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EVIDENCE FOR GROUNDWATER SEEPAGE IMPACTS ON THE CENTRAL BITTERROOT RIVER, WESTERN MONTANA

ABSTRACT

Channel instability on the Bitterroot River poses a threat to floodplain property between the towns of Hamilton and Stevensville, Montana. This stretch of river exhibits a complex multi-thread channel pattern characterized by a braided main stem within a network of narrower anastomosing channels covering a floodplain up to 5 km in width. While substantial channel migration and shifting are thought to have occurred in the area, historic changes are undocumented and the processes at work are poorly defined. This investigation employed a comparative analysis of channel features digitized from three sets of aerial photographs spanning a 50-year period to document and quantify historic channel changes of the Bitterroot River. Analysis in a geographic information system indicated that the main braided channel (the braid belt) widened substantially during the first half of the study period. However, lateral channel migration was limited and the positions of bifurcation nodes have remained constant. Evidence is presented suggesting that both the river's multi-channel configuration and tendency for rapid bank erosion are related to groundwater discharge. Groundwater seepage through the channel banks appears to be an important component of bank erosion and channel widening in the study area. Small discontinuous channels on the floodplain appear to be surface expressions of a groundwater discharge network. These observations suggest that groundwater interaction can have large effects on channel and floodplain morphology, and that changes in groundwater flow are among the impacts to be considered when evaluating stream perturbation.

Key Words: stream, anastomosing, braided, channel, morphology, pattern, groundwater, seepage, bank, erosion

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INTRODUCTION

The Bitterroot River in Western Montana flows 120 km northward from its mountain headwaters near the Idaho border to its confluence with the Clark Fork River near Missoula, Montana. Through much of its middle course, the river exhibits an unusually complex network of interconnecting braided and anastomosing channels that wander over an extensive valley bottom as wide as 5 km. This portion of the river has also acquired a reputation for channel instability. Local land managers consider a high rate of channel migration and shifting to be a greater hazard to property than flood inundation (Bitterroot Conservation District 1995). State and local government agencies have funded previous investigations into the possible causes for this instability and the feasibility of various bank stabilization options (Cartier and Curry 1980, Simons *et al.* 1981). While substantial channel changes have been observed, previous workers have not systematically

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described the changes or the processes at work. This investigation employed a comparative analysis of channel features digitized from a series of aerial photographs spanning a 50-year period to document and quantify historic channel changes of the Bitterroot River. Mechanisms of channel change and network development were inferred from the relationships between historic changes, field observations, and various physiographic parameters.

PREVIOUS WORK

The Montana Department of Natural Resources and Conservation and the U.S. Natural Resources and Conservation Service published a flood-hazard analysis in which the surface elevations of the Bitterroot River floodwaters were modeled throughout Ravalli County (Bitterroot Conservation District 1993). McMurtrey *et al.* (1972) provided a comprehensive description of the surficial geology, aquifer characteristics, and groundwater budget of the Bitterroot Valley. The multi-channel pattern and associated channel instability has been hypothesized to be a response to aggradation in the central part of the valley related to comparatively recent tectonic movement (Cartier and Alt 1982, Cartier 1984). According to this hypothesis, the multi-channel reach occupies a down-dropped fault block in which valley filling has promoted the development of an extensive braided channel pattern. This idea is based largely on the assumption that the multiple-channel morphology of the central Bitterroot River implies net aggradation. While stream braiding is generally considered to involve processes such as bank erosion, channel widening, and deposition of in-channel bars in a bed-load stream, it is unclear that net aggradation is a necessary prerequisite (Leopold *et al.* 1964). In addition, a wide range of channel morphologies exists within the Bitterroot network, many of which are narrow, sinuous, stable, and well vegetated. Many of these channel branches are better described as anastomosing rather than braided. Anastomosing streams are considered by many authors to be stable multi-channel suspended-load streams of relatively low gradient (Smith and Smith 1980, Harwood and Brown 1993, Rosgen 1994). Anastomosing streams are also described as multiple channels separated by relatively large islands which are excised from the continuous floodplain rather than by bars deposited within the channels (Knighton and Nanson 1992). This process of floodplain dissection is driven by overbank flows that spill on to the floodplain and incise new channels. Carson (1984a, 1984b) described a similar process in certain gravel-bedded streams, which he refers to as "wandering" gravel-bedded streams.

Other authors have addressed stream morphology at the floodplain level, and so accommodate diversity in channel morphology within the framework of a single functioning stream system. In his review of the literature on floodplain morphology, Lewin (1978) distinguished between braid-bar plains with switching zones of active channels, floodplains with stable anastomosing channel networks, and floodplains where a braided main channel with migrating bars is found among multiple meandering accessory channels. This last floodplain type, type F in Lewin's terminology, most closely matches the configuration of the central Bitterroot River.

