# STREAM CLASSIFICATION, STREAMBANK EROSION AND FLUVIAL INTERPRETATIONS FOR THE LAMAR RIVER AND MAIN TRIBUTARIES

FOR

USDI NATIONAL PARK SERVICE
YELLOWSTONE NATIONAL PARK

BY

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## OBJECTIVES

Wildland Hydrology was contracted in 1988 to perform the following tasks for Yellowstone National Park:

1. Classify the Lamar River drainage and it's major tributaries, namely; Calfee Creek, Soda Butte Creek, and Slough Creek on 1:62,500 scale maps.

2. Description of stream morphology, channel stability, channel patterns, and channel forming processes of the mainstem lamar river and tributaries.

3. Determine whether the lamar river and it's tributaries are transporting sediment loads "out of character" with it's present geologic and geomorphic setting.

4. Determine if the Lamar River is in equilibrium with the present combination of climate, landform, vegetation and geology.

5. Locate primary sediment procuring processes including upland mass-movement, surface erosion, and channel related erosion. Delineate riparian areas with respect to sensitivity, consequence of disturbance and recovery potential.

6. Provide field training for park personnel in stream classification and bank erosion studies.

These tasks were undertaken and training provided to Roy Ewing and Jana Mohrman of the NPS. Field assistance for the bank erosion studies and stream classification reference reach data was also provided by Roy and Jana.

In order to meet these tasks, a stream

classification system (Rosgen, 1985, 1993) was utilized to stratify the mainstem Lamar River and it's tributaries into morphologically similar reaches.

## INTRODUCTION

### GEOMORPHOLOGY/GEOLOGY/SOILS

A portion of the stream classification system is associated with an understanding of the historical development of the landforms and soils associated with the Lamar River watershed. Mapping of major landscape groups by Shovic, Ewing, and Mohrman, (1988), aided the most recent river classification as depositional history, etc. provided interpretations of channel materials from aerial photography.

The upper basin consists of andesitic volcanic rocks, mixed with glacial scour and depositional landforms. Lower elevations have soft, cretaceous-aged shale. Landslide debris derived from the shale are common, as are deposition from debris torrent/debris slide activity of the steep upper slopes. Glacial lacustrine deposits in many of the basins are not uncommon. Coarse, unconsolidated, non-cohesive deposits associated with glacial moraines are also common.

The broad alluvial valleys have evidence of lacustrine and river terraces. The alluvium present in these valleys range from very coarse to very fine sorted material. The erodibility of these soils/landforms is not only a function of the material associated with them, but the steepness of the terrain, streamflow characteristics, vegetation condition, etc.

Specific maps indicating these delineations can be studied in the Technical Report by Shovic, Ewing and Mohrman, (1988).

Many valley features indicate past and present high rates of geologic erosion. Alluvial fans and other depositional debris continue to override valley features. The streams that are incised in these features have a very high sediment supply. The channels incised in slump/earthflow and debris torrent/avalanche terrain are not only associated with high sediment supply, but also have high energy for transport.

Alluvial valleys, whose streams are currently adjusting to the very high sediment supply and current streamflow regime of the watershed, show the evidence of climatic change during the Holocene period with the characteristic three river terrace levels. Glacial terraces are also present at levels higher than the alluvial terraces.

Alluvial channels have migrated within the valleys and have changed their vertical position by abandoning their floodplains, thereby creating a new river terrace. These major elevation changes have been associated with climatic changes starting 11,000 years ago at the start of the Holocene period. The last base level change was associated with the altithermal (dry) period at the turn of the century. This left a terrace remnant approximately 4 feet above the current floodplain of the river. The other, much older river terraces, are at approximately 8 and 18 feet above the low terrace.

Due to the extensive glaciation, much of the bed material of the alluvial channels in these broad valleys is composed of relatively coarse gravel and cobble. Bank materials are characteristically finer than that of the bed material. Specific particle size distribution of the bed materials were collected by NPS personnel during the reference reach characterization

## STREAM CLASSIFICATION

The mainstem of the Lamar and the major tributaries were classified using the classification system developed by Rosgen, (1985,1993). This morphological delineation groups stream reaches of similar character into categories based on:

* Entrenchment
* Width/depth ratio
* Sinuosity
* Slope
* Channel materials

The objective of the stream classification system is to be able to: a). Predict a rivers behavior from it's appearance, b). Develop relations/interpretations from extrapolation of data from rivers of the same type, c). Determine stability, potential vs existing stream type, and, D), Provide a basis of communication between the many various disciplines working with rivers. Delineative criteria for broad level classification (stream types A-G), is described in Table 1. Longitudinal, cross-sectional and plan view of major stream types are shown in Figure 1. Entrenchment ratio is a quantitative expression of whether a stream has a well developed floodplain or not. If a stream is entrenched (defined as a vertical containment), the width associated with flows greater than the normal high water (bankfull stage) does not increase as fast as depth. Streams that are slightly entrenched increase their width faster than depth with flows greater than the bankfull stage. The computation involves dividing the floodprone area width by the bankfull width. The floodprone area width is determined at the elevation of twice maximum bankfull depth. This is illustrated in Figure 2. (Rosgen, 1993). The illustrative guide of stream types is summarized in Figure 3, and the classification key is shown in Figure 4, which utilizes a continuum concept for the delineative criteria.

Field measurements of slope, entrenchment ratio (confinement), width/depth ratio, sinuosity, and channel materials were determined at reference reach locations in each major sub-drainage and along the mainstem Lamar River. This data is too voluminous to include in this report, however the data is located with the Research Division of Yellowstone National Park, Mammoth, Wyoming. The categories classified by Roy Ewing and Jana Mohrman were those of the 1985 classification methodology. These categories were recently changed and updated to the 1993 classification procedure).

The stream classification maps for the Lamar and the major tributaries were recently prepared by Wildland Hydrology based on a review of the reference reach site data collected by the NPS and aerial photography interpretations. They are included in Appendix I of this report. The distribution of stream types by miles and the per cent of occurrence of stream types in the major tributaries is shown in Tables 2a and 2b.

## EXAMPLES OF STREAM TYPES IN THE LAMAR RIVER WATERSHED

The variety and distribution of stream types in the Lamar River watershed are shown in Tables 2a and 2b. Photographs of some of the stream types are shown in Appendix II of this report. Aerial and corresponding cross-section views of the same stream type indicate the interrelationships of the delineative criteria and channel morphology.

## STREAM CLASSIFICATION INTERPRETATIONS

Additional information associated with stream types which is utilized in this report involves computation of meander width ratio (belt width/bankfull width) (Figure 5). Mean values as well as ranges are shown in this figure. The large range of meander width ratio (MWR) values provide an interpretation of state or condition.

For example, high MWR values are very typical for stable "E" stream types, however, when these values start to drop below 20, a change in stream type occurs. This is often related to an associated increase in width/depth ratio due to increased bank erosion. Wnen the MWR values for a "C" channel start to drop below 10-11, then an increase in width/depth ratio, bar deposition and bank erosion generally are observed (Rosgen, 1993). When MWR values drop below 4 for a "C" stream type it is generally working towards a morphological shift to a "D" stream type.

These changes which lead to a morphological shift, can be induced by increased sediment supply, streambank instability, and climatic shifts that effect timing and quantity of runoff. These changes are shown in Figures 6 and 7, indicating evolutionary adjustment of stream types.

Interpretations of sediment supply by stream type as well as sensitivity to disturbance, recovery potential, streambank erosion potential, and vegetation controlling influence are shown in Table 3.

## EROSION/SEDIMENTATION

The sediment yields (suspended and bedload) in the Lamar River are naturally very high. The soils and channel types are characteristic of very high rates due to the nature of the steep upper erodible slopes and stream types which provide an unlimited sediment supply to the valleys. The low relief valleys are the sites for sediment storage, while the mid to upper position mainstem reaches have numerous debris fans occupying their valleys. Many reaches of the tributary mainstem have extensive bar deposition adjacent to debris fans and reaches where the channel has rejuvenated the valley walls and is headcutting up the valley. These channel adjustments are currently providing very high sediment supply to the downstream reaches.

The sediment study initiated by the NPS earlier only measured suspended sediment. Bedload for many of these stream types is greater than the suspended sediment (Rosgen, 1990). Channel stability is influenced more by bedload than suspended sediment. Future water quality studies need to incorporate both to better understand the magnitude of sedimentation rates.

## STREAMBANK EROSION PROCESSES

One of the objectives for this study was to determine streambank erosion rates in different locations for various stream types to determine contributions to sedimentation rates.
The two general categories that are responsible for bank erosion rates are: streambank erodibility and distribution of stress in the near-bank region (energy distribution).

### STREAMBANK ERODIBILITY

There are multiple, complex, interrelated variables which influence streambank erodibility. However, studies have been conducted on a few of the processes which can provide some interpretations. For example, work by Smith (1976) indicated that a soil column with 16-18 per cent root volume had 20,000 times more resistance to detachment/erosion as did banks with no roots for the same soil type. The significance of this research would lead one to include a vegetation component in any bank erosion prediction. Variables which would indicate various levels of streambank erodibility are included in Table 4. (Rosgen, 1990). They include particle sizes, ratio of bank height to bankfull stage, bank angle, presence of layers in the bank stratigraphy, root density, root depth/bank height ratio, and surface area protected by vegetation/debris. These relations were put into indices on a quantitative scale to predict streambank erodibility (Rosgen, 1990) and is shown in Table 4.

Examples of streams with low vs high bank erodibility potential for the same stream type is shown in Figure 8. Erosion rates should be less in the top photo with the lower streambank erodibility rating. The width/depth ratio and extent of bar deposition also shows a marked contrast between the "state" or condition of these two C4 stream types.

## STRESS IN THE NEAR-BANK REGION

Velocity gradients, boundary shear stress (distribution of the depth/slope/density product), and velocity distributions in the near-bank (defined as 1/3 width of channel next to stream bank) influence bank erosion rates. A typical velocity isovel is shown in Figure 9, where velocity gradients (velocity in ft./sec. per unit orthogonal length which are perpendicular to velocity isovel) are calculated. Since this is complex field work to compute, a simpler computation was developed from these empirical relations using the ration of stress in the near-bank region as a ratio of total available shear stress (Table 5).

## STREAMBANK EROSION RATES

These relations of streambank erodibility and stress in the near-bank region were developed for the US Forest Service from research efforts on the Front Range of Colorado (Rosgen, 1990). The results of this integrative approach to erodibility/stress relations were tested with actual measurements of lateral erosion rates and are shown in Figure 12. Statistical relations using an analysis of variance found that the dependent variables of bank erodibility and stress in the near-bank region predicted the independent variable of bank erosion rate such that the coefficient of determination ($R^2$) was 0.93, highly significant at the 95 percent level of confidence.

This field procedure can then be applied where a comparison of approximate bank erosion rates between various streams can be made using these variable relations.

Streambank erosion can make up a large contribution of total sediment yields. For example, recent total sediment studies on a braided reach of the East Fork San Juan River showed over 49 per cent of the total sediment contribution was made to a 52 sq. mi. watershed by 3.5 miles of unstable, braided channel (Rosgen, 1990).

## SEDIMENT/BANK EROSION/CHANNEL INSTABILITY CONSEQUENCES

Channel instability can lead to higher width/depth ratios, steeper slopes due to decreased sinuosity, excessive bar deposition which in turn increases stress in the near-bank region. This leads to increased streambank erosion rates, loss of land, degraded fish habitat, and often, very long-term adjustments of the river. A good example of this occurred on the Weminuche River (C4 stream type) in Colorado when a land owner converted his meadow from willows to a grass/forb community. This initiated a streambank erosion problem due to a streambank erodibility increase. The stream increased its width/depth ratio, decreased sinuosity, increased slope, increased bar deposition and added more sediment from accelerated bank erosion rates. The stream became less competent to move it's own sediment, and thus, aggraded. When this occurred, overbank flooding became frequent associated with discharges less than flood stage (Figure 13). As a result of this damage by a willow/grass conversion, willows and channel patterns have been re-established by the Author in a large scale restoration effort. This is an example of the evolutionary shifts in stream types presented in Figures 6 and 7 earlier without a corresponding shift in climate, often responsible for such large scale impacts to the river.

## RIPARIAN FACTORS IN CHANNEL STABILITY

Since streambank vegetation is very sensitive to streambank erosion, changes in vegetative composition can have a marked effect on bank erosion/sedimentation rates. Grazing/browsing impacts, especially in late fall/winter seasons has caused removal of willows from many western ranges. The conversion shown with the fence line contrast of late-season grazing by livestock eliminated willows from this C4 stream type. The willow pasture is grazed (see trails) but not late and with a lower stocking rate (Figure 14) This meadow is in South-Central Colorado at 7200 feet elevation. Another example of willow/grass conversion is at a detailed study site on Goose Creek in South-Central Colorado (tributary to the South Platte River). The lower left photograph (Figure 15) shows the streambank/stability conditions 900 feet upstream on the same stream and same C4 stream type of the lower right photo. Two different grazing strategies of season/intensity of uses created a vegetation conversion of Willow to grass. The resultant erosion rates for the upper vs lower reach were .03 vs 3.0 feet/year respectively.

Similar results of vegetative conversions from willow/grass to grass/forb communities due to browsing ungulates have been reported by research in Yellowstone National Park (Kay and Chaddle, 1991), (Kay, 1990), (Putman and others 1989), and (Risenhoover and Maass, 1987). Large herds of elk did not inhabit the Greater Yellowstone Ecosystem until the late 1800's (Wright 1984), and evidence of elk browsing on willows was not evident on photographs from 1870-90 (Kay 1990). Thus, conversion of willows to grass communities due to heavy late-season/winter browsing on the Lamar River and many of it tributaries has changed bank erodibility potential and associated bank erosion rates as presented earlier. The replicate photographs (Kay,1990) shown in Figures 16a-18b depict this dramatic conversion.

## INTERPRETATIONS FOR THE LAMAR RIVER AND TRIBUTARIES

### SEDIMENT/EROSION

Since measurement of bedload data was not contracted to be collected within each of these watersheds, and the sediment data available included some reaches with suspended sediment only, a sediment budget by sub-watershed or for the Lamar River could not be determined. However, interpretations of sediment supply from various erosional process can be inferred.

A large contribution of sediment from debris slides and other forms of mass wasting occurs in the upper basin, as well as fluvial erosion of the A3 and A4 stream types associated with these erosional processes. During each runoff, whether a debris slide occurs or not, there are large quantities of sediment contributed from fluvial entrainment, bank and tributary rejuvenation, etc. Accumulation of sediment at the toe of these very steep banks due to dry ravel, creep, freeze-thaw, ice scour, surface erosion, slumping, etc. provide a constant source of sediment to be removed at the base of these banks during runoff periods. The aerial and cross-section views of the A3 stream types shown in Appendix II are typical of these high sediment supply/high sediment transport stream types common to the upper basin and some of the lower canyon faces.

Channel erosion processes on the A3,A4,G3 stream types are very high due to the unlimited supply and high transport capacity. Since these stream types are both entrenched and confined (vertical and lateral containment, respectively), flood waters cannot be dispersed onto floodplains. The photographs for these stream types in Appendix II show the exposed soils and deposition typical of these high sediment supply stream types.

## SEDIMENT SUPPLY FROM STREAMBANK EROSION

The mid to lower reaches of the C3, C4, D3, D4 stream types of Soda Butte, Slough, Cache, Little Lamar and the main Lamar River are contributing excess sediment supply due to a combination of variables which relate to channel instability. When sediment supply produced from upstream sources exceeds the competence to move it, deposition occurs generally associated with lateral adjustment. When bars deposit on "C" type streams in valley bottoms, several processes are activated;

* Local slope is steepened
* Width/depth ratio is increased
* Stress is increased in the near-bank region
* Depending on bank erodibility, bank erosion is increased
* Sinuosity decreases
* Meander width ratio decreases
* Meander wavelength and radius of curvature is increased
* Sediment supply is increased due to streambank erosion
* Stream type can evolve to "D" or "F" types which are highly unstable
* Abandonment of floodplains, creating entrenched streams
* Degradation "F" and aggradation "D" processes are accelerated

Examples of these changes are shown on an aerial photo overlay for a reach on the Main Lamar River from a conversion of a "C4" to an "F4" stream type (Figure 19). Computed values for the changes in the channel stability are shown in Figure 19.

