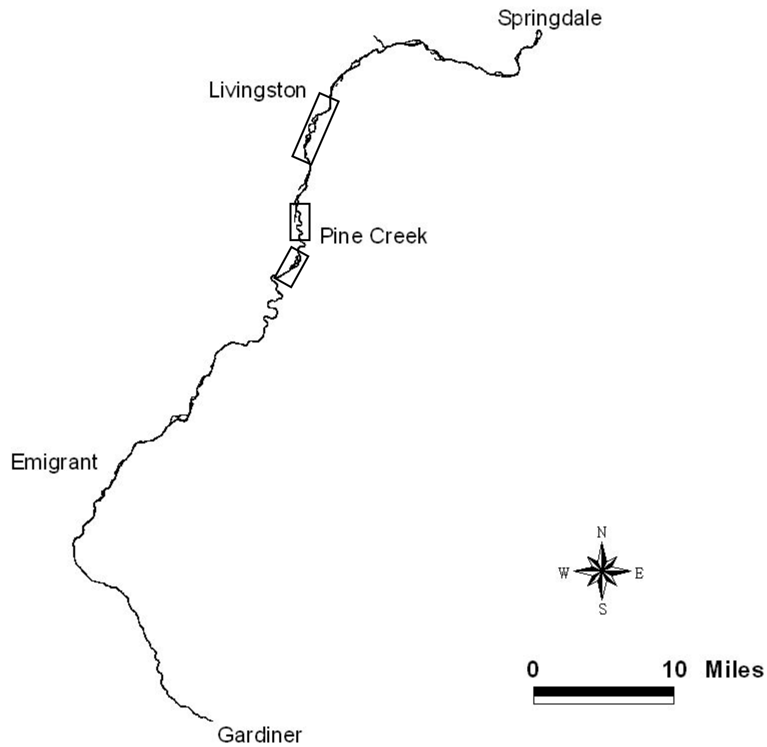

Figure 23. Spatial scope of fish bank use study (Zale and Rider, 2003).

ephemeral side channels as a refuge during high discharge. Other studies have shown that habitats found in backwaters and side channels provide refuge from high current velocities in main channel areas (Hjort and others, 1984) that can displace small fish downstream, particularly during periods of high discharge (Ottaway and Clarke, 1981; Ottaway and Forest, 1983).

4. The combined results from the fish population and fish habitat studies present strong evidence that during runoff, SSCV habitat is most abundant in side channel and overbank areas and that juvenile salmonids use these habitats as refugia.

Metrics

1. Juvenile trout abundances.
2. Mean juvenile trout abundances among different bank types and in side channel.
3. Area of shallow water habitat during flood flows would be a useful variable for assessing the cumulative impacts of river structures on fish populations in the upper Yellowstone River.
4. Another measure of trout habitat availability is the length of channel per valley length.
5. Catch per unit effort data for trout could then be used to tie biological information to habitat analysis. Biological data collected over multiple years would provide the ability to examine variability in salmonid numbers (or other biological variables) under a

variety of water year types and provide a clearer picture of the effects of bank stabilization structures.

Needs for Further Study

1. This study focused on juvenile salmonids and their use of main channel banks during low flows and side channels during runoff. Other habitat requirements include spawning habitat, adult habitat, and overwintering habitat. Populations of trout can be limited by a deficiency in any of these or by non-habitat variables (e.g., food availability). For protecting salmonid populations it is critical to determine which factors, including physical habitat, are most directly regulating numbers of adult salmonids. These limiting factors then could become the focus of additional study or action.
2. Assessment of the effects of bank stabilization on non-salmonid fishes and other aquatic biota would provide additional insight to how bank modification affects salmonids in the context of the upper Yellowstone River ecosystem.

Temporal Patterns of Channel Migration, Fluvial Events, and Associated Vegetation along the Yellowstone River, Montana (Merigliano and Polzin, 2003)

Scope and Methods

Study objectives were to classify and characterize streamside vegetation, including the age distribution of cottonwood forest; and determine flood-plain turnover rate and its relations to flow magnitude and frequency.

The study produced two primary data sets: (a) maps of forest (cottonwood) patches of different ages; and (b) maps of vegetation types. The study area was defined as the bottomland likely to be flooded in the current climate if not blocked by human influence, and is extended somewhat in entrenched or confined reaches to a topographic break (e.g., terrace tread) where vegetation changed substantially. Four reach types were sampled using the Flood-Plain Classification (Merigliano and Polzin, 2003; see previous Classification section of this report). The Urbanized reach around Livingston and the Yankee Jim Canyon reach were not sampled. Sampled reaches were subdivided divided into equally sized sections and from 8 to 15 sections were sampled in each reach type. The overall spatial extent of the study is shown in Figure 24. Sampling involved a combination of photointerpretation, ocular age estimates, tree coring and aging, and sediment pits. All recent (2000) maps were ground truthed.