STUDY AREA

This study investigated the portion of the Bitterroot River between the town of Hamilton in the south to near Stevensville in the north, a distance of about 30 km (Figure 1). The river flows northward in the Bitterroot Valley, an elongate north-trending basin bounded by the Sapphire Mountains on the east

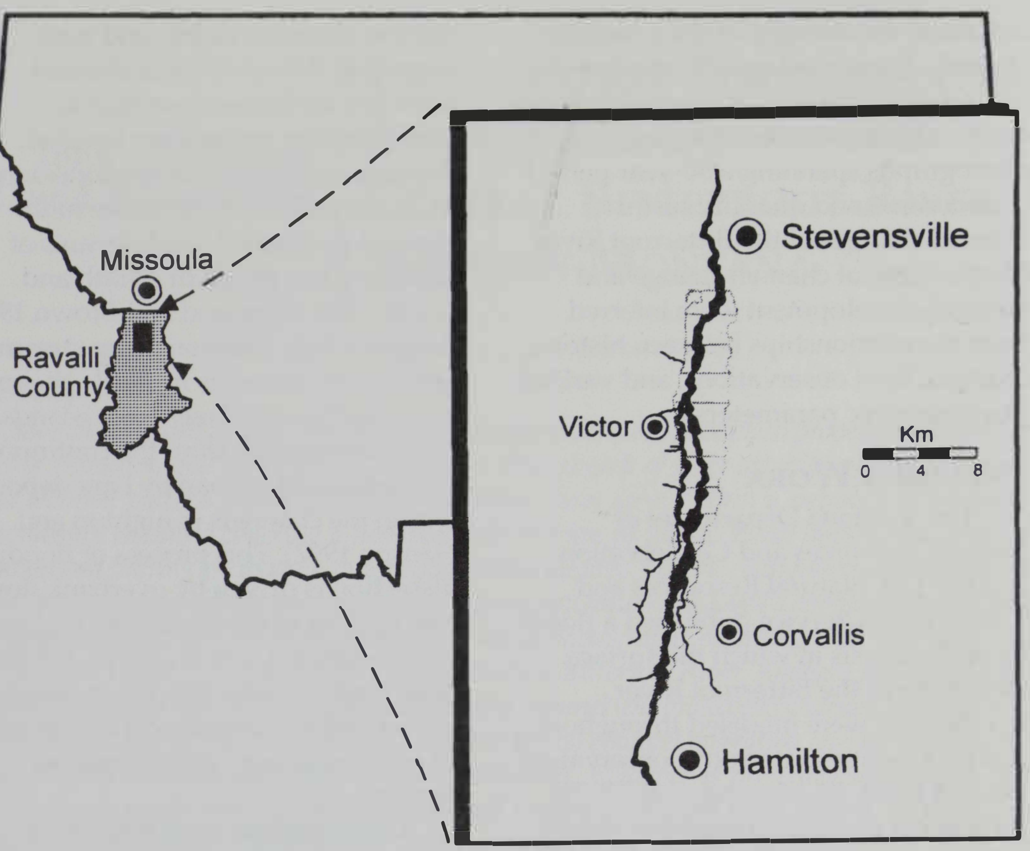

Figure 1: *Study area location.*

and the rugged Bitterroot Mountains on the west. The upper valley south of Hamilton is relatively narrow and the river is generally confined to a single channel. North of Hamilton, the valley widens to an average width of about 11 km and the river divides into numerous channels that spread widely across the bottom land. Channels within this bottom network display great diversity in both morphology and scale. The largest feature is the river's main stem, which can be described as a braided, gravel-bed stream with occasional single-thread reaches. Its bankfull sinuosity is generally 1.2 or less and its average gradient is about 0.0025. At a more detailed level of resolution, numerous active and inactive sinuous channels with fine-grained, well-vegetated banks are seen. Their scale ranges from that of a main-stem channel to that of micro-features observable only in the field. These smaller sinuous channels, as well as some bifurcated branches of the main-stem channel separated by expanses of floodplain, give the river an anastomosing character in many locations. The large Burnt Fork alluvial fan and extensive artificial channelization structures near Stevensville constrict valley bottom width and reduce channel pattern complexity north of the study area.