The changes are accelerated if the width/depth ratio is increased. If not, the competence of the river is maintained and the excess sediment can be move through the sediment without adding more to it from bank erosional processes. If, on the contrary, width/depth ratio is increased, the decrease in shear stress to move sediment leads to increase in bar deposition, and in turn more stress is placed on the banks. The key to maintaining a lower width/depth ratio is the maintenance of the woody species where rooting depth protects the banks from excess erosion rates. In this case - the willows.

**RIPARIAN INFLUENCE ON BANK EROSION RATES.**

The stream types evaluated in Table 3 as related to vegetative controlling influence which would not be effected by composition change are the A's, B1,B2,F1,F2,G1,and G2 stream types. The C3,C4,D3,D4,E3,E4,F3, F4, G3 and G4, are influenced by streambank vegetation.

To determine bank erosion rates on various reaches on the main stem Lamar and on several of the tributaries, Roy Ewing and Jana Mohrman installed erosion pins in several different stream types. The design was to find different bank erodibility and stress conditions for the SAME stream types, to compare how changes in stress and/or erodibility effects bank erosion rates for the same stream types. Some stream types, however, due to their natural geologic high erosion rates would not have low streambank erodibility (A3,A4 stream types).

On the mid to lower elevations on the tributaries and on the Lamar River which is within the winter range, willows were either gone from the composition, or densities were so low to be ineffective at adding to the bank strength. In several locations, remnant willow roots, many greater than 30mm diameter, were present under water. The photographs in Figures 16-18 and the remnant dead roots verify that willows were present at one time at these locations along the river.

Willow composition for the same stream types occurs on the mid to upper valleys in Slough, Soda Butte, Cache, upper Lamar, etc. These reaches appear to be above the heavy concentrations of browsing ungulates during late-season/winter periods. When these areas are accessible, animals would tend to be dispersed, thus associated with lower animal concentrations. This is consistent with the plant response discussed earlier on willow composition changes to various levels and seasons of plant use.

The results of the bank erosion pins, bank erodibility and stress in the near-bank region are very similar to work done for the Forest Service in Colorado. Some of the actual erosion rates during a "normal" runoff season in 1989/1990 exceeded the expected rate by eroding out the entire 3.0-4.0 foot erosion pins. For example on Soda Butte Creek near the footbridge, (SBR-1), with a very high bank erodibility and high stress, a 3.0 foot erosion pin was lost, thus rates were greater than 3.0 feet (Figure 20).

Streambank erosion rates for Soda Butte Creek #2 based on Bank erodibility-very high, stress-high...lost 3 ft. pin (Figure 21). Soda Butte # 5 also had no willows on bank...results: bank erodibility-very high, stress-high...lost a 3 ft. erosion pin (Figure 22). A major contrast of streambank erodibility potentials shown with and without willows for the same stream type in the same river (Figure 23). Results of bank erosion rates on Soda Butte Creek #7 where bank erodibility-extreme, but stress was moderate +. Bank erosion rate was 1.2 feet/year (Figure 24). On a reach where willows were present on Soda Butte # 12, the erodibility potential rating was low, and stress was moderate. The erosion rate was 0.1 ft./yr. (Figure 25).

Bank erosion rates on the lower reaches of the Lamar River at station # 1, which had a bank erodibility of very high, but low stress, yielded an erosion rate of

0.78 ft./year (Figure 26). Data from the lower Lamar River at station #2 with a bank erodibility rating of very high and a stress of high had an erosion rate of 2.1 ft./yr. (upper pin), and 0.9 ft./yr. (lower pin), with an average rate of 1.5 feet/yr. (Figure 27). Another erosion study site on the Lamar River (#5) for a bank erodibility rating of very high, but a stress of low, yield an erosion rate of 0.76 (Figure 28). There is considerable more data, thus the data is summarized and statistically analyzed similarly to the data set of the U S Forest Service (Figure 29). An analysis of variance was conducted on this data set and the coefficient of determination, ($R^2$) of 0.87 was obtained. This was highly significant at the 95 per confidence level.

This field data and subsequent analysis allows a calculation to estimate bank erosion rates for various bank erodibility potentials and for various stress conditions. For example based on measured data, a C4 stream type on Soda Butte Creek that has a streambank erodibility and stress rating of low, would yield approximately .03 ft./year. For an 8 foot terrace bank (one side only) this would amount to approximately 2 tons/year/mile. Comparing that to another reach for the same stream type, but for an extreme bank erodibility and stress rating, a value of 3.0 feet/year erosion rate could be expected. For the same height of bank, this would yield approximately 211 tons/mile/year. Depending on how many miles, that this condition would persist, this can add up to be a large number over time. This is not atypical however, from actual total sediment measurements and measured bank erosion contributions determined from previous studies.

## SUMMARY

The Lamar River and it's tributaries are associated with naturally high sediment supply which is primarily geologically controlled. Large volumes of sediment are delivered from steep erodible terrain and stream types in the upper watershed to the flatter gradient valleys in the mid and lower watershed position. How the stream in these valleys accommodates this sediment, has a key to general stability or equilibrium condition of these rivers. The C3 and C4 stream types in the mid watershed position which are first to receive this sediment delivered from the watershed are some of the most stable within the basin. That is due to a healthy, functioning riparian system with a combination of woody species, grasses and forbs. To be stable, a stream will deposit, scour and migrate over time such that over time, the pattern, dimension, grade and profile does not change. Often a general statement about equilibrium is sediment in vs sediment out with little change in storage. The streams in the upper valleys that have low width/depth ratios, stable patterns and dimensions, and healthy riparian systems meet those conditions of stability/equilibrium (even though they are very active in sediment transport).

The mid to lower reaches of these rivers, however of the same stream type as their upstream counterparts, are not in the same stability category. The discussion on changed patterns, dimensions, slope, etc.,as shown in Figure 19 indicates a trend that is not associated with a climatic change. If that were the case, then all of the same stream types would be responding similarly. However, the higher erodibility ratings and stress due to excess bar deposition has led to an ACCELERATION of natural processes. This has created downcutting and abandonment of floodplains in many reaches which have not been exposed to a climatic change. The increased sediment supply due to channel disequilibrium must be understood and eventually built into a sediment budget for the watershed.

The reach of the Lamar River above the bedrock control and nick point at Tower Junction appears to be aggrading which is adding to the lateral migration of the river in this valley. Even though this process has been going on for some time, it is accelerated due to the added sediment supply from bank erosion in an already very high sediment supply watershed.

Riparian conditions above vs below and before vs after for the same reaches verify that the stream types of the mid to lower Lamar River and its tributaries have been changed. To restore these systems back to natural, stable channels in these reaches, it would be necessary to re-establish the woody species, primarily willow. This will help start to add the natural resistance to the stress imposed in the near-bank region and lower the width depth ratios to regain the competence of these channels. This can start to re-build the dimension, pattern and profile of the stable river.

Carrying capacities of riparian ecosystems are not well understood, however, when major species are eliminated from the composition, it is evident that natural balances are "out of balance". Grazing ungulates can occur in a mutual, stable, co-existence with riparian ecosystems and be compatible with river stability. Fall River, a C4 stream type with a dense willow stand, in Rocky Mountain National Park is an example of such a coexistence. The Lawn Lake flood several years ago which was a major flood, brought thousands of tons of sediment down the mountain immediately upstream of the river. The stream did not change its dimension, pattern, profile or stability as a result. If the stream type did not have the healthy riparian system, corresponding low width/depth ratio and proper distribution of shear stress, Fall river would not be stable today following that flood and very high sediment supply. Streams have evolved to handle large amounts of sediment, however their patterns, dimensions and profiles must be maintained so that as streams are self made, they also can be self-maintained.

## LIST OF FIGURES

Figure 13. Weminuche River in Colorado (C4 stream type) showing change in channel stability, pattern, dimension, and bank erosion due to a willow/grass conversion.

Figure 14. Contrast of late fall/winter grazing-heavy stocking on C4 stream type showing conversion to a grass/forb riparian community from a willow/grass community

Figure 15. Goose Creek, Colorado, upstream (lower left photo) and 900 feet downstream (below) on C4 stream type showing effects on bank stability and channel shape due to willow conversion from grazing impacts.

Figure 16a. Lamar River, 1921 Haynes photograph showing willow covered streambanks(Kay, 1990)

Figure 16b. Lamar river replicate photo, 1988 showing loss of willows in composition (Kay, 1990).

Figure 17a. Soda Butte Creek, 1896, photo by Bradley, showing tall willows along creek (Kay, 1990).

Figure 17b. Replicate photo of Soda Butte Creek, 1988, showing loss of willows from the Creek (Kay,1990).

Figure 18a. Photo by Haynes, 1893 of Yancy's hole showing tall willow (Kay, 1990).

Figure 18b. Replicate photo of Yancy's hole, 1988, showing loss of willows from stand(Kay,1990).

Figure 19. Aerial photo overlay showing change in dimension, pattern and slope due to channel adjustment/lateral migration.

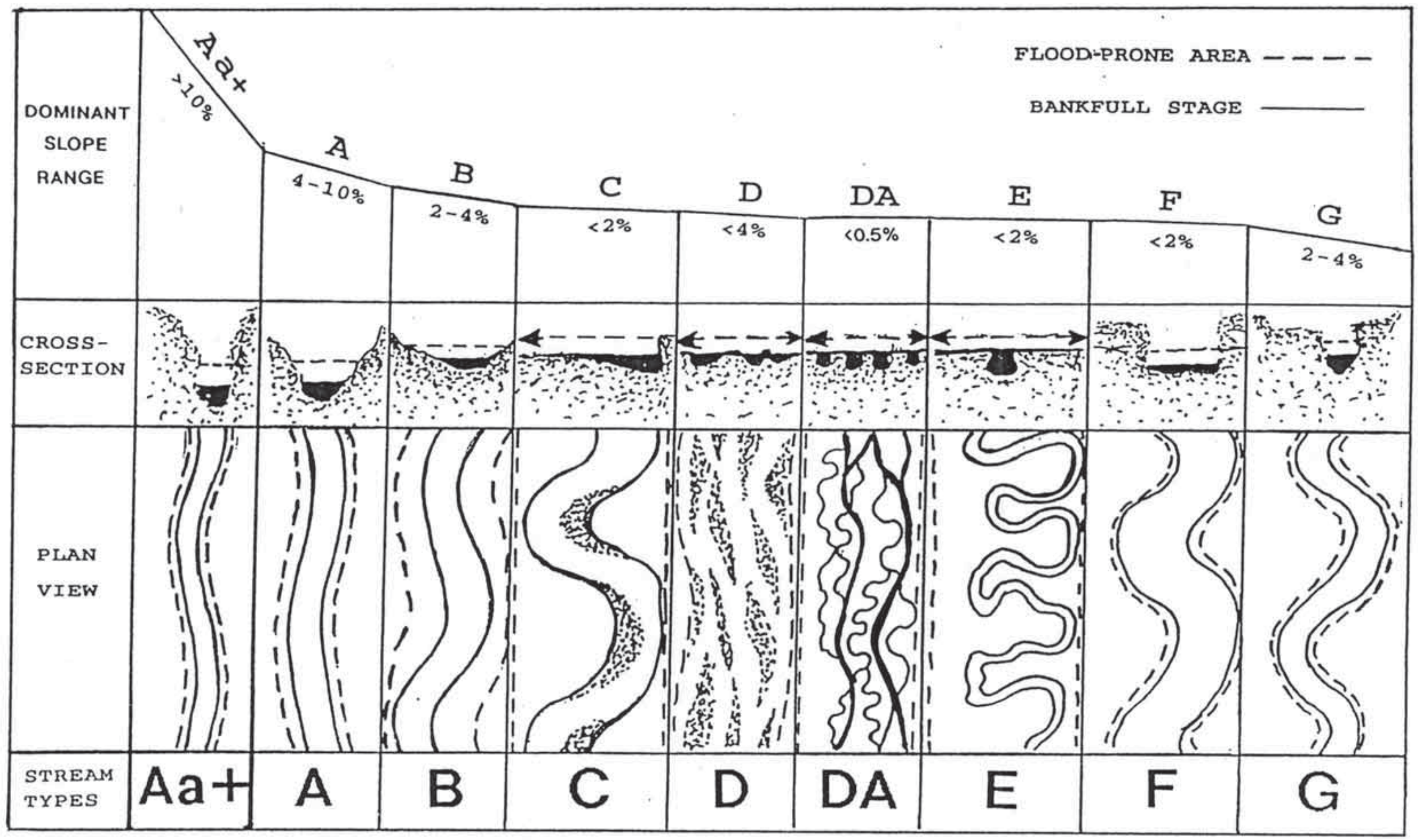



Figure 1. Longitudinal, cross-sectional and plan views of major stream types.

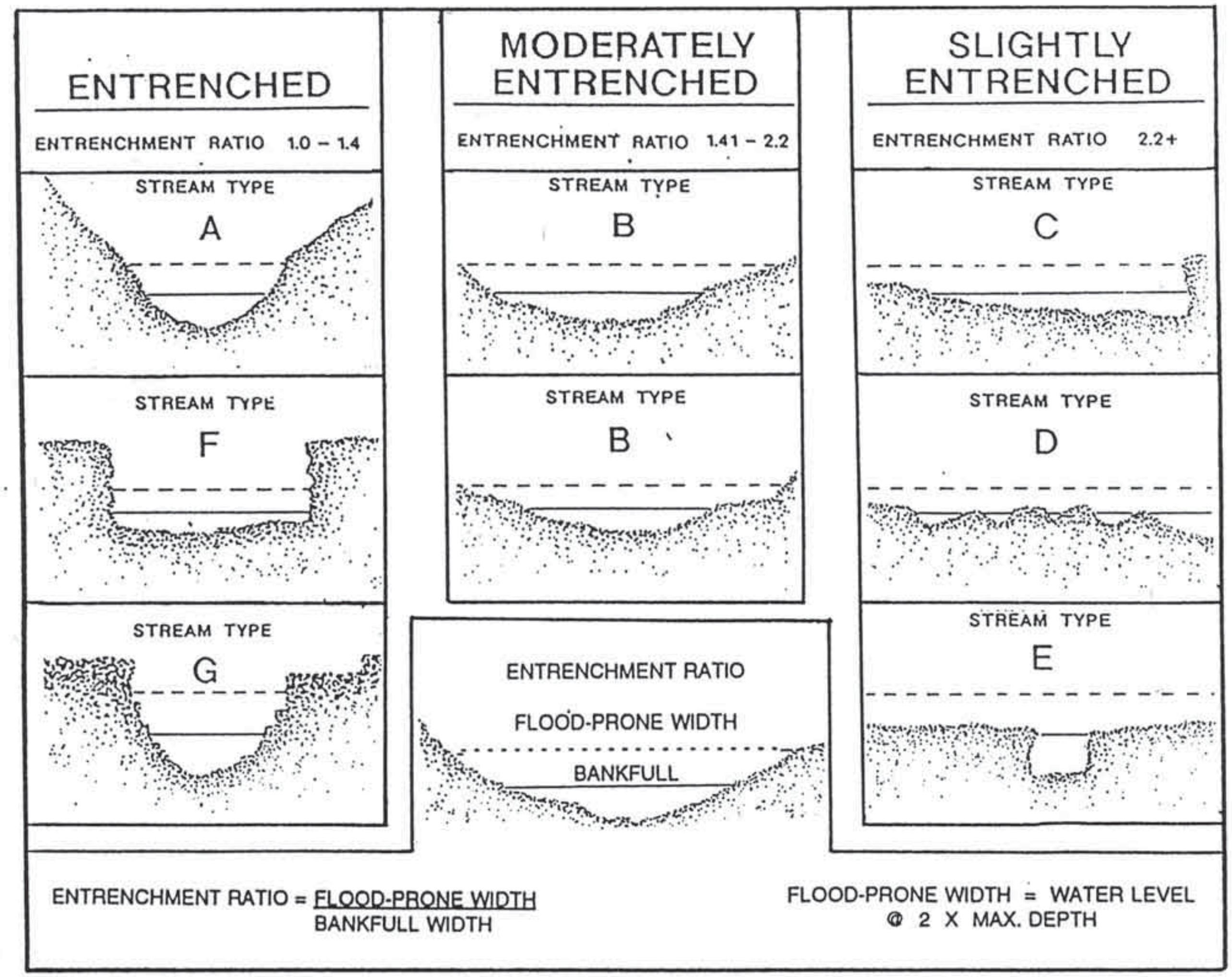



Figure 2. Example and calculation of entrenchment ratio.