Findings

1. There are substantial differences in vegetation across different geomorphic reaches related to degree of confinement. In general, the less confined geomorphic strata (Wandering Gravel Bed and Confined Wandering Gravel Bed) have more cottonwood and willow area, and less juniper (though common in the understory) and limber pine area, than the more confined Entrenched and Confined Coarse Textured strata. The two less confined strata also had higher diversity, both richness and Shannon diversity index, of vegetation communities than the more confined strata. This pattern was also evident in a gradient analysis that identified a significant relation between community type and

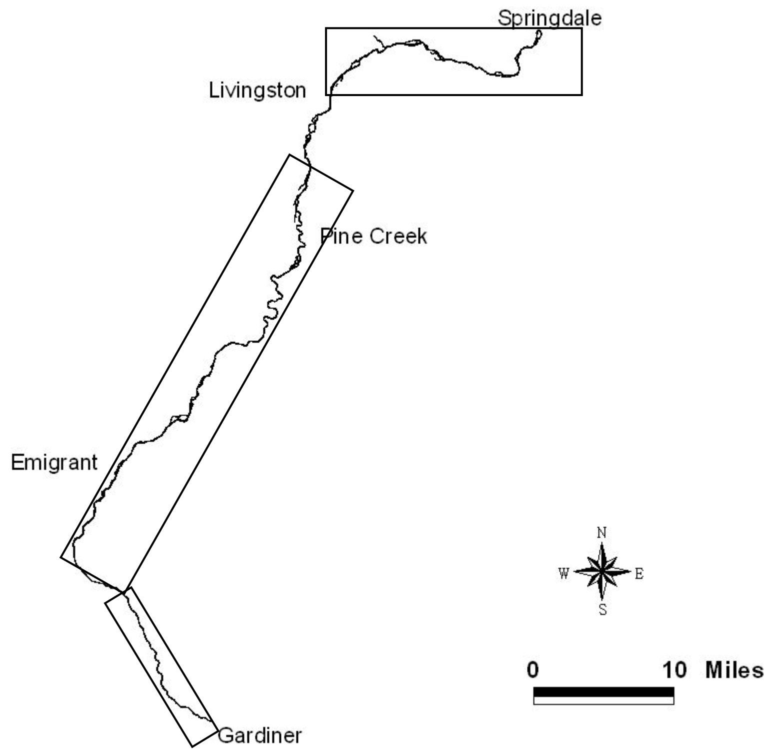

Figure 24. Spatial scope of riparian vegetation study (Merigliano and Polzin, 2003).

confinement ratio with less confined sites having a more riparian and less upland composition.

2. Rates of cottonwood and flood-plain turnover were similar for both confined and unconfined Wandering Gravel Bed strata, with the exception of whole flood-plain (including non-forested flood-plain) of the Wandering Gravel Bed stratum that was calculated to turn over more slowly due to presence of a large non-forest area estimated to have been undisturbed for more than 200 years. The less confined, Wandering Gravel Bed stratum had more extensive cottonwood forest and overall flood-plain than the Confined Wandering Gravel Bed stratum. Flood-plain turnover was not determined for the Entrenched or Confined Coarse Textured geomorphic strata, where channel migration was negligible, or for the unsampled, Urbanized reach.
3. A disproportionate area of cottonwood forest dates to 100–150 years ago. This suggests a period of much more active channel movement from the mid-1800’s to early 1900’s than what has been experienced since 1900. It also means that the cottonwood forest is naturally aging and diminishing to a steady-state age distribution associated with the current rate of channel movement as the “pulse” of forest originated between 1850 and 1900 works its way through the age distribution. Effects of recent or further channel stabilization on reducing the rate of channel movement and the regeneration of cottonwood would thus be layered on a background of natural change. In fact, Merigliano and Polzin (2003) found an overall trend of decreasing young cottonwood and increasing mature cottonwood in comparing 1948 and 1999 photography. These

findings are consistent with the results of similar trend analyses conducted by Hansen and others (2003), although Merigliano and Polzin were better able to establish significance of the changes for some of the individual strata and cover types. These patterns are most pronounced in the Wandering Gravel Bed and Confined Wandering Gravel Bed geomorphic strata that have large areas of cottonwood forest and more channel movement.