The Bitterroot River drains a 725,200 hectare (2,800 square miles) watershed and has an estimated bankfull discharge at its confluence with the Clark Fork River of about 410 cubic meters per second (14,450 cfs) (Cartier 1984). Runoff is highest in the spring, with about 55 percent of the river's annual discharge occurring in May and June (McMurtrey *et al.* 1972). Numerous tributaries emerge from the mountain canyons along the valley margins. Except for some westside streams in May and June, the tributaries are mostly dry in their lower courses because of diversions for irrigation and rapid seepage into unconsolidated terrace alluvium along the valley margins (McMurtrey *et al.* 1972).

METHODS

Study Area Partitions

For purposes of comparison, the study area was divided into 15 longitudinal partitions averaging approximately 1.5 km in length (Figures 2A-2B). Partition boundaries were chosen to coincide with changes in valley or river morphology where possible. Morphological parameters for each partition were derived from aerial photographs and used for statistical and spatial analysis.

Aerial Photography

Features visible on aerial photographs from 1937, 1955, and 1987 were digitized for GIS analysis. The 1955 and 1937 photographs have scales of 1:20,000; the scale of the 1987 set is 1:40,000. All visible active and inactive stream channels, areas of bare bed material, vegetated islands and bars, and tributary channels were digitized. Features were classified as follows:

1. Thalweg: The deepest channel of the main river bed, where discharge is maintained at low flow.
2. Braid Belt: A polygonal feature defined as the region occupied by washed bed material and essentially lacking vegetation. This feature ranges from less than 30 meters to more than half a kilometer in width.
3. Overflow channels: Ephemeral light colored gravelly swales that exit the braid belt and arc a short distance over the floodplain before terminating or re-entering the braid belt.
4. Secondary channels: Relatively narrow, stable, often sinuous channels outside the braid belt lacking visible bars or other bed materials. Secondary channels are generally on the order of 10 meters in width, and cut continuously across the floodplain for long distances before intersecting the braid belt.
5. Capillary channels: This end-member class of channels is similar to secondary channels, but is distinguished from them on aerial photographs by frequent and irregular bifurcation, smaller scale, and a lack of continuity. They frequently dissipate into the floodplain before reaching a topological connecting point with the larger channel network.
6. Tributary channels: These occur on terrace surfaces above the floodplain. Upon reaching the valley bottom, tributary channels may enter the braid belt directly or merge with the network of minor floodplain channels.
7. Bars: These are small sparsely vegetated areas lying within the braid belt. They are assumed to be the product of bar deposition within the active channel.
8. Islands: Areas surrounded by braid belt are considered true islands when their large size, irregular shape, and well-established vegetation suggest they are remnants of the floodplain surface that have been circumscribed by channel incision.

Root-mean-square (RMS) errors returned by Tosca digitizing software were less than 10 meters for 22 of 30 photographs digitized. Photographs from the 1937 set were sometimes damaged and contained fewer usable control point features. As a result, three photographs from this set yielded unacceptable RMS errors of 42, 48, and 55 meters that required digital resampling before the separate files could be concatenated into a single coverage. Of the three coverages produced, the 1955 coverage is of the