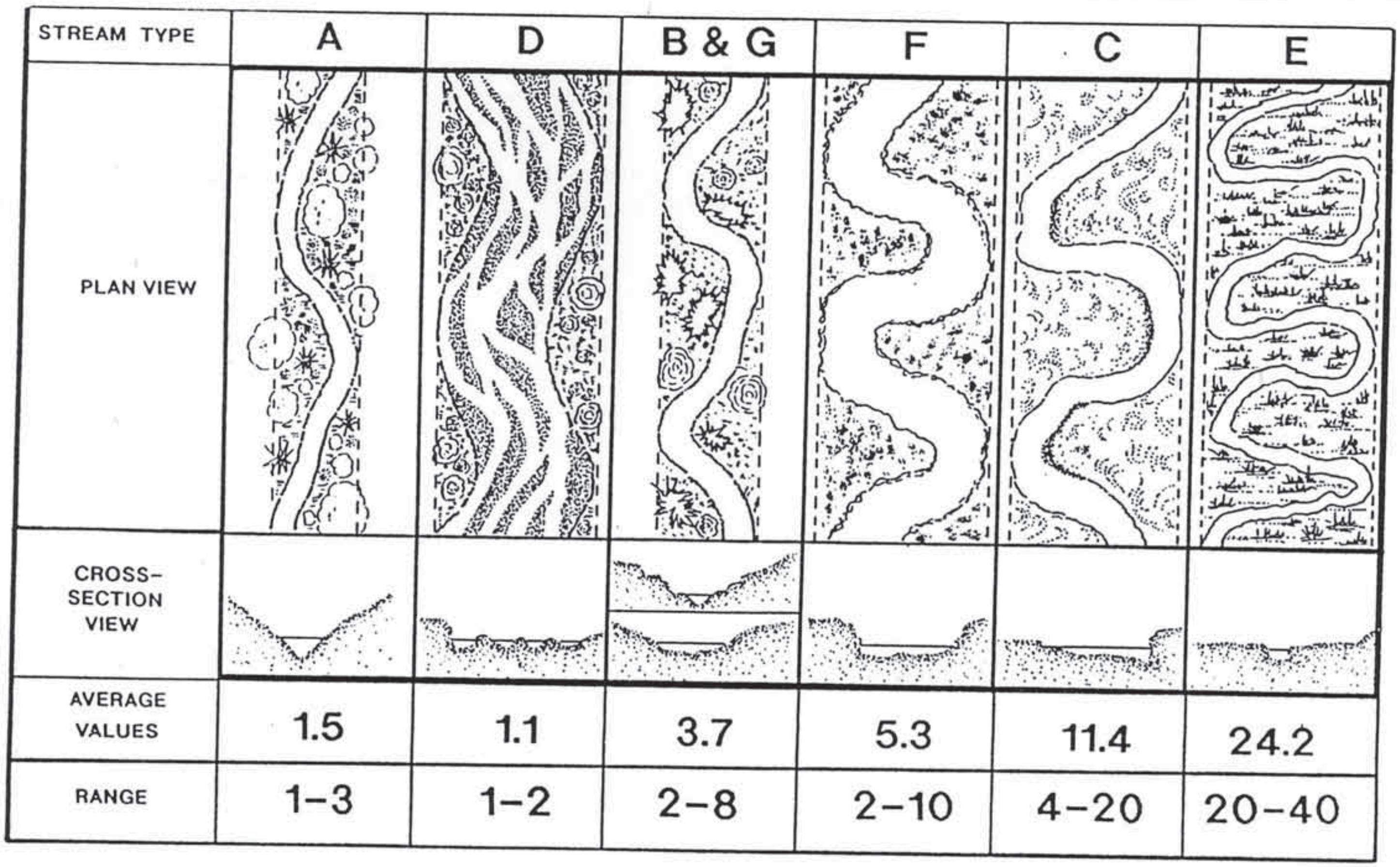
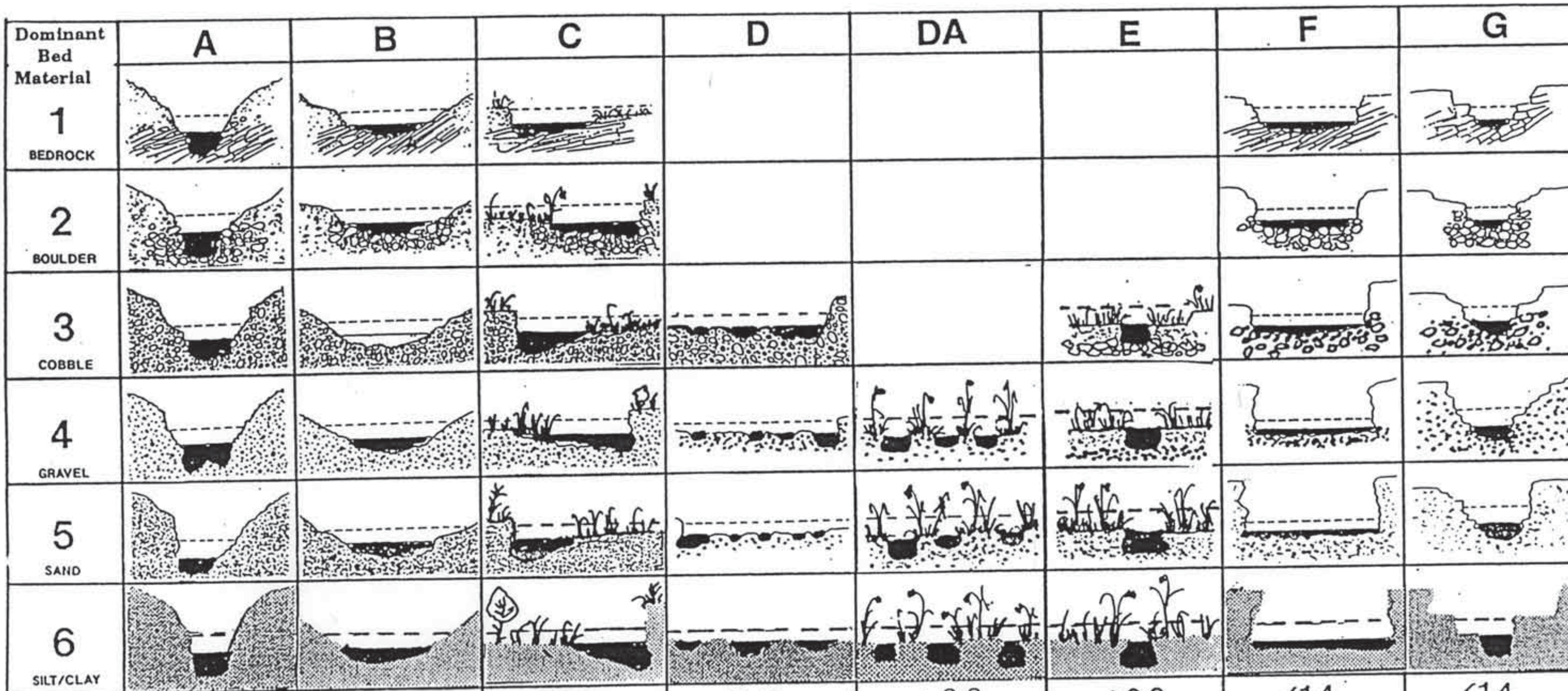
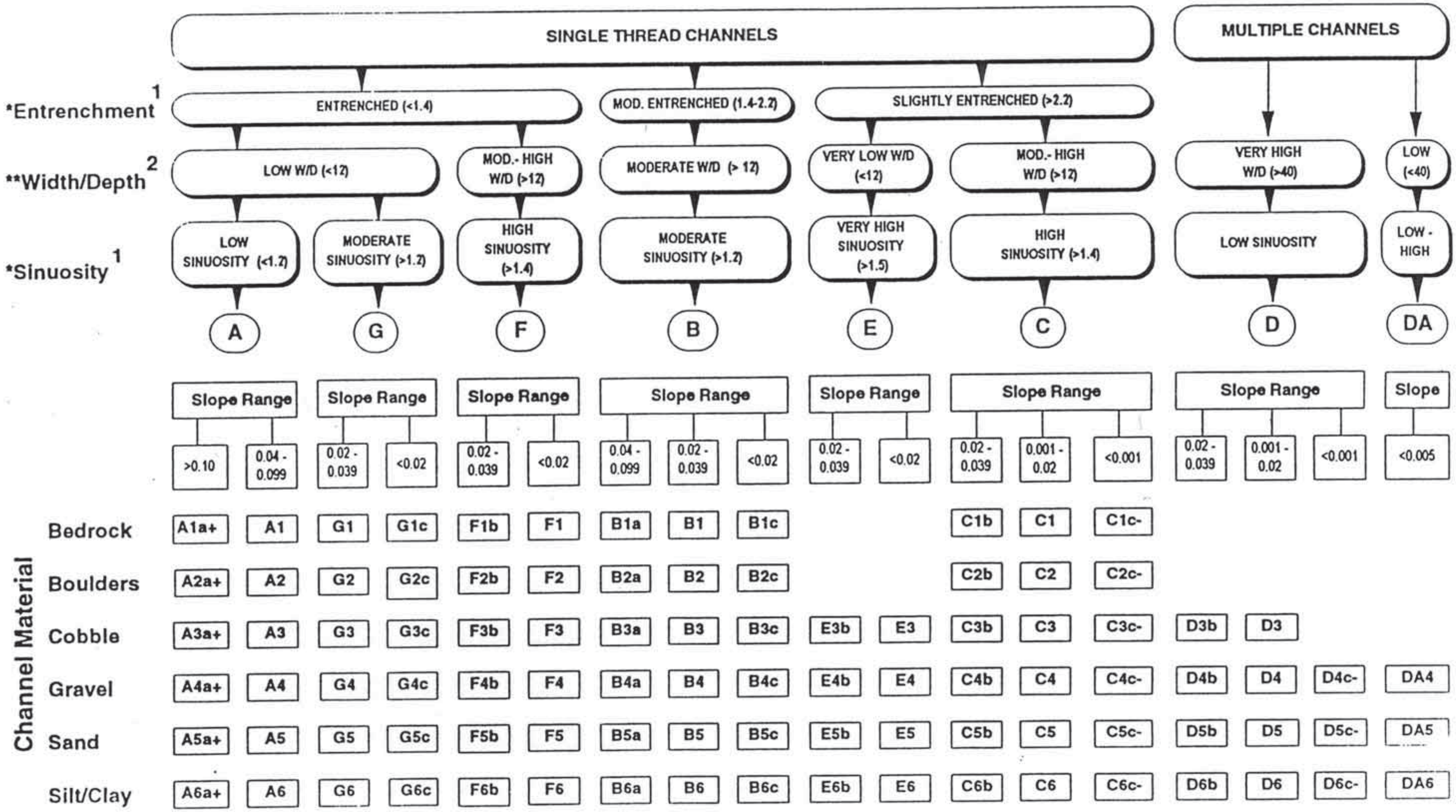



Figure 3. Meander width ratio by stream type categories




| | A | B | C | D | DA | E | F | G |
|---|---|---|---|---|---|---|---|---|
| ENTRH. | <1.4 | 1.4–2.2 | >2.2 | N/A | >2.2 | >2.2 | <1.4 | <1.4 |
| SIN. | <1.2 | >1.2 | >1.4 | <1.1 | 1.1-1.6 | >1.5 | >1.4 | >1.2 |
| W/D | <12 | >12 | >12 | >40 | <40 | <12 | >12 | <12 |
| SLOPE | .04–.099 | .02–.039 | <.02 | <.02 | <.005 | <.02 | <.02 | .02–.039 |

Figure 4. Illustrative guide showing cross-sectional configuration, composition and delineative criteria of major stream types.




1 Values can vary by ± 0.2 units as a function of the continuum of physical variables within stream reaches.
2 Values can vary by ± 2.0 units as a function of the continuum of physical variables within stream reaches.

Figure 5. Key to classification of natural rivers.

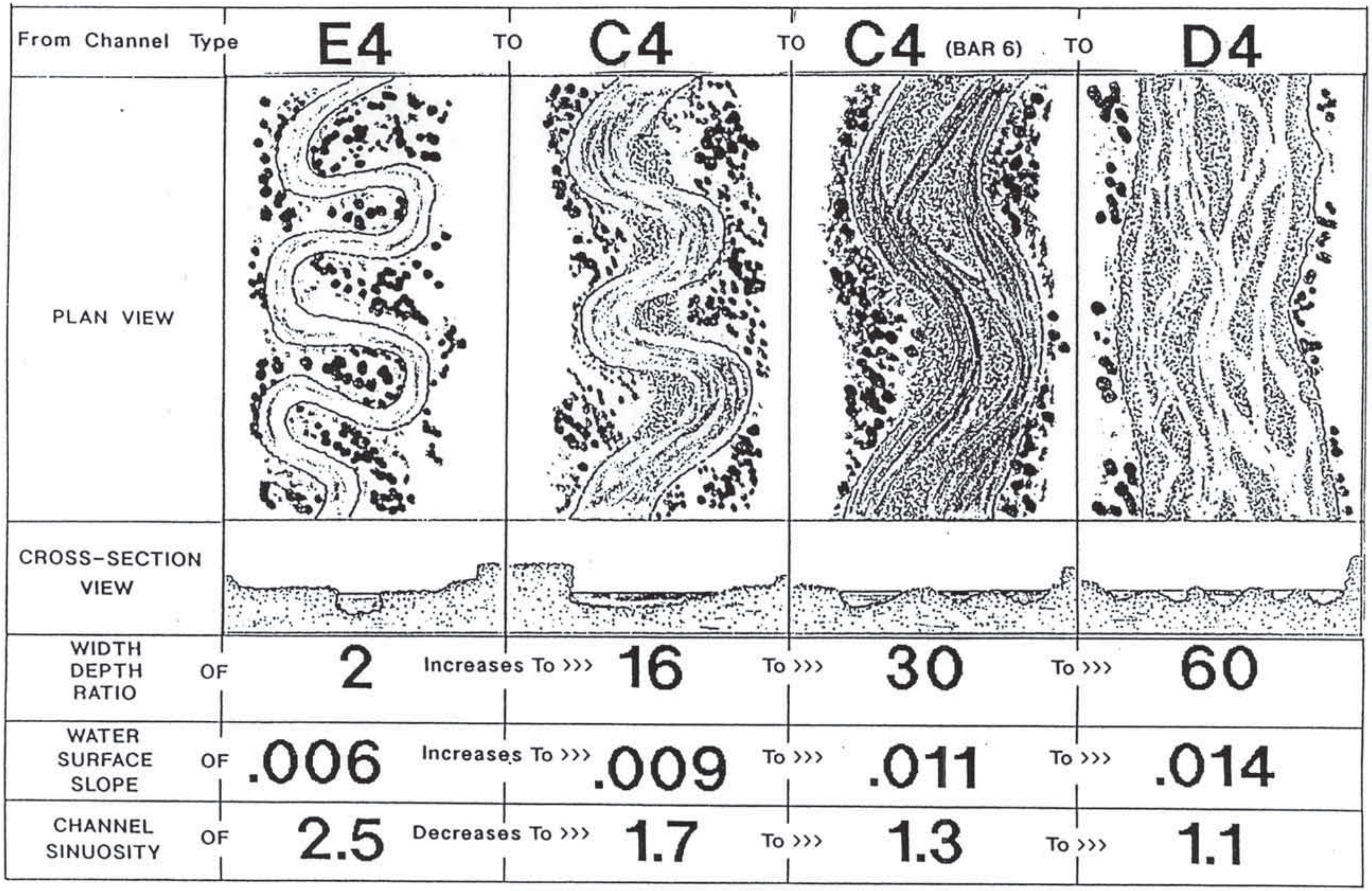



Figure 6. Progressive stages of channel adjustment due to imposed streambank instability.