4. Other vegetation findings included: (a) a positive relation between area of flood-plain created and the magnitude of floods in Wandering Gravel Bed and Confined Wandering Gravel Bed strata; (b) the common occurrence of cottonwood seedlings on surfaces disturbed by the 1996 and 1997 floods; (c) the general similarity of current vegetation in the non-urbanized reaches to that of 100 years ago based on paired photographs; and (d) a pattern of increasing understory cover, most commonly of Rocky Mountain juniper, with increasing age of cottonwood stands in the Wandering Gravel Bed and Confined Wandering Gravel Bed geomorphic strata where enough data were available for analysis across stand ages.

Metrics

1. Ages, locations, and sizes of cottonwood patches.
2. Areas occupied by vegetation communities.
3. Forest and flood-plain turnover rates.

Needs for Further Study

The most important uncertainties about riparian vegetation center on how it will change if inundation and disturbance (channel migration) are reduced or eliminated. A mixed age structure of riparian forest overall provides important wildlife values (Hansen and others, 2003). Boggs and Weaver (1994) identified a successional sequence of plains cottonwood and sandbar willow to cottonwood forest to shrubland to grassland associated with sediment accretion and cottonwood aging in the absence of disturbance along the Lower Yellowstone River. It is not clear how applicable this sequence is to narrow-leaf cottonwood along the upper Yellowstone River, especially if disturbance is stopped by channel stabilization, but sites remains wet by continued flooding. The vegetation shifts associated with human activities such as rural non-farm development and grazing intensity might also be incorporated into an overall, semi-quantitative model of vegetation transitions and rates. Important questions for a change analysis include:

1. How will flood-plain vegetation respond to reduced flooding?
2. What will cottonwood and willow communities become if they are not replaced through riverine disturbance?
3. How important is clonal reproduction of cottonwood, and can it maintain a mixed age cottonwood community in the absence of disturbance?
4. How much will human land use and development activities alter natural riparian vegetation?

Riparian Dynamics and Wildlife along the Upper Yellowstone River (Hansen and others, 2003)

Scope and Methods

Bird and vegetation data were collected in eight vegetation types (successional stages) and three geomorphic reach types using a modification of the Merigliano and Polzin (2003) Flood-Plain Classification (Figure 25). Aerial photography from 1948 and 1999 was used to investigate change in riparian vegetation over time. There were three basic study objectives:

1. Quantify the distribution of bird and shrub communities across riparian successional stages and geomorphic types.
2. Project bird species richness as a function of successional stage and geomorphic type.
3. Quantify changes in riparian vegetation community composition from 1948 to 1999.

Findings

1. Species richness (and diversity) varied among vegetation types; the highest richness was found in the mature cottonwood vegetation types. The variation in bird species richness among vegetation types is explained by well-known phenomena. Bird species richness is affected by structural complexity within a vegetation type (MacArthur and MacArthur, 1961) and different species typically use different seral stages. Within the study area, mature cottonwood forests provide the most complex structure and hence support more bird species than do the early seral stages.
2. Bird species richness also varied among the river reach types — more bird species were seen in the braided, and moderately braided types than in the confined reach type. The less confined reach types had greater extents of the structurally complex mature cottonwood vegetation type that supported the highest bird richness. In addition, species richness is influenced by features of the landscape. Important landscape features in the study area include habitat diversity (Willson, 1974) and habitat patch size (Galli and others, 1976; Robbins, 1979), which tends to be larger in the downstream, braided reaches.
3. From 1948 to 1999 in the braided reach sample area there was an 8% increase in early successional stages (gravel bar, cottonwood-willow shrub, and young cottonwood); a decrease of 36% in middle-aged cottonwood; and an increase of the mature cottonwood stage of 13%. over the same time period in the moderately confined sample area, young successional stages decreased by 29%; mature cottonwood gained 38% and mixed grassland/sage increased 33%. braided reaches had more riparian vegetation overall, as well as greater extent of mature cottonwood. These findings are generally consistent with trends described by Merigliano and Polzin (2003).

Metrics

1. The best variables for assessing the habitat for the bird community would be direct measures of foliage height diversity within each vegetation type, as well as measures of stand size and stand age. An index of habitat diversity (i.e., some measure of the number of vegetation types and their relative abundance) within each reach would also be important.