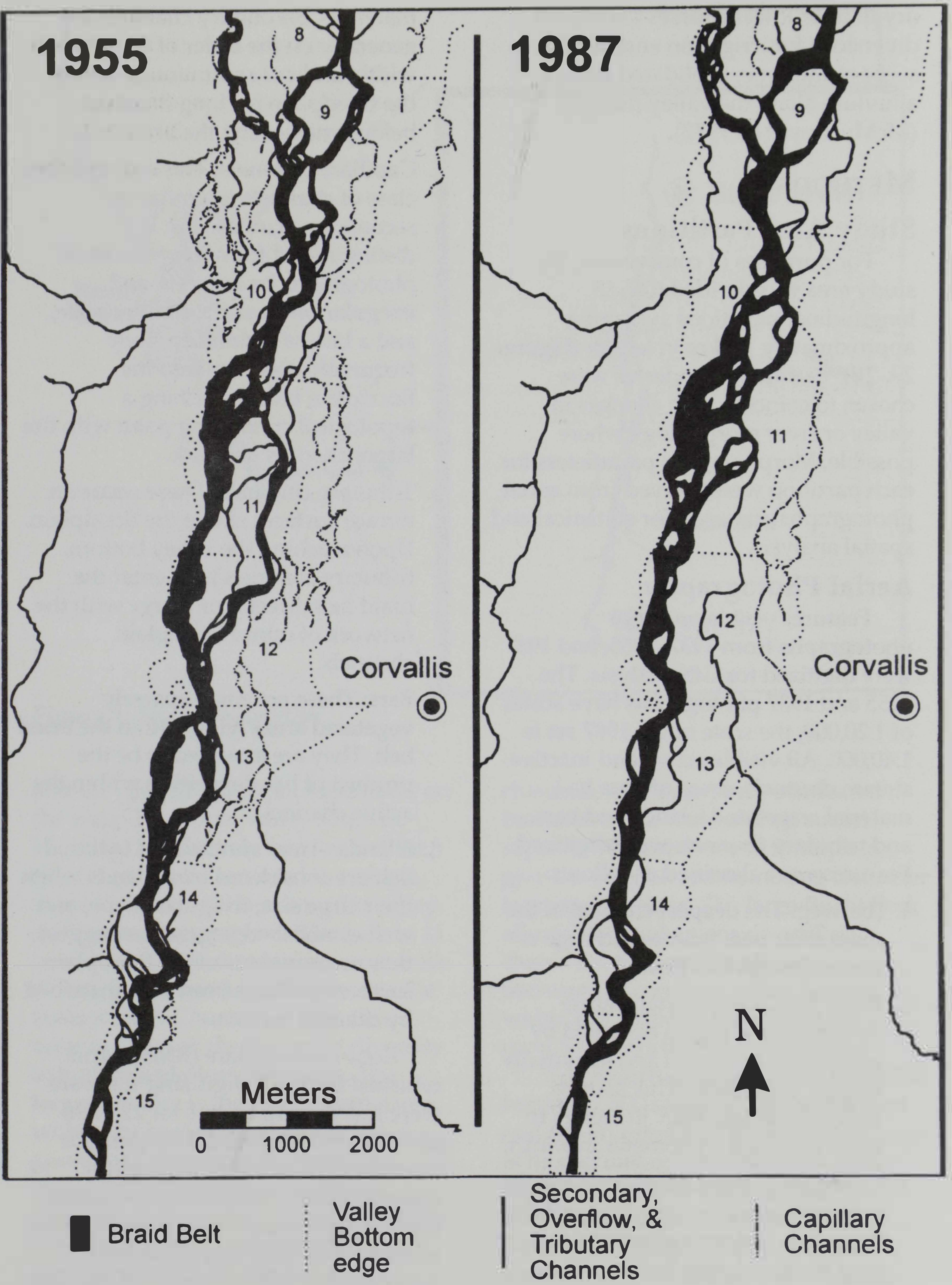

Figure 2A: *Southern half of study area.*

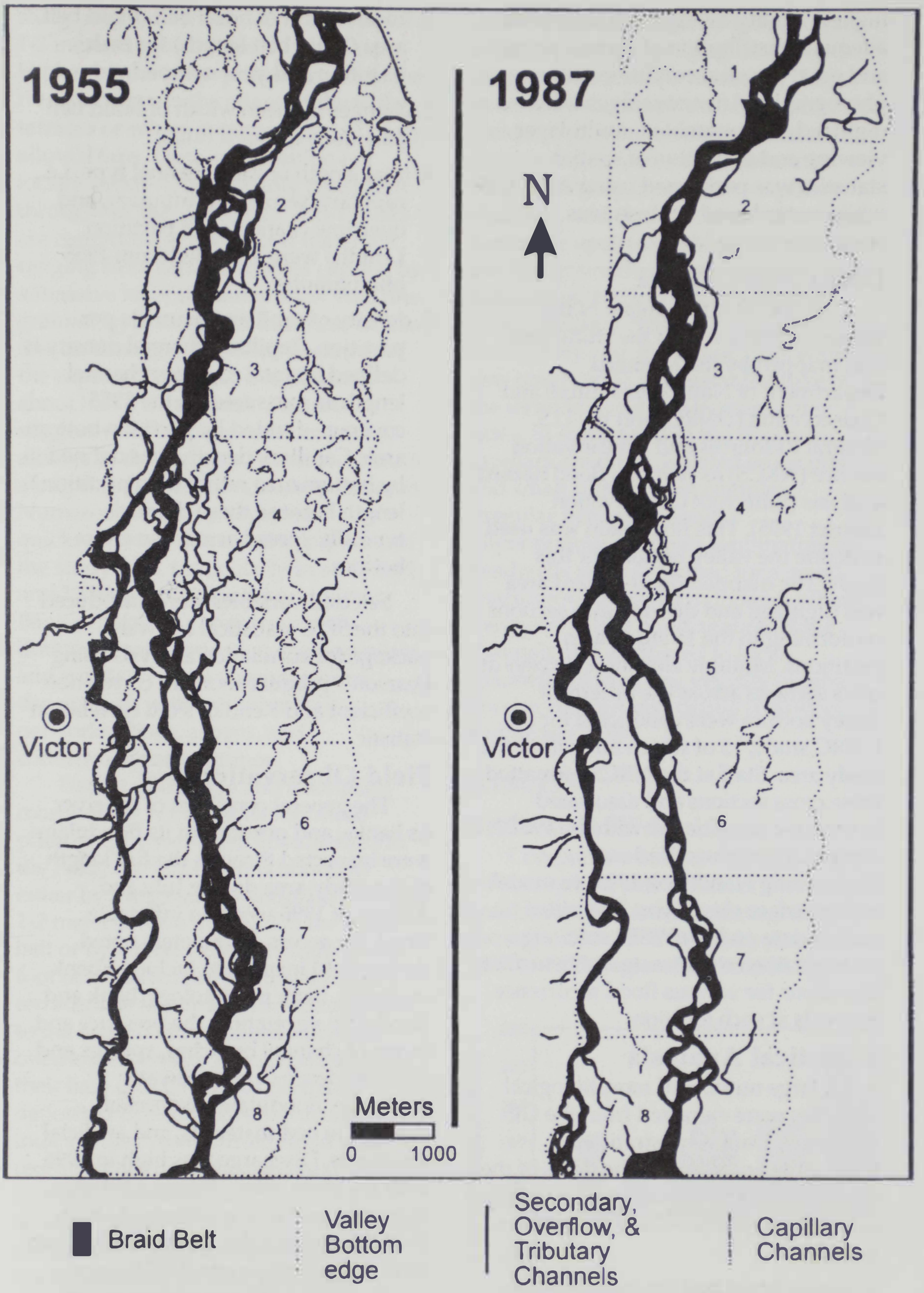

Figure 2B: *Northern half of study area.*

highest quality owing to its large scale, adequate distribution of control points, and good physical condition of the photographs. After coverages were digitized and assembled, multi-layer viewing and extraction of spatial statistics was performed using Atlas GIS while raster-based analysis was conducted using Idrisi.

DNRC/NRCS Data

The 500-year floodplain of the Bitterroot River within the study area was mapped by the Montana Department of Natural Resources and Conservation (DNRC) and the U.S. Natural Resources and Conservation Service (NRCS) as part of a flood hazard analysis (Bitterroot Conservation District 1995). This floodplain was used to define the valley bottom for this study. The mapped flood-hazard area was digitized and divided into sections conforming to the 15 study area partitions. Multiple elevation surveys at cross sections across the Bitterroot Valley bottom were conducted for the DNRC study, 15 of which fall within the study area. Staff at the NRCS formatted these cross sections and associated hydrologic data for use with the WSP2 computer program (National Engineering Handbook 1993) to model water surface elevations. The cross-section data and the WSP2 software were obtained to estimate water surface elevations for various flood recurrence intervals at each location.

Statistical Analysis

A large number of morphological variables were extracted from the GIS coverages. Data were stratified temporally according to the dates of the three sets of aerial photos, and spatially according to partition. These variables included:

1. area of braid belt for each partition and year mapped. Bars are included in braid belt area, islands are excluded;
2. mean width of braid belt (braid belt area/braid belt length) for each partition and year mapped.
3. changes in mean width of braid belt partitions through time;
4. total length of each channel type, i.e., capillary, secondary, tributary, and overflow channels per partition. Lengths were extracted from 1955 photographs;
5. density of capillary channels per partition. Capillary channel density is defined by total capillary channel length as measured on the 1955 coverage divided by partition bottom area. Capillary density was defined by bottom area rather than partition length because these channels typically spread across the entire bottom.

Selected variables were introduced into the SPSS statistical software package for correlation analysis using Pearson's product-moment correlation coefficient and Kendall's tau correlation statistic.

Field Observation

The general condition of the river, its banks, and portions of its floodplain were inspected through the full length of the study area during July and August of 1996 using an inflatable kayak for access. Parameters noted during field inspection included bank materials, bank morphology, bank and floodplain vegetation, the presence and forms of channel branches, springs and other evidence of groundwater discharge, floodplain microrelief, changes in bed materials, and artificial structures. Discharge was high in 1996, with the river rising during a February thaw and sustaining a relatively high level throughout the spring. Daily mean flow at the Darby gage (USGS gage number 12344000) attained its eighth highest level on record with a discharge of 9,320 cfs on June 9.