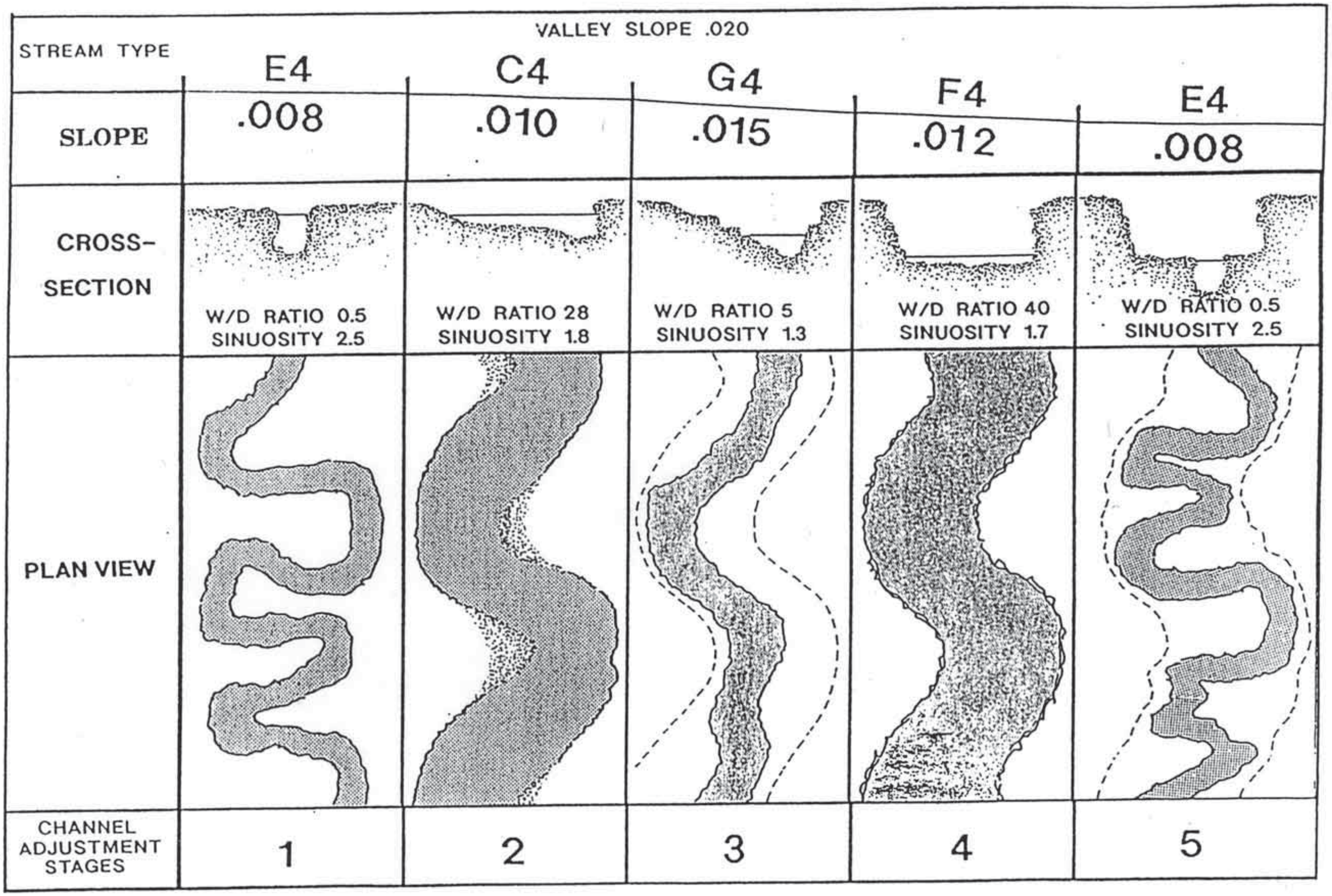



Figure 7. Evolutionary stages of channel adjustment.

Figure 8. Comparison of streambank erodibility (low vs high erodibility) for C4 stream types. (lower photo is lower Soda Butte Creek).

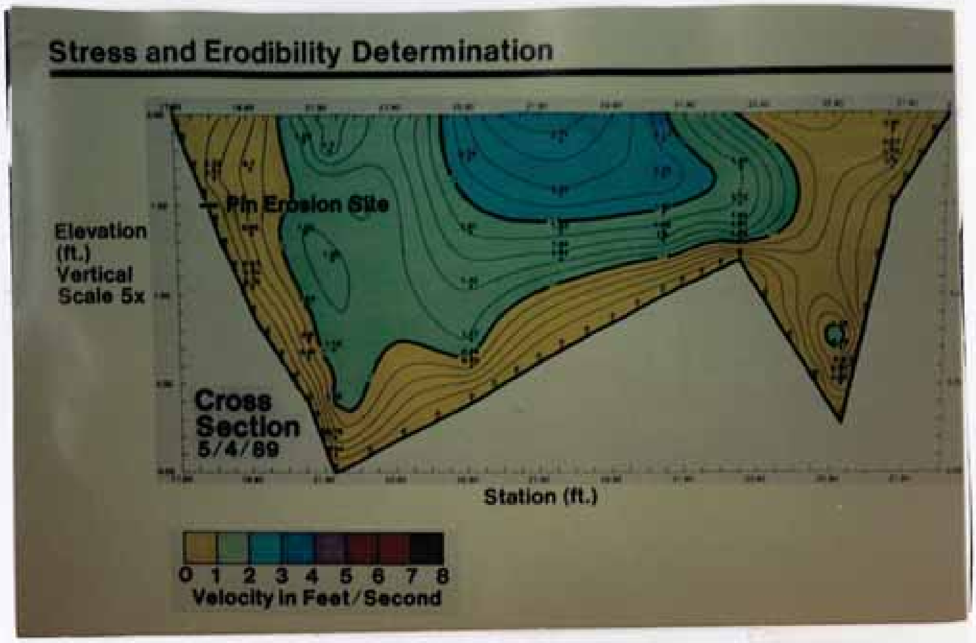
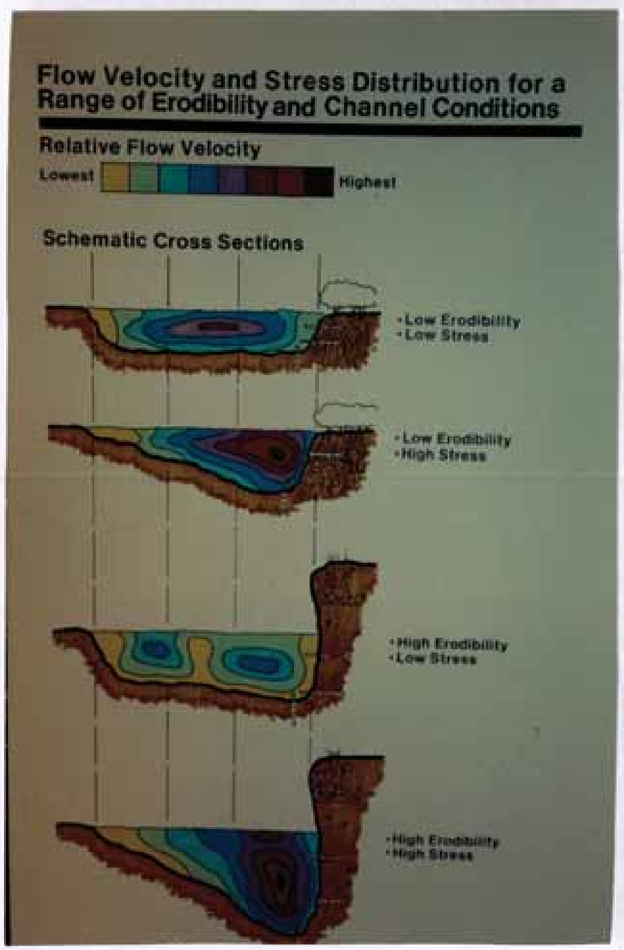



Figure 9. Velocity isovel showing distribution of velocity in the near-bank region (Rosgen, 1990).



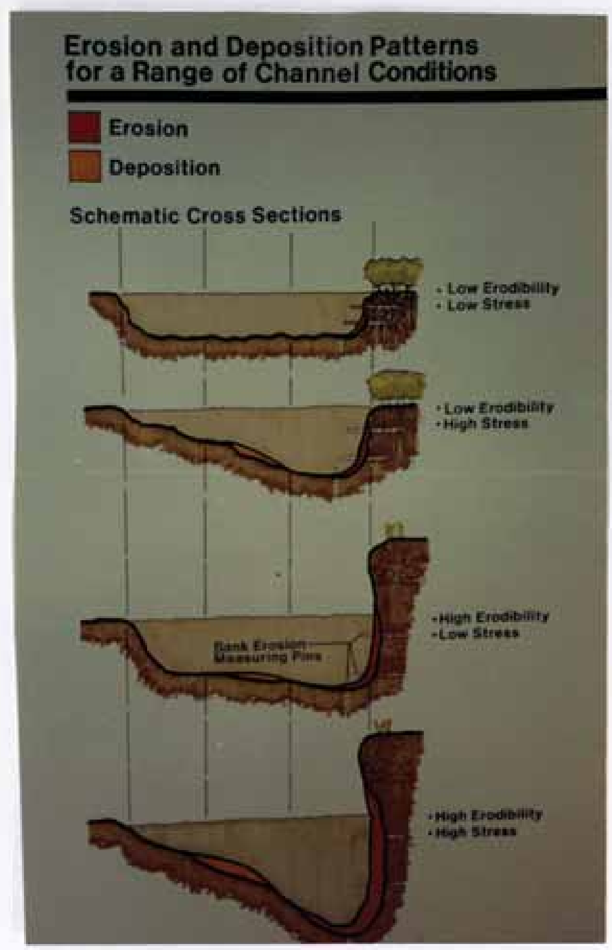




Figure 10. Velocity distribution for a range of streambank erodibilities and channel configurations (Rosgen, 1990).

Figure 11. Erosion and deposition patterns for a range of different channel conditions

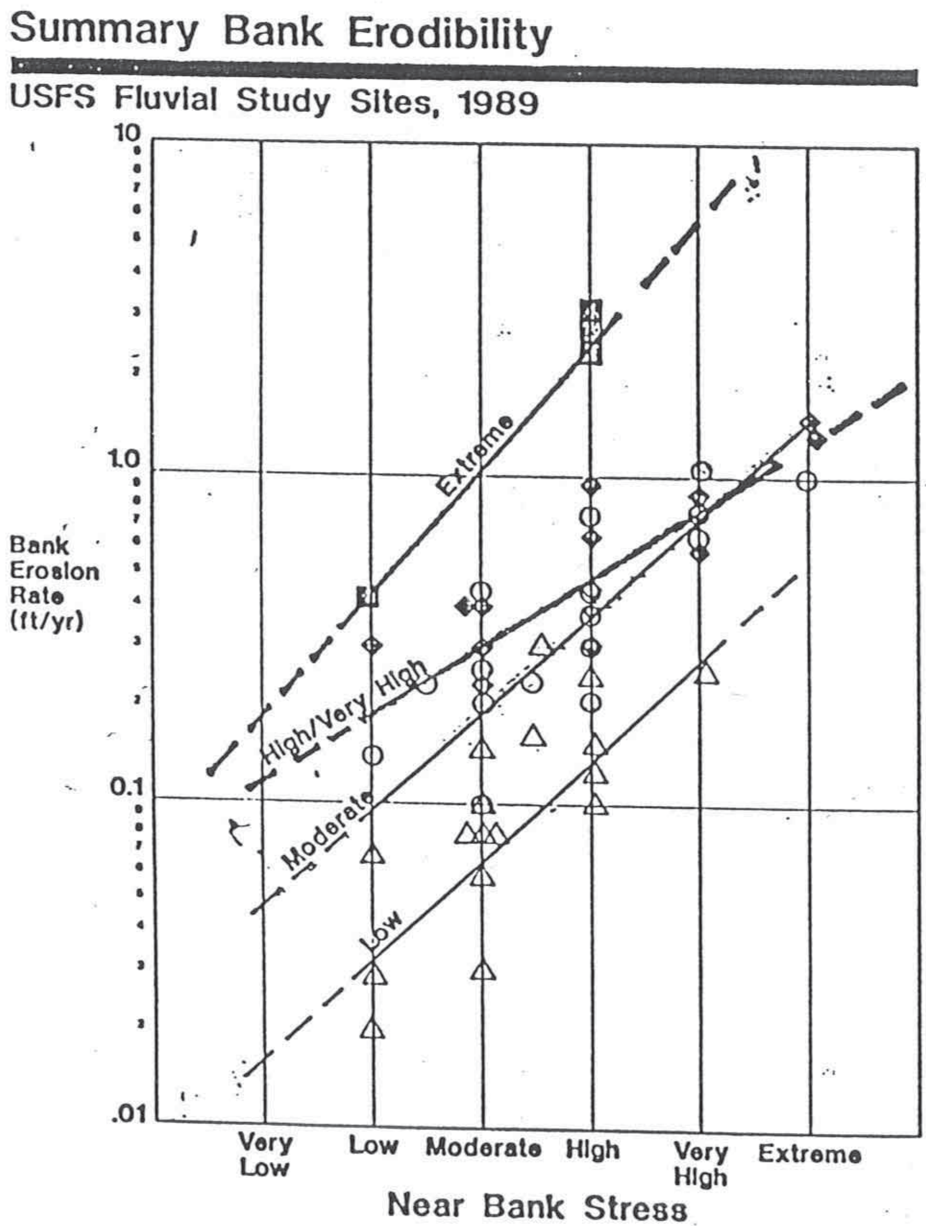



Figure 12. Relationship of streambank erodibility and stress in the near-bank region vs measured stream bank erosion rate - Colorado (Rosgen, 1990).

Figure 13. Weminuche River in Colorado (C4 stream type) showing change in channel stability, pattern, dimension, and bank erosion due to a willow/grass conversion.

← Figure 14.

Contrast of late fall/winter grazing-heavy stocking on C4 stream type showing conversion to a grass/forb riparian community from a willow/grass community

Figure 15. ↓

ose Creek, Colorado, upstream (lower left oto) and 900 feet downstream (below) on C4 ream type showing effects on bank stability and channel shape due to willow conversion from grazing impacts.