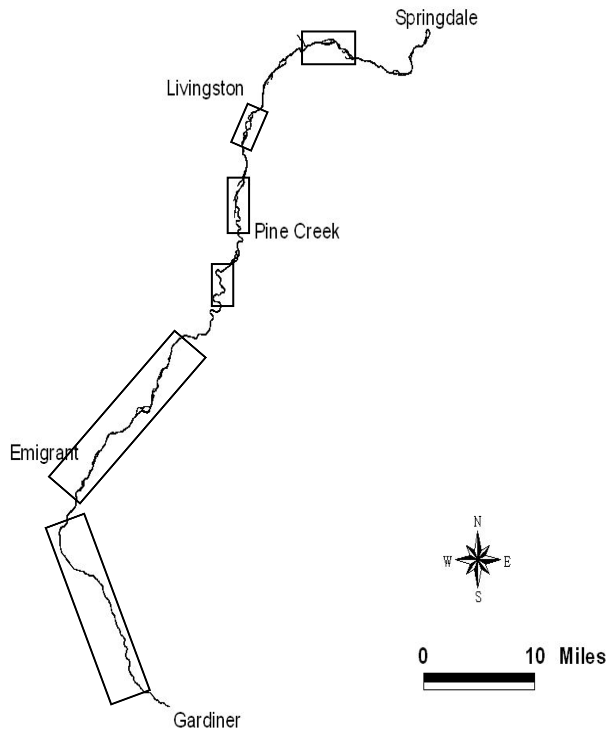

Figure 25. Spatial scope of bird community study (Hansen and others, 2003).

2. The area of each of several types of vegetation within each reach and size metrics for cottonwood stands by reach could be used to estimate habitat diversity for birds.

Needs for Further Study

1. The effects of flood-plain drying due to levees are not well understood in the study area. Will drying lead to more or less vegetation complexity (i.e., foliage height diversity) in flood-plain forests? Similarly, effects of grazing and the role of cottonwood vegetative reproduction are not well understood in the successional relations among vegetation types.
2. Information on the effects of stand size on bird species richness in the study area is limited. Hansen and others (2003) did not clearly identify the effects of stand size, although their discussion hints that perhaps stand size does play a significant role.
3. Hansen and others (2003) focused on the bird community. Cumulative impact assessments should likely also address other taxonomic groups including mammals, amphibians, and reptiles, with an emphasis on species of special concern.

Socioeconomic Assessment of the Upper Yellowstone River Valley (BBC Research and Consulting, 2002)

Scope and Methods

The goal of this study was to provide a socioeconomic portrait of the upper Yellowstone River Valley, from Gardiner to Springdale, Park County, Montana (Figure 1), by completing the following:

1. Review the history of the river valley, identifying social and economic values and cultural heritage.
2. Identify key stakeholder groups and their special interests and economic and social/cultural values related to management of the upper Yellowstone River.
3. Document current economic and social/cultural values held by residents, business owners, and visitors to Park County, Montana.
4. Characterize local economic and demographic trends in Park County.
5. Describe changes in land use and land-use plans in recent years and provide a picture of past trends.
6. Describe the institutional framework in which historic and current river management are conducted.
7. Identify elements of quality of life that are potentially affected by growth and change in the study area.
8. Project expected social and economic conditions in 2025 if current river management remains the same (No-action Scenario).

Methods consisted of: (a) secondary data summaries; (b) interviews with key stakeholders identified using a "snowballing" technique; (c) three surveys of randomly chosen Park County residents, Park County business owners, and visitors to Park County; and (d) two public meetings and presentations to the Governor's Upper Yellowstone River Task Force and the stakeholders.

Findings

1. Park County's population and housing market are growing moderately. Almost all growth is occurring outside, but surrounding, Livingston, Montana, and in the more rural areas of the county. Minimal annexation around Livingston and preference for rural lifestyles likely is the reason. Seasonal residents account for about 8% of the population, although they have a notable economic presence in the county. Assuming the no-action scenario, Park County's population will grow from about 15,700 to 19,000 by 2025 (21% growth).
2. Ranching is a long-time industry that generates income and earnings for hundreds of ranchers, their employees, and their families. Local residents and business owners recognize and understand the importance of ranching to the local community. Out-migration of long-time ranchers is being driven by increasing land prices and an adverse ranching economy.
3. Tourism has become increasingly important to the local economy and is clearly the strongest element of the economy as of 2002. Park County employment is projected to increase by 40% (from 8,900 in 2000 to 12,600 in 2025 under the no action scenario);

this increase will mostly occur in the tourism-related sectors. Personal incomes have risen substantially in the past 30 years, mostly in the non-farm sectors from non-wage components of income, including dividends, interest, rent, and transfer payments. Local residents and business owners perceive tourists, ranchers, and long-time residents as important to the Park County economy. New and seasonal residents are viewed as less important to the economy than the other groups, although they have a strong economic presence.