Bitterroot River banks within the

study area were observed to be typically 1-2 meters high and nearly vertical. Higher banks occur primarily where the river encounters the edges of the valley terraces or where it carves into tributary alluvial fans. Bank composition is locally variable, but broadly consistent throughout the study area. Most banks are composed of coarse bed materials ranging from sand to cobbles capped by a massive layer of loamy fines. This fine-grained layer ranges in thickness from a few centimeters to the full thickness of the exposed bank, but it is normally about half a meter thick. Features suggestive of seepage erosion, such as alcoves in the bank and detached blocks along the channel margins, are common. Numerous seeps, springs, and quicksand were observed in portions of the study area, particularly in sections 9 and 10 between Corvallis and Victor. Bank vegetation varies from well-drained areas supporting sparse grasses and weeds to moist clayey areas of dense brush with extensive root networks. Pines, aspens, and cottonwoods are common.

Details of channel and floodplain morphology not apparent on aerial photography were also documented in the field. The braid belt is bounded either by a vegetated floodplain surface 1-2 meters above the level of the braid belt or by a relatively high scarp at the foot of a Quaternary or Tertiary valley terrace. The floodplain surface adjacent to the braid belt contains numerous overflow channels. Though usually dry, their bare gravelly beds and debris deposited upstream of obstructions indicate they have carried flood waters recently. Overflow channels may become increasingly incised in the downstream direction before re-entering the braid belt or terminate on the floodplain where their discharge is captured by portions of the channel system outside the braid belt.

Secondary channels were observed to often grow in discharge in the downstream direction by ground water additions or by capturing flow from a range of other minor channels. They eventually discharge into the braid belt. Field observation confirmed that a continuous gradation in scale exists from secondary channels to capillary channels, which were observed to often terminate upstream at steep headcuts in the fine-grained vertical accretion deposits of the floodplain. Although many capillary channels were dry during July and August of 1996, water was observed to emerge at the base of the terminal headcuts in many other cases. In some parts of the floodplain, capillary channels, isolated scour pits, and small rills occur in complex irregular networks. Similar discontinuous channels terminating in headwalls were described for a small anastomosing stream in Ireland, where they were called blind anabranching channels and attributed to local channelization of low velocity overbank flood waters around debris (Harwood and Brown 1993).

RESULTS

Braid Belt Widening

Comparison between data from different photo sets indicates that the braid belt width increased considerably throughout most of the study area from 1937 to 1955 (Figure 3). The 1937 braid

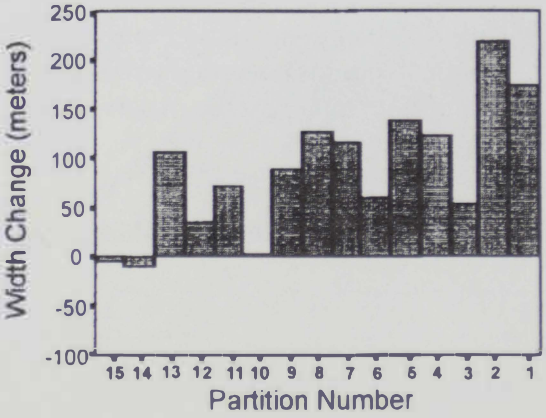

Figure 3: *Change in braid belt width 1937-1955.*

belt covered 493 hectares over all partitions. The average width of the 1937 braid belt was 200 meters. The 1955 and 1987 braid belts covered 685 and 769 hectares for average widths of 278 and 313 meters, respectively. This constitutes a 39 percent increase in width from 1937 to 1955. Following 1955, changes in braid belt width become more erratic. Continuing increases in some areas were balanced by narrowing in others, resulting in a net increase in braid belt width from 1955 to 1987 of 12.6 percent. The total increase in braid belt width between 1937 and 1987 was 56.5 percent. These relationships are summarized in Table 1. After 1955, widening continued in some partitions, although many areas remained stable or narrowed (Figure 4).

Changes in Braid Belt Position

Despite the Bitterroot River's reputation for rapid migration and continual large channel displacements, the positions of the braid belt and extra-braid belt channels have changed little over most of the study area. Lateral migration observed during the 50-year period documented on the aerial photographs is generally small relative to braid belt and floodplain dimensions. The 1901 edition USGS 1:125,000 Missoula and Hamilton quadrangles depict an essentially static channel configuration since the area was surveyed in 1887 and 1888. Despite rapid bank erosion, lateral migration of the braid belt appears to be limited by a tendency for point bars to wash out. Bends in the thalweg were observed to grow in amplitude until development of a cut-off chute restored flow to a former straighter course away from the braid belt margin. Bankfull sinuosities of the main stem channels rarely reach values as great as 1.3 except locally along the river's west branch around an extremely large island (8 km long) near Victor. Portions of this relatively narrow channel are somewhat entrenched at the foot of a valley-side terrace and lack a well-developed braid belt.