Figure 16a. Lamar River, 1921 Haynes photograph showing willow covered streambanks(Kay, 1990)

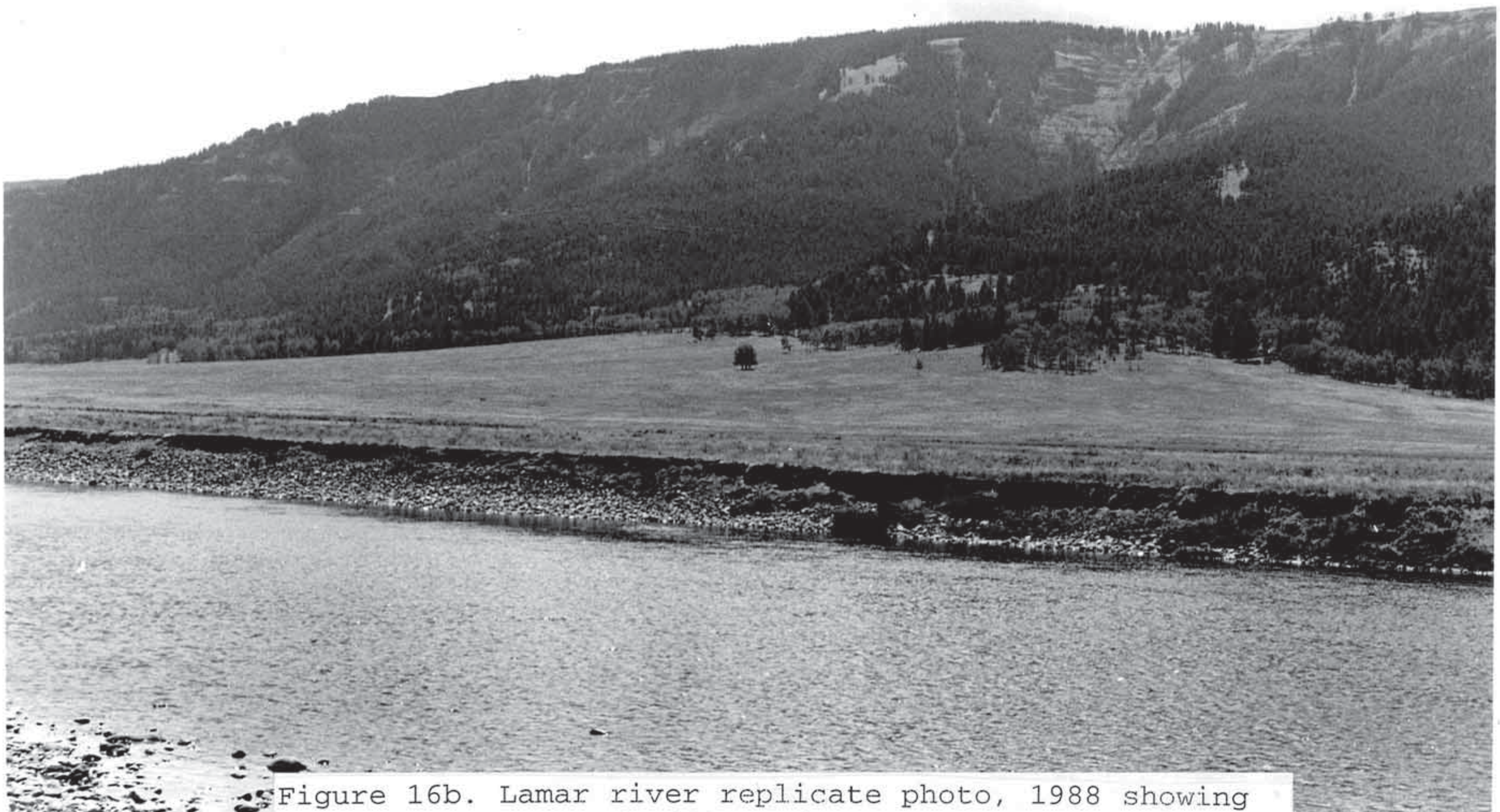


Figure 16b. Lamar river replicate photo, 1988 showing loss of willows in composition (Kay, 1990).

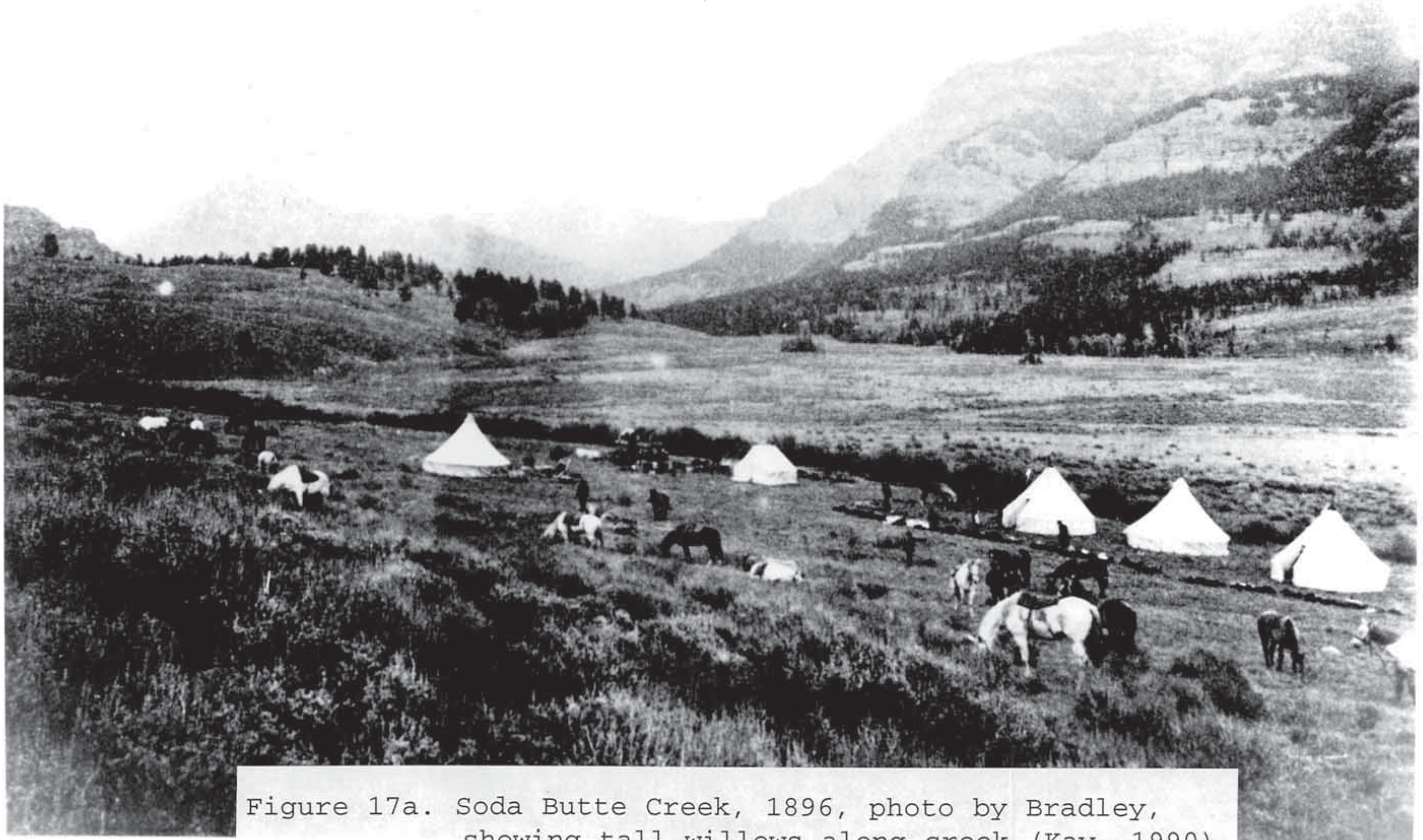


Figure 17a. Soda Butte Creek, 1896, photo by Bradley, showing tall willows along creek (Kay, 1990).

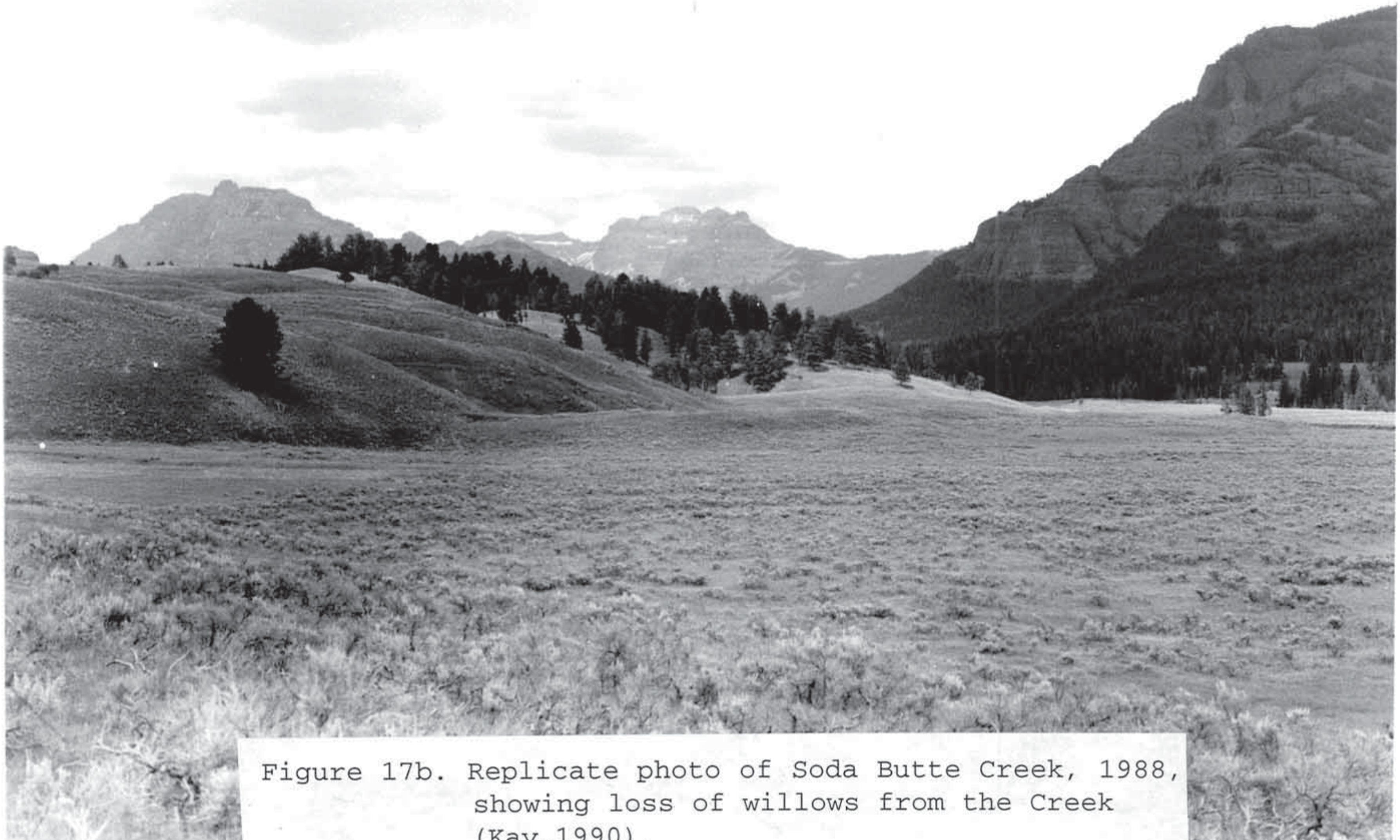


Figure 17b. Replicate photo of Soda Butte Creek, 1988, showing loss of willows from the Creek (Kay, 1990).

Figure 18a. Photo by Haynes, 1893 of Yancy's hole showing tall willow (Kay, 1990).

Figure 18b. Replicate photo of Yancy's hole, 1988, showing loss of willows from stand(Kay,1990).

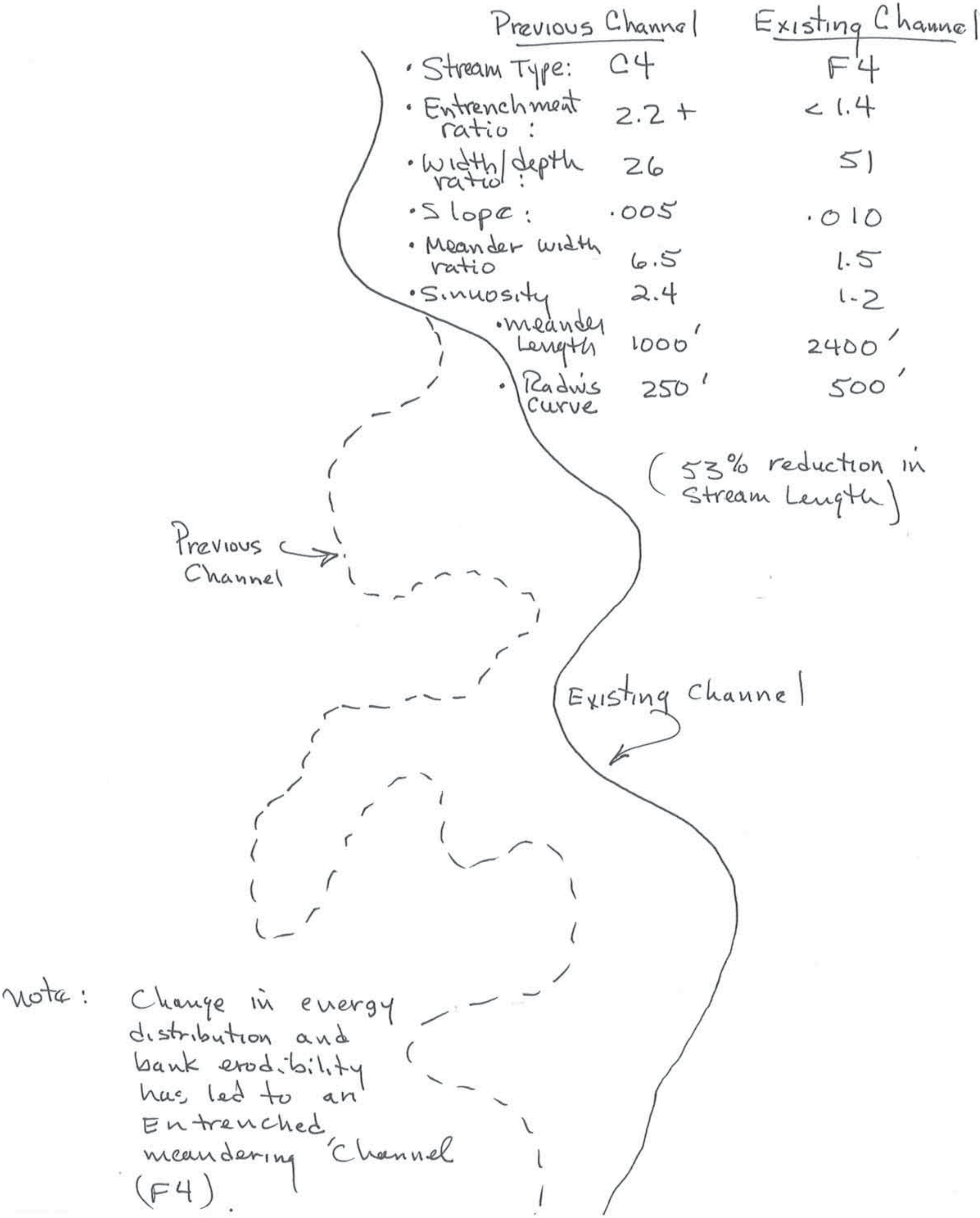



Figure 19. Aerial photo overlay showing change in dimension, pattern and slope due to channel adjustment/lateral migration.

Figure 20. Soda Butte Creek site #1, bank erodibility BEH: Very high, Stress: high, Bank erosion rate: lost 3 ft. pin.