4. Residents and businesses recognize the river as being vitally important to the economy. Visitors contribute significantly to that economy and when asked, said if they could plan their trip over, they would stay longer in Park County. Residents generally appreciate the contributions tourists make to the community.
5. Residents historically and currently value the river and believe it an important amenity to local quality of life. Issues identified as important quality of life indicators include: recreation, aesthetics/scenery, development/land use, ranching and displacement, and movement and displacement of people. The beauty of the river is paramount in its contributions to local quality of life, as are fishing and other river-related recreational activities, such as rafting and floating. The river is a central, valuable part of the visitor's experience, as well. Ranchers and long-time residents are perceived as being the most important groups contributing to the social and cultural environment of Park County. Seasonal residents are seen as less important. The communities of the county are strong and civically oriented. Spring creeks and the related activities that occur in them are not well understood by either residents or business owners.
6. Residential development and other land use changes are occurring, but slowly. Wealthy out-of-state landowners are replacing Montana ranchers, but at a slow rate. This replacement is primarily driven by the national and local economy and its effect on demand for second homes in the Paradise Valley. Most large parcels of ranchland are remaining intact or growing larger, though some smaller parcels have been subdivided into 5- to 40-acre parcels. Residents view residential development and changes in land use in the river valley as threats to quality of life, but visitors do not yet see it as a distraction.
7. Although Montana and other western states tend to have strong private property rights ideals, both Park County residents and business owners believe that property owners should not have the right to subdivide and build in the flood-plain. Subdivision has centered along the upper Yellowstone and its tributaries, and this corridor has the greatest potential for growth. The rest of the county has some growth potential as well, though it will primarily be dependent upon infrastructure development in order to occur.
8. Although views of stakeholders are varied, there is widespread recognition of the importance of the river and some recognition of the need to compromise to achieve good management. Most everyone considers the water level in the river important to the economy, and droughts are perceived more negatively than floods. Water levels in 2002 were viewed as a positive part of the visitor's experience. There are several disconnects between values and perceptions of residents and business owners versus those of visitors regarding river management. Residents and business owners agree that management of the river to prevent flooding and erosion is best for the overall economy and social well-being of the county. More households and businesses agreed than disagreed that prior channel modification has been ineffective and inconsistent. They

also believe overuse of the river is a major problem. Visitors, however, believe that a free-flowing river is best. Interestingly, man-made structures generally do not detract from visitors' experiences, and visitors do not see overuse of the river as a problem.

9. Most residents and business owners prefer proactive river management for flood control and erosion; however visitors prefer the free-flowing river.
10. Channel modifications may have significant impacts on the local economy, with services (primarily related to river tourism) comprising 33% of the 2000 economic earnings in Park County. Of particular importance may be income sources from spring creeks; however, the degree of impact is not well understood.

Metrics

1. Employment, revenues, and sales.
2. Direct data gathered from residents, business owners, and visitors on important quality of life features of the community and river; aspects important to visitor experiences; and economic and social values of residents.
3. Specific measures for change in social and economic issues: (a) movement of people, (b) economic shifts, (c) land-use transitions, (d) spiritual/religious shifts, (e) social change/evolution, (f) shift in historical appreciation, and (g) change in view on river management.
4. Quality of life indicators: (a) recreation, (b) aesthetics/scenery, (c) noise, (d) development/land use, (e) ranching and displacement, and (f) movement and displacement of people.

Needs for Further Study

1. What is the threshold of channel modification at which public acceptability and the local economy are affected (e.g., how much channel modification has to occur before there is a noticeable change in visitation)?
2. Which areas of the river are most economically viable and/or socially valued?
3. What is the economic impact of river management alternatives on visitation to the area?

Appendix B. Relationships among Metric and English Units

Length

1 inch = 2.54 centimeters (cm)
1 foot = 0.305 meters (m)
1 mile = 1.609 kilometers (km)

Area

1 square foot = 0.0929 square meters (m2)
1 acre = 0.4047 hectares (ha)

Flow Rate

1 cubic foot per second (cfs) = 0.0283 cubic meters per second (cms or m^3/s)