Changes in the magnitudes of existing channels can produce changes in the location of the river's thalweg even though the positions of individual channels and points of bifurcation network are generally stable through time. Where two or more channel branches are separated by islands or expanses of floodplain, one may widen and intercept the bulk of the river's discharge while other channel branches fill. However, incision of new large-scale channels was not observed.

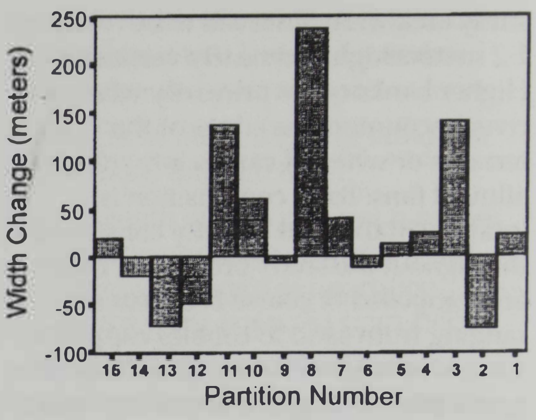

Figure 4: *Change in braid belt width 1955-1987.*

Table 1: *Changes in Braid Belt Width.*

	1937	1955	1987	1937-1955	1955-1987	1937-1987
Mean Braid Belt Width (m)	200	278	313			
Change in Braid Belt Width (m)				78	35	113
Percent Braid Belt Width Increase				39	12.5	56.5
Percent Total Increase 1937-1987				69	31	100

Statistical Analysis

Few interesting relationships emerged from the large number of variables subjected to correlation analysis. In general, only known relationships produced significant correlations. For example, braid belt width correlates strongly with valley bottom width. A very wide braid belt can clearly not exist in a narrow valley. One relatively weak but nonetheless significant correlation lacking obvious explanations was between capillary channel density and braid belt expansion during 1937-1955. Capillary density correlates with 1937-1955 braid belt widening at the 95 percent confidence level (R = 0.594).

DISCUSSION

Widening of the braid belt has been the dominant change observed in the main stem Bitterroot River during the study period, particularly between 1937 and 1955. Braid belt widening on the Bitterroot River can probably be attributed to bank recession and loss of the floodplain surface. Detachment of large blocks of adjacent floodplain was observed to be a major contributor to bank erosion on the Bitterroot River following the 1996 run-off season (Figure 5). These blocks were often observed intact where they fell at the base of the bank, indicating the failures occurred after peak flows had passed. Numerous authors have attributed this type of bank failure to groundwater sapping (Schumm and Lichty 1963, Twildale 1964, Schumm and Phillips 1986, Simon and Hupp 1986, Keller *et al.* 1990). Block detachment commonly occurs during flood recession when water held in the saturated floodplain materials discharges back into the river channel. This return flow into the channel causes erosion of the more permeable layers in the bank profile. After being undermined in this fashion, the upper portion of the bank may break loose and fall into the channel as an

Figure 5: *Example of bank block failure (kayak paddle for scale).*

intact block. The process was described in detail by Keller *et al.* (1990) who identified 4 modes of block failure related to seepage along sand seams or other weak permeable layers in the bank profile on a section of the Ohio River. In addition to the detached blocks themselves, pipes and slit-like cavities at the base of banks and alcove in the banks where seepage is concentrated are described as visual evidence of seepage erosion. Such cavities and alcoves were observed on the Bitterroot River. The hydraulic gradient present where groundwater is seeping into a channel also contributes to bank erosion by lowering the flow and gravitational forces necessary to entrain particles of bank material (Burgi and Karaki 1971, Dunne 1990). In addition to the numerous block failures observed through the study area, bank structure and demonstrated groundwater discharge on the floodplain suggest that bank recession on the Bitterroot River can be attributed in part to seepage processes.