Figure 21. Soda Butte Creek, Site #2 BEH:Very High, Stress: Very High. Bank erosion rate:, lost 3 foot erosion pin.

Figure 22. Soda Butte Creek # 5, BEH: Very High, Stress: High, Bank erosion rate:, lost 3 foot pin.

Figure 24. Soda Butte Creek #7, BEH: extreme, Stress: moderate + erosion rate: 1.2 feet/ year.

Figure 25. Upper Soda Butte Creek # 12 with willow bank. BEH: low, stress: moderate, bank erosion rate 0.1 ft./yr.

Figure 26. Lamar River # 1, BEH: Very high, Stress: Low, Erosion rate: 0.78 feet/year (note: exposed erosion pin).

Figure 27. Roy Ewing,NPS, at lower Lamar River site #2 with BEH: Very High, Stress: High, Erosion rate: 2.0/0.9, ave.: 1.5 ft./yr.

Figure 28. Lower Lamar River #5 Beh: Very High, Stress: Low, Bank erosion rate: 0.76 ft./yr.

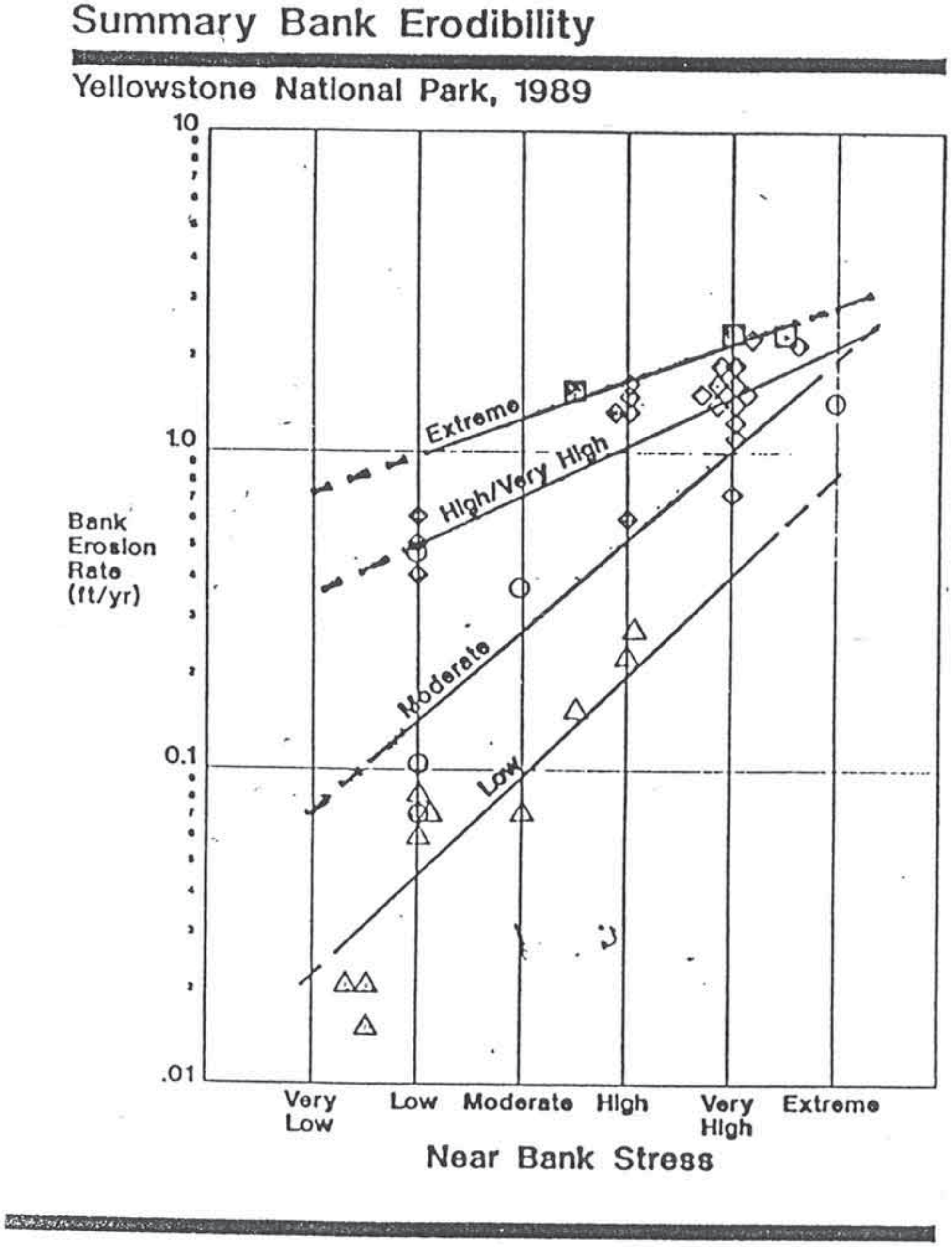



Figure 29. Relationship of dependent variable, bank erosion rate vs. the independent variables of near-bank stress and stream bank erodibility

**LIST OF TABLES**

Table 1. Summary of delineative criteria for broad-level classification.

| Stream Type | General Description | Entrenchment Ratio | W/D Ratio | Sinuosity | Slope | Landform/Soils/Features |
|---|---|---|---|---|---|---|
| Aa+ | Very steep, deeply entrenched ,debris transport streams. | <1.4 | <12 | 1.0 to 1.1 | >.10 | Very high relief. Erosional, bedrock or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with/deep scour pools; waterfalls. |
| A | Steep, entrenched, cascading, step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel. | <1.4 | <12 | 1.0 to 1.2 | .04 to .10 | High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step-pool bed morphology. |
| B | Moderately entrenched, moderate gradient, riffle dominated channel, with infrequently spaced pools. Very stable plan and profile. Stable banks. | 1.4 to 2.2 | >12 | >1.2 | .02 to .039 | Moderate relief, colluvial deposition and/or residual soils. Moderate entrenchment and W/D ratio. Narrow, gently sloping valleys. Rapids predominate w/occasional pools. |
| C | Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad,well defined floodplains | >2.2 | >12 | <1.4 | <.02 | Broad valleys w/terraces, in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channel. Riffle-pool bed morphology. |
| D | Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks. | n/a | >40 | n/a | <.04 | Broad valleys with alluvial and colluvial fans. Glacial debris and depositional features. Active lateral adjustment, w/abundance of sediment supply. |
| DA | Anastomosing (multiple channels) narrow and deep with expansive well vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. stable streambanks. | >4.0 | <40 | variable | <.005 | Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomosed (multiple channel) geologic control creating fine deposition w/well-vegetated bars that are laterally stable with broad wetland floodplains. |
| E | Low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander width ratio. | >2.2 | <12 | >1.5 | <.02 | Broad valley/meadows. Alluvial materials with floodplain. Highly sinuous with stable, well vegetated banks. Riffle-pool morphology with very low width/depth ratio. |
| F | Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio. | <1.4 | <12 | >1.4 | <.02 | Entrenched in highly weathered material. Gentle gradients, with a high W/D ratio. Meandering, laterally unstable with high bank-erosion rates. Riffle-pool morphology. |
| G | Entrenched "gulley" step/pool and low width/depth ratio on moderate gradients. | <1.4 | <12 | >1.2 | .02 to .039 | Gulley, step-pool morphology w/moderate slopes and low W/D ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials; i.e., fans or deltas. Unstable, with grade control problems and high bank erosion rates. |

Table 2a. Distribution of stream types by mainstem Lamar River and major tributaries.

SUB-DRAINAGES

| | TIMOTHY | SLOUGH | CACHE | MILLER | CALFEE | COLD |
|---|---|---|---|---|---|---|
| Stream Type | River/mi. | River/mi. | River mi. | River/mi. | River/mi. | River/mi . |
| A1 | | 0.8 | | | | 0.6 |
| A2 | | 1.8 | 1.1 | 10.9 | 7.7 | 1.2 |
| A3 | 6.8 | 21.0 | 3.3 | | | 5.6 |
| B1/B2 | | 0.9 | | | | |
| B3 | 7.8 | 10.9 | 11.0 | 4.5 | | 6.2 |
| B4 | | 1.0 | 2.6 | | 8.5 | |
| C3 | 0.5 | | 1.7 | | | |
| C4 | | 13.9 | 5.4 | 9.4 | | |
| D3 | | 0.5 | | | | |
| D4 | | | | | | |
| E3 | | 2.1 | | | | |
| E4 | 1.2 | | | | | |
| F3 | 1.0 | | | | | 0.6 |
| F4 | | 15.6 | | | | |
| G4 | 0.9 | | | | | |
| TOTALS | 18.2 | 68.5 | 25.1 | 24.8 | 16.2 | 14.2 |

Table 2b. Distribution of stream types, con't.

SUB-DRAINAGES

| | MIST CR. | LITTLE LAM. | SODA BT. | LAMAR RIV. | TOTALS | PRCNT |
|---|---|---|---|---|---|---|
| Stream Type | Miles | Miles | Miles | Miles | Miles | % |
| A1 | | 1.6 | | | 3.0 | 0.3 |
| A2 | | | | | 23.0 | 2.0 |
| A3 | 2.5 | 6.9 | 27.0 | 19.4 | 941 | 76.5 |
| B1/B2 | | 0.5 | 0.3 | | 1.7 | .2 |
| B3 | 6.2 | 2.8 | 5.9 | 16.6 | 82.2 | 6.8 |
| B4 | | | | | 3.6 | 0.3 |
| C3 | 0.9 | 2.1 | 5.5 | 3.4 | 35.1 | 2.0 |
| C4 | 0.9 | | 20.4 | 13.1 | 53.7 | 4.0 |
| D3 | | 1.9 | 1.4 | 7.8 | 11.6 | 1.0 |
| D4 | | | 7.0 | 6.3 | 13.3 | 1.1 |
| E3 | 6.7 | | | | 12.8 | 1.0 |
| E4 | | | 4.0 | | 1.2 | 0.1 |
| F3 | 0.5 | 1.8 | | 10.2 | 30.3 | 2.6 |
| F4 | | | | 9.8 | 25.4 | 2.0 |
| G4 | | 0.5 | | | 1.4 | 0.1 |
| TOTALS | 17.7 | 17.6 | 71.5 | 86.6 | 1,239.3 | 100.0 |

Table 3. Management interpretations of various stream types.

| Stream Type | Sensitivity to Disturbance[1] | Recovery Potential[2] | Sediment Supply[3] | Streambank Erosion Potential | Vegetation Controlling Influence[4] |
|---|---|---|---|---|---|
| A1 | very low | excellent | very low | very low | negligible |
| A2 | very low | excellent | very low | very low | negligible |
| A3 | very high | very poor | very high | high | negligible |
| A4 | extreme | very poor | very high | very high | negligible |
| A5 | extreme | very poor | very high | very high | negligible |
| A6 | high | poor | high | high | negligible |
| B1 | very low | excellent | very low | very low | negligible |
| B2 | very low | excellent | very low | very low | negligible |
| B3 | low | excellent | low | low | moderate |
| B4 | moderate | excellent | moderate | low | moderate |
| B5 | moderate | excellent | moderate | moderate | moderate |
| B6 | moderate | excellent | moderate | low | moderate |
| C1 | low | very good | very low | low | moderate |
| C2 | low | very good | low | low | moderate |
| C3 | moderate | good | moderate | moderate | very high |
| C4 | very high | good | high | very high | very high |
| C5 | very high | fair | very high | very high | very high |
| C6 | very high | good | high | high | very high |
| D3 | very high | poor | very high | very high | moderate |
| D4 | very high | poor | very high | very high | moderate |
| D5 | very high | poor | very high | very high | moderate |
| D6 | high | poor | high | high | moderate |
| DA4 | moderate | good | very low | low | very high |
| DA5 | moderate | good | low | low | very high |
| DA6 | moderate | good | very low | very low | very high |
| E3 | high | good | low | moderate | very high |
| E4 | very high | good | moderate | high | very high |
| E5 | very high | good | moderate | high | very high |
| E6 | very high | good | low | moderate | very high |
| F1 | low | fair | low | moderate | low |
| F2 | low | fair | moderate | moderate | low |
| F3 | moderate | poor | very high | very high | moderate |
| F4 | extreme | poor | very high | very high | moderate |
| F5 | very high | poor | very high | very high | moderate |
| F6 | very high | fair | high | very high | moderate |
| G1 | low | good | low | low | low |
| G2 | moderate | fair | moderate | moderate | low |
| G3 | very high | poor | very high | very high | high |
| G4 | extreme | very poor | very high | very high | high |
| G5 | extreme | very poor | very high | very high | high |
| G6 | very high | poor | high | high | high |

[1] Includes increases in streamflow magnitude and timing and/or sediment increases.
[2] Assumes natural recovery once cause of instability is corrected.
[3] Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.
[4] Vegetation that influences width/depth ratio-stability.

Table 4. Bank erodibility hazard rating guide (Rosgen, 1990).

| | BANK EROSION POTENTIAL | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CRITERIA | VERY LOW | | LOW | | MODERATE | | HIGH | | VERY HIGH | | EXTREME | |
| | VALUE | INDEX | VALUE | INDEX | VALUE | INDEX | VALUE | INDEX | VALUE | INDEX | VALUE | INDEX |
| Bank Ht/Bkf Ht | 1.0-1.1 | 1.0-1.9 | 1.0-1.19 | 2.0-3.9 | 1.2-1.5 | 4.0-5.9 | 1.6-2.1 | 6.0-7.9 | 2.1-2.8 | 8.0-9.0 | >2.8 | 10 |
| Root Depth/Bank Ht | 1.0-0.9 | 1.0-1.9 | 0.89-0.50 | 2.0-3.9 | 0.49-0.30 | 4.0-5.9 | 0.29-0.15 | 6.0-7.9 | 1.14-.05 | 8.0-9.0 | .05 | 10 |
| Root Density (%) | 80-100 | 1.0-1.9 | 55-79 | 2.0-3.9 | 30-54 | 4.0-5.9 | 15-29 | 6.0-7.9 | 5-14 | 8.0-9.0 | <50 | 10 |
| Bank Angle (Degrees) | 0-20 | 1.0-1.9 | 21-60 | 2.0-3.9 | 61-80 | 4.0-5.9 | 81-90 | 6.0-7.9 | 90-119 | 8.0-9.0 | 120+ | 10 |
| Surface Prot. (%) | 80-100 | 1.0-1.9 | 55-79 | 2.0-3.9 | 30-54 | 4.0-5.9 | 15-29 | 6.0-7.9 | 10-15 | 8.0-9.0 | <10 | 10 |
| TOTALS | | | | | | | | | | | | |
| | | 5-9.5 | | 10-19.5 | | 20-29.5 | | 30-39.5 | | 40-45 | | 46-50 |
| Numerical Adjustments | | | | | | | | | | | | |

BANK MATERIALS:

BEDROCK: BANK EROSION POTENTIAL ALWAYS VERY LOW
BOULDERS: BANK EROSION POTENTIAL LOW
COBBLE: DECREASE BY ONE CATEGORY UNLESS MIXTURE OF GRAVEL/SAND IS OVER 50%, THEN NO ADJUSTMENT
GRAVEL: ADJUST VALUES UP BY 5-10 POINTS DEPENDING ON COMPOSITION OF SAND
SAND: ADJUST VALUES UP BY 10 POINTS
SILT/CLAY: NO ADJUSTMENT

STRATIFICATION: 5-10 POINTS (UPWARD) DEPENDING ON POSITION OF UNSTABLE LAYERS IN RELATION TO BANKFULL STAGE

Table 5. Stress in the near-bank region, conversion of numerical indices to adjective ratings.

## CONVERSION OF NUMERICAL INDICES TO ADJECTIVE RATINGS

| Near Bank Stress Rating | Near Bank Stress/Mean Shear Stress* | A nb/A** | Velocity Gradient*** |
|---|---|---|---|
| Low | 1.0-1.2 | .32 or less | .32 or less |
| Moderate | 1.21-1.6 | .33-.41 | .3-.5 |
| High | 1.61-2.0 | .42-.45 | .6-1.0 |
| Very High | 2.1-2.3 | .46-.50 | 1.1-1.3 |
| Extreme | 2.4 or more | .51 or more | 1.4 or more |

*Near bank shear stress/mean shear stress
(shear stress = depth*slope*water density)

**A = cross-sectional area: Near-bank cross-sectional area = width*depth* of 1/3 width of channel in near bank region.

***Velocity gradient in ft/sec/ft is the difference in velocity from the core of velocity isovel along orthogonal length to bank region in feet.

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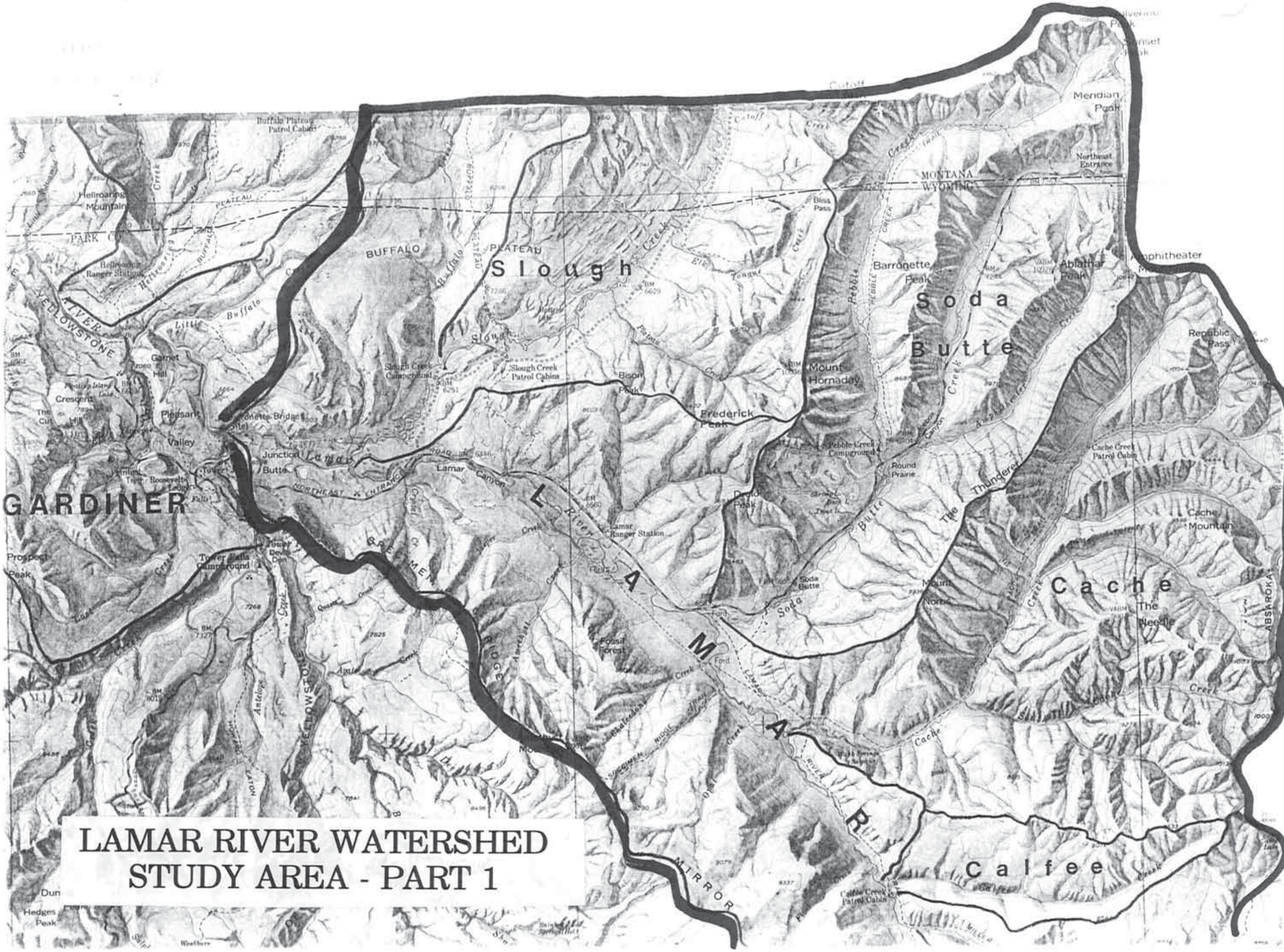
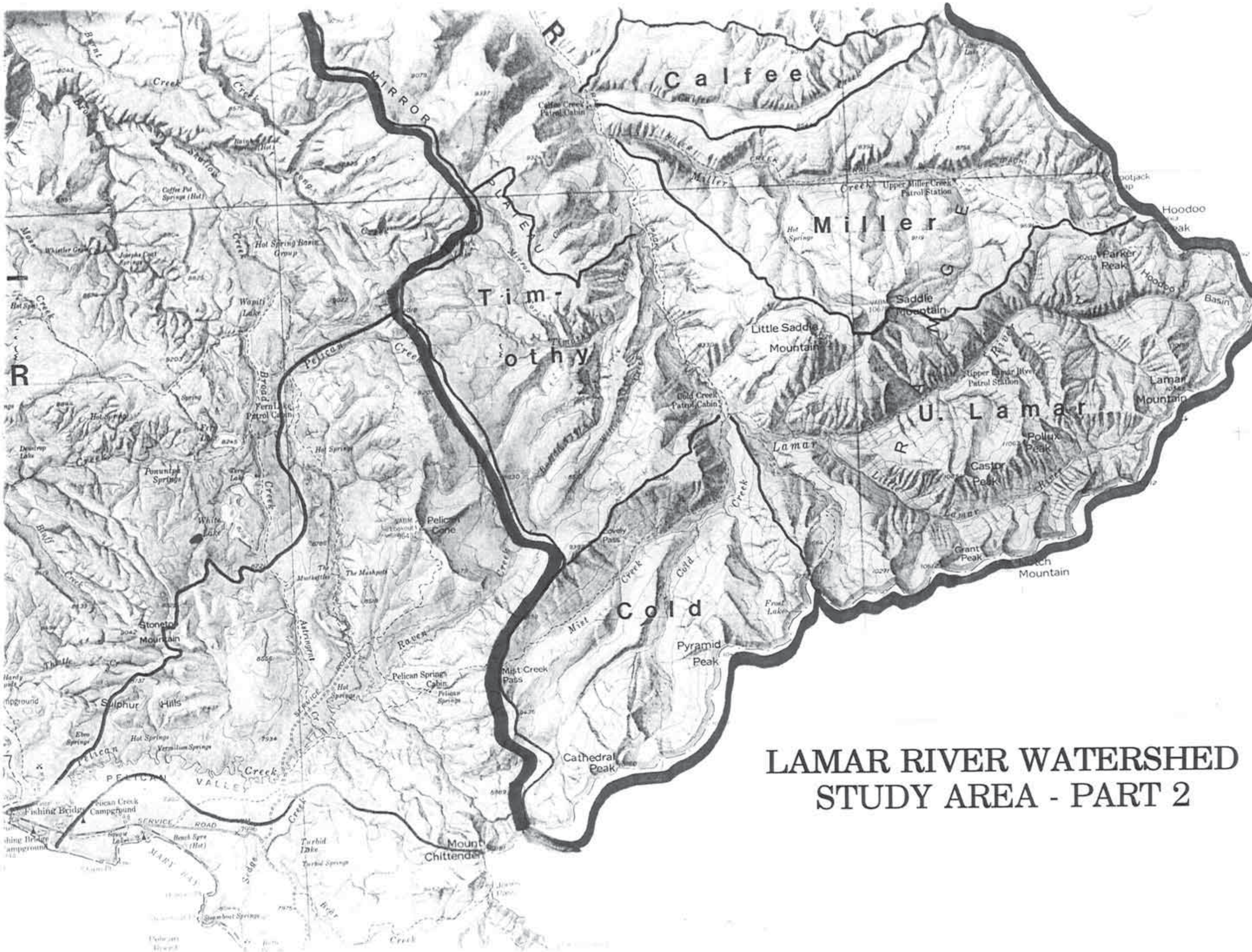
# APPENDIX I

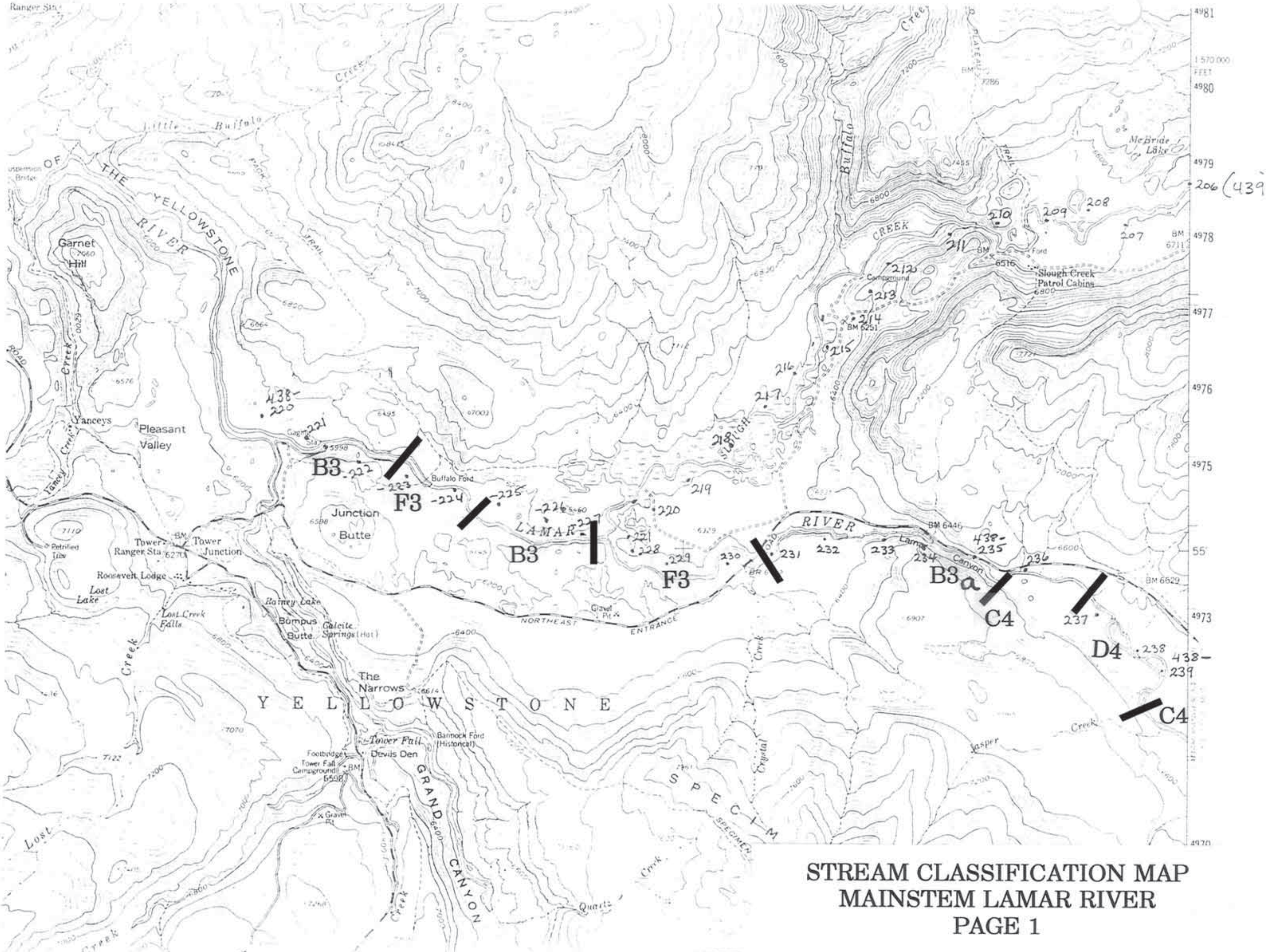
# STREAM CLASSIFICATION MAPPING



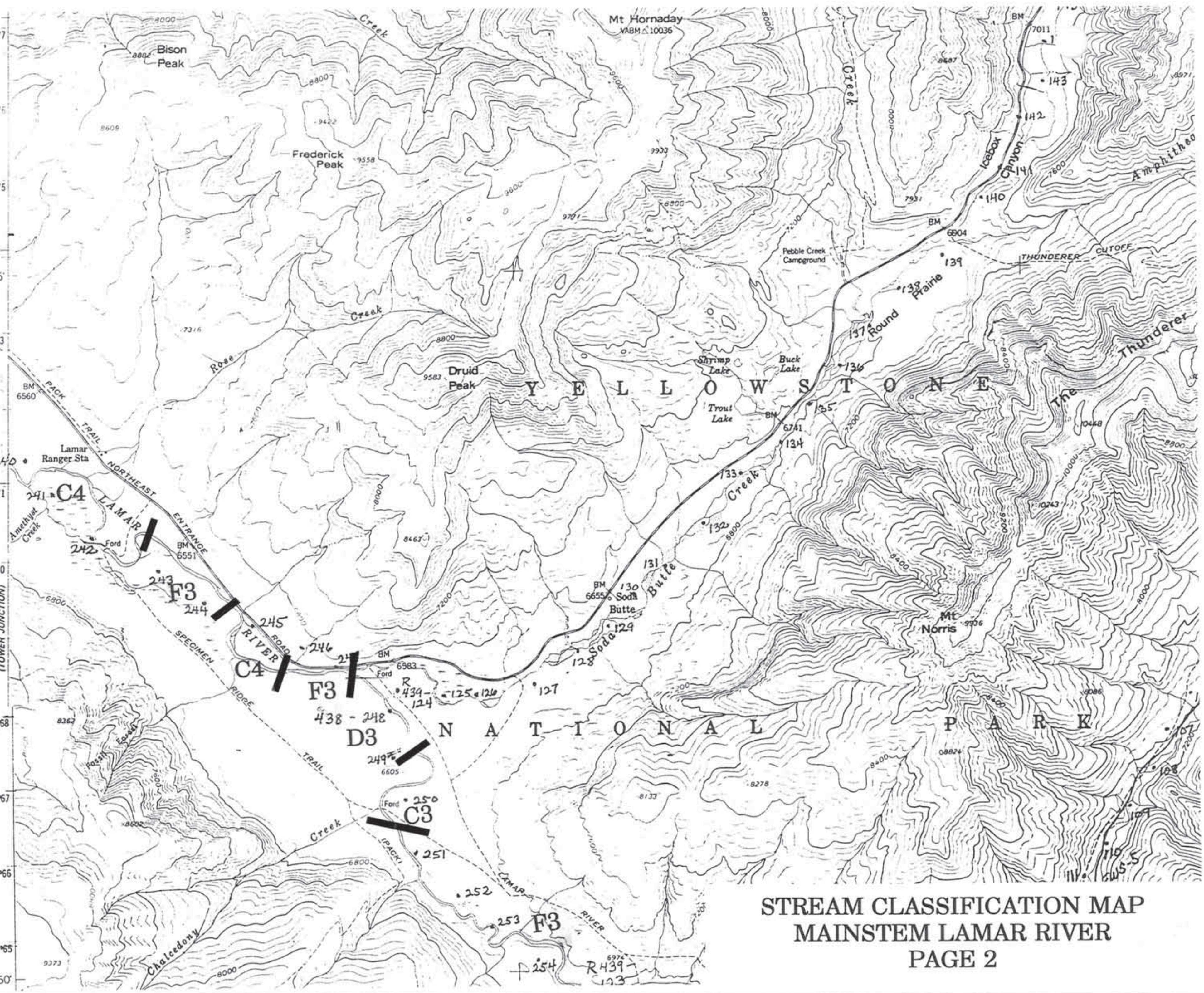
LAMAR RIVER WATERSHED
STUDY AREA - PART 1




LAMAR RIVER WATERSHED
STUDY AREA - PART 2




STREAM CLASSIFICATION MAP
MAINSTEM LAMAR RIVER
PAGE 1

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# MAINSTEM LAMAR RIVER
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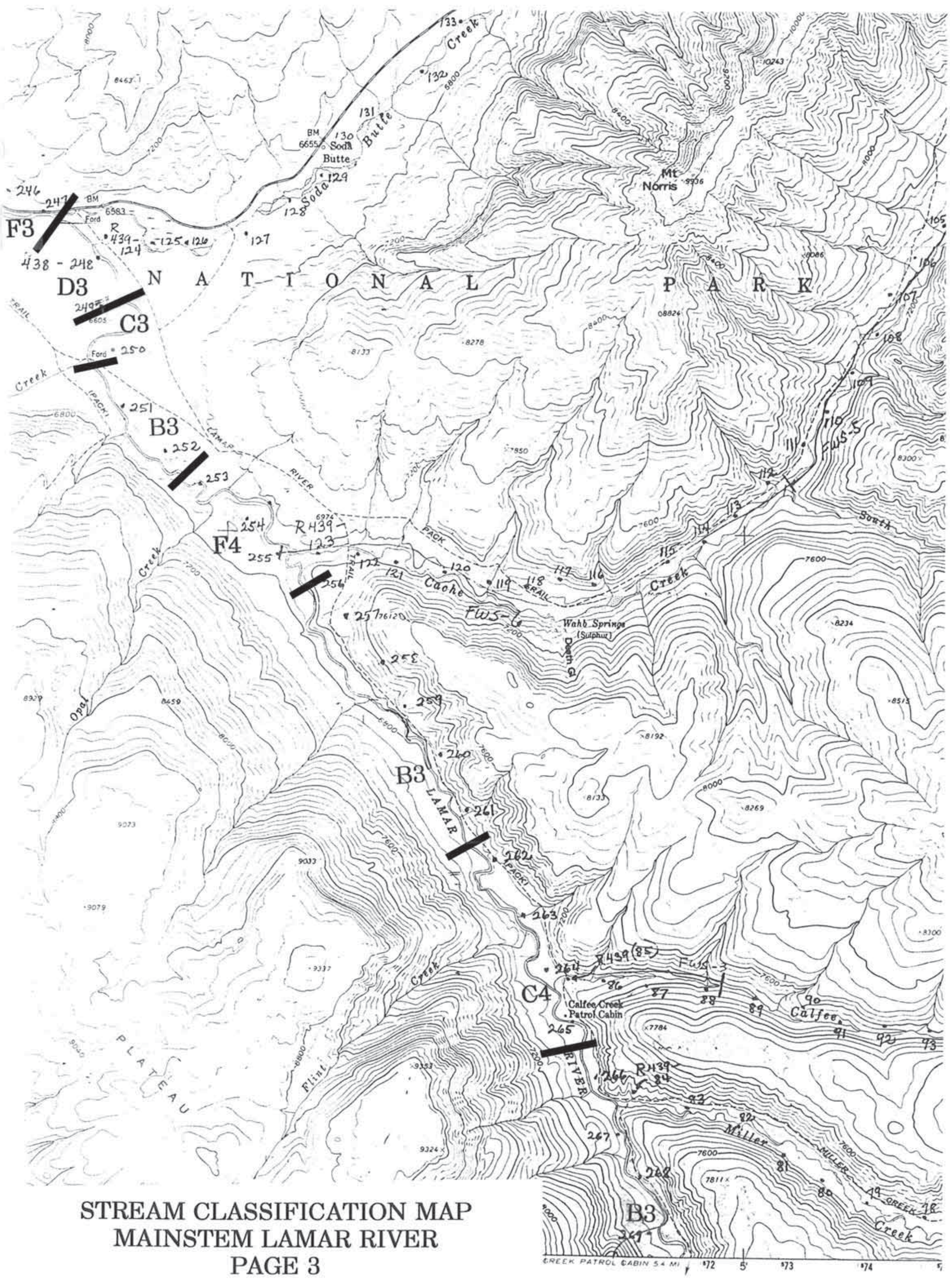
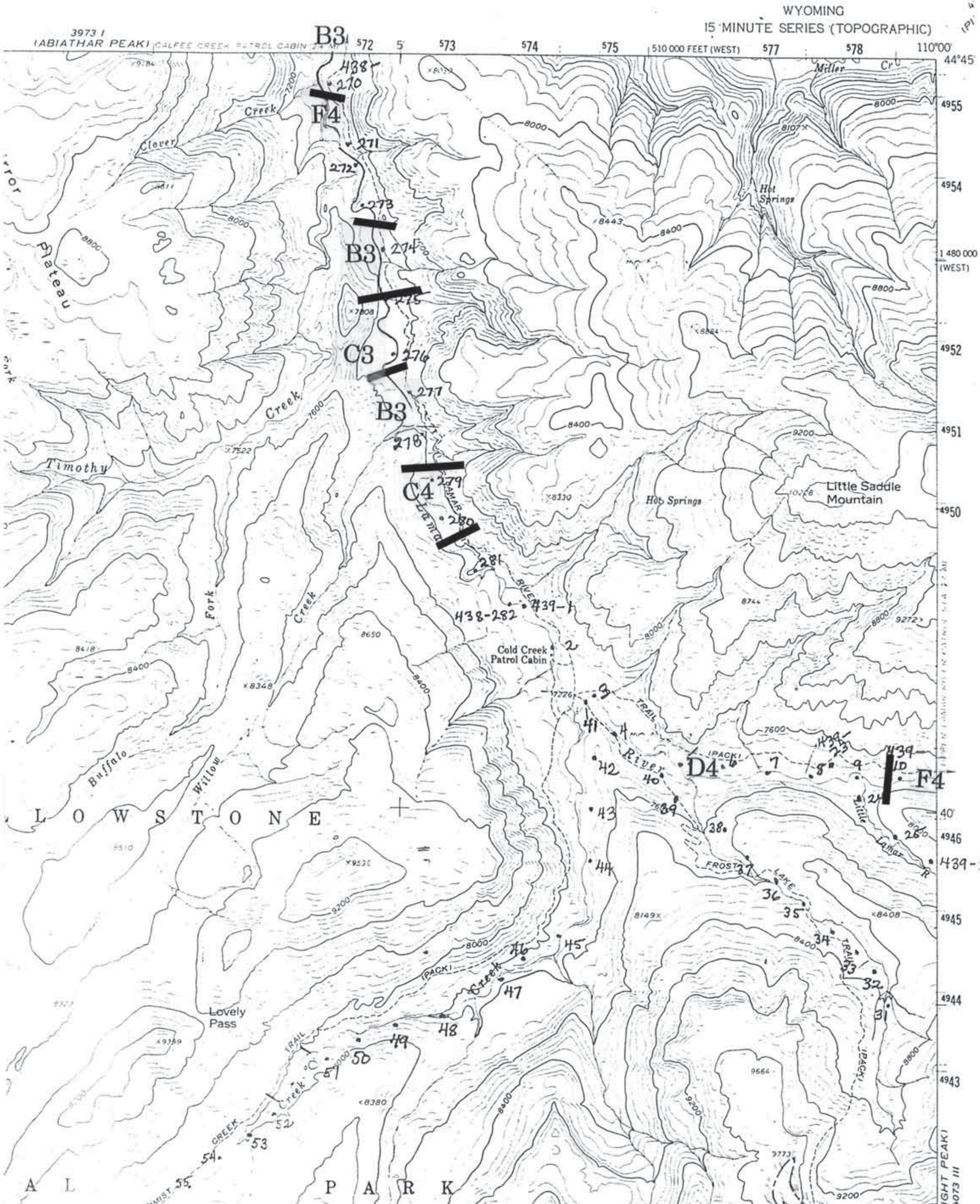



STREAM CLASSIFICATION MAP
MAINSTEM LAMAR RIVER
PAGE 3

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# MAINSTEM LAMAR RIVER
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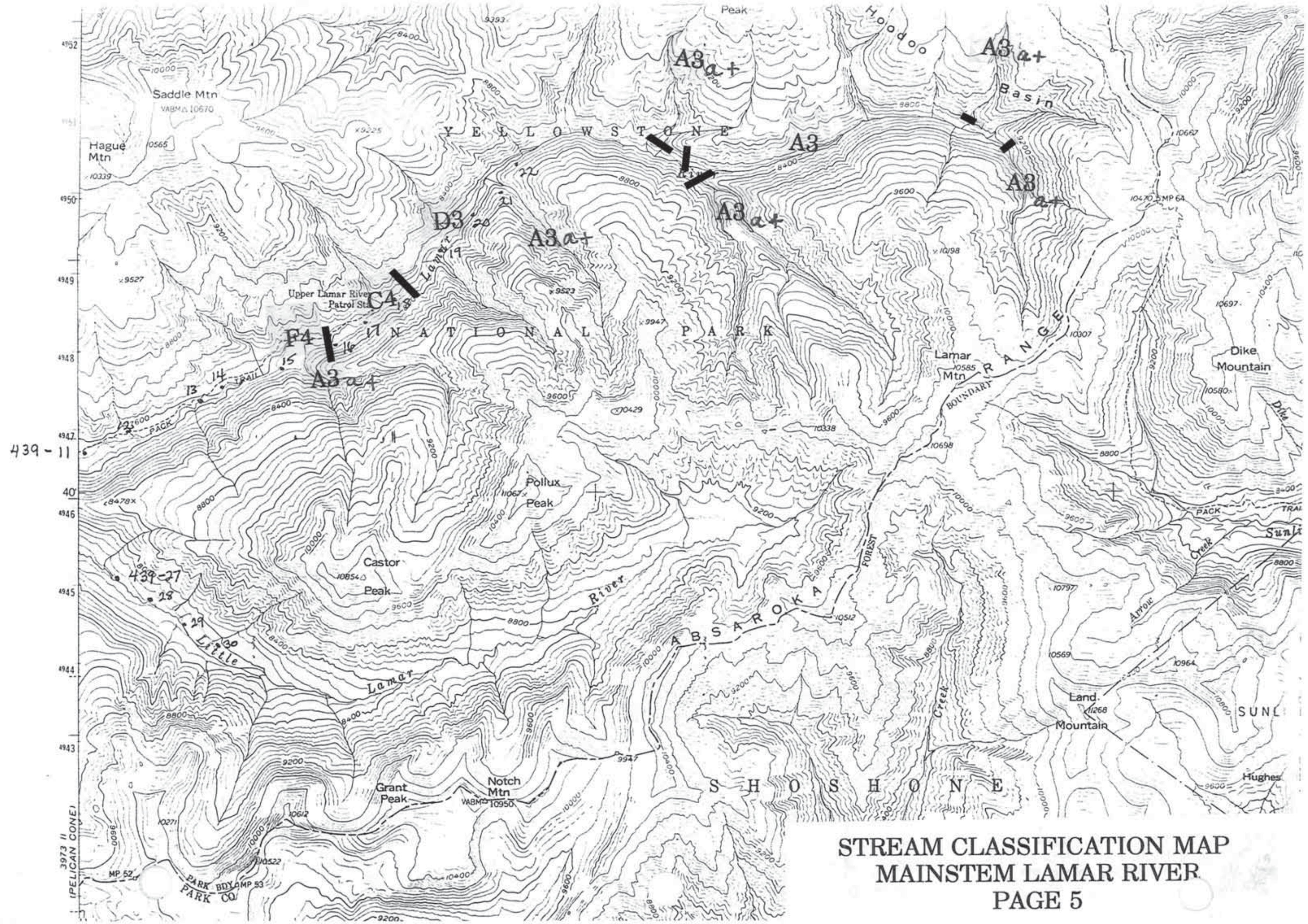


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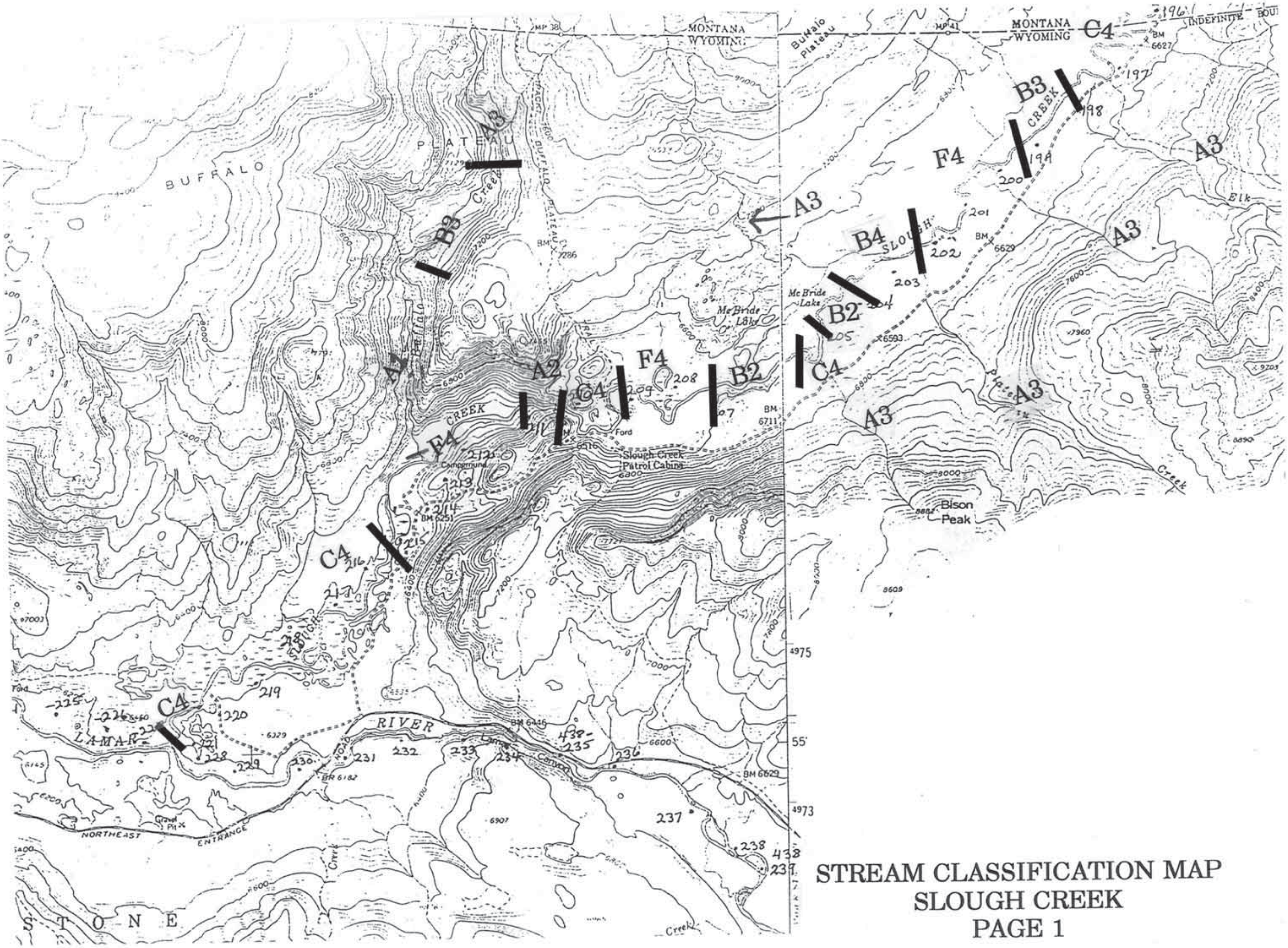