Observation of channel widening on the Cimmaron River of southwestern Kansas suggests that floodplain elimination may be typical of degradation on certain streams in semi-arid environments (Schumm and Lichty 1963). As defined by Schumm and Lichty, the term "degradation" includes any net loss of sediment from a portion of the stream and floodplain system. The authors proposed that channel widening may be an alternative to channel incision as an expression of degradation; the floodplain is eliminated while the bed elevation remains the same. Channel expansion on the Cimmaron was postulated to be initiated by the destruction of bank vegetation during the maximum flood on record. Vegetation loss was then exacerbated by a prolonged dry period that prevented new bank vegetation from becoming established. This does not appear to be the case for widening of the Bitterroot River braid belt. Precipitation records for Hamilton and Stevensville reveal no notable deficits during the 1937-1955 period of pronounced Bitterroot braid belt widening. Nor does this period contain extraordinarily high or frequent large peak flows as measured at the Darby gaging station (the maximum peak flow on record occurred in 1947, but it is not extraordinary compared to other recorded peaks). One possible impact that has been overlooked is the rise of irrigated agriculture in the Bitterroot Valley. Large-scale irrigation works were initiated near the turn of the last century. The Big Ditch, a major project delivering water through the valley from Como Reservoir (south of Hamilton) to Stevensville, was completed in 1909. During the apple boom of the early 1900s, irrigated and cultivated acreage increased substantially, as did agricultural production. For example, apple production in the area increased 20-fold from 20,000 bushels in 1898 to 400,000 bushels by 1919 (Zeisler 1982). Previous researchers have demonstrated that groundwater levels on the valley terraces respond directly to recharge from irrigation ditches (McMurtrey *et al.* 1972, Finstick 1986, Uthman 1988). Static well levels are reported to rise rapidly in May and June, remain high throughout the irrigation season, and decline after irrigation ends. Whether this source of recharge materially affects groundwater flow near the river banks is uncertain. Alternatively, braid belt widening in the central valley may be viewed as a return to the river's normal state following a period of abnormal channel narrowness. A period of low flow beginning about 1930 is reported to have created the impression that the Bitterroot River was a stable meandering stream (Simons et al 1981). However, this claim is difficult to evaluate as stream gaging records for the river begin in 1937 and earlier channel conditions are poorly documented.

The intricate network of small-scale floodplain channels in much of the study area may also be genetically linked to groundwater discharge. The significant correlation between braid belt widening during 1937-1955 and capillary channel density in the anastomosed central part of the valley (R = .594, probability < .05 and tau = .352, probability = .07) suggest that the two processes may be related to a common factor. A theoretical framework for drainage system development through groundwater discharge has been proposed by DeVries (1976), who describes a groundwater outcrop-erosion model (GOEM). In the GOEM model, surface channels are viewed as groundwater "outcrops," and are considered to be components of a groundwater discharge system. The model is described as one end-member in a spectrum of erosion models where the opposite end is occupied by overland flow as defined by Horton (1945). GOEM is applied to relatively flat areas of high subsurface permeability and moderate precipitation rates where water enters into subsurface flow before appearing in the surface channel system (DeVries 1976). The requirements of GOEM seem to match the circumstances of the Bitterroot Valley. Most tributary and irrigation discharge infiltrates into the permeable alluvium of the low valley terraces before discharging on the flat valley bottom. Measurements of static well levels indicate that groundwater circulation in the central valley is predominantly toward the valley center, where flow turns northward and discharges into the Bitterroot River (McMurtrey *et al.* 1972, Finstick 1986, Uthman 1988). Woessner (1998) describes such situations, where subsurface flow entering permeable floodplain materials is refracted parallel to the direction of stream flow, as "fluvial plain" groundwater systems. The fluvial plain is a zone of dynamic groundwater-surface water exchanges, and the stream channel is regarded as one of its components.

Many of the morphological characteristics defining capillary channels of the Bitterroot floodplain are indicative of a significant subsurface connection. Lack of connectivity within the network and large upstream and downstream variations in discharge within individual channels are solid evidence of a substantial subsurface flow component. Many of the minor floodplain channels may be remnants of formerly larger channels that have filled incompletely, perhaps because of the maintenance of a base groundwater flow. In other cases, groundwater discharge may be actively excavating channels by the retreat of headcuts at the end of small channels or in alcoves in the banks of larger channels. The suggested process is analogous to basal sapping at the base of gully headcuts as described by Higgins *et al.* (1990). The capture of overbank flood flow by these incipient channels is probably also an important factor in their growth and network development.

CONCLUSIONS

The main Bitterroot River channel has widened considerably since 1937. Much of the widening occurred between 1937 and 1955. In spite of the rapid bank erosion during this period, channel migration has been modest relative to floodplain and channel dimensions. Channel and floodplain morphology on the central Bitterroot River may be substantially impacted by groundwater discharge on the valley floor. Bank erosion on the main channels is characterized by block failures, which appear to be promoted by groundwater seepage through the banks. Groundwater discharge on the floodplain may also contribute to floodplain dissection and development of anastomosing characteristics of the

Bitterroot channel network. Causes for the dramatic channel widening of the central Bitterroot River after 1937 are uncertain and no doubt complex. Climatic fluctuations, floodplain deforestation, livestock grazing, and upland erosion are sometimes cited. However, changes in the rate of groundwater discharge through the river banks, possibly related to intensive irrigation in the valley, is also a potential impact in this system.

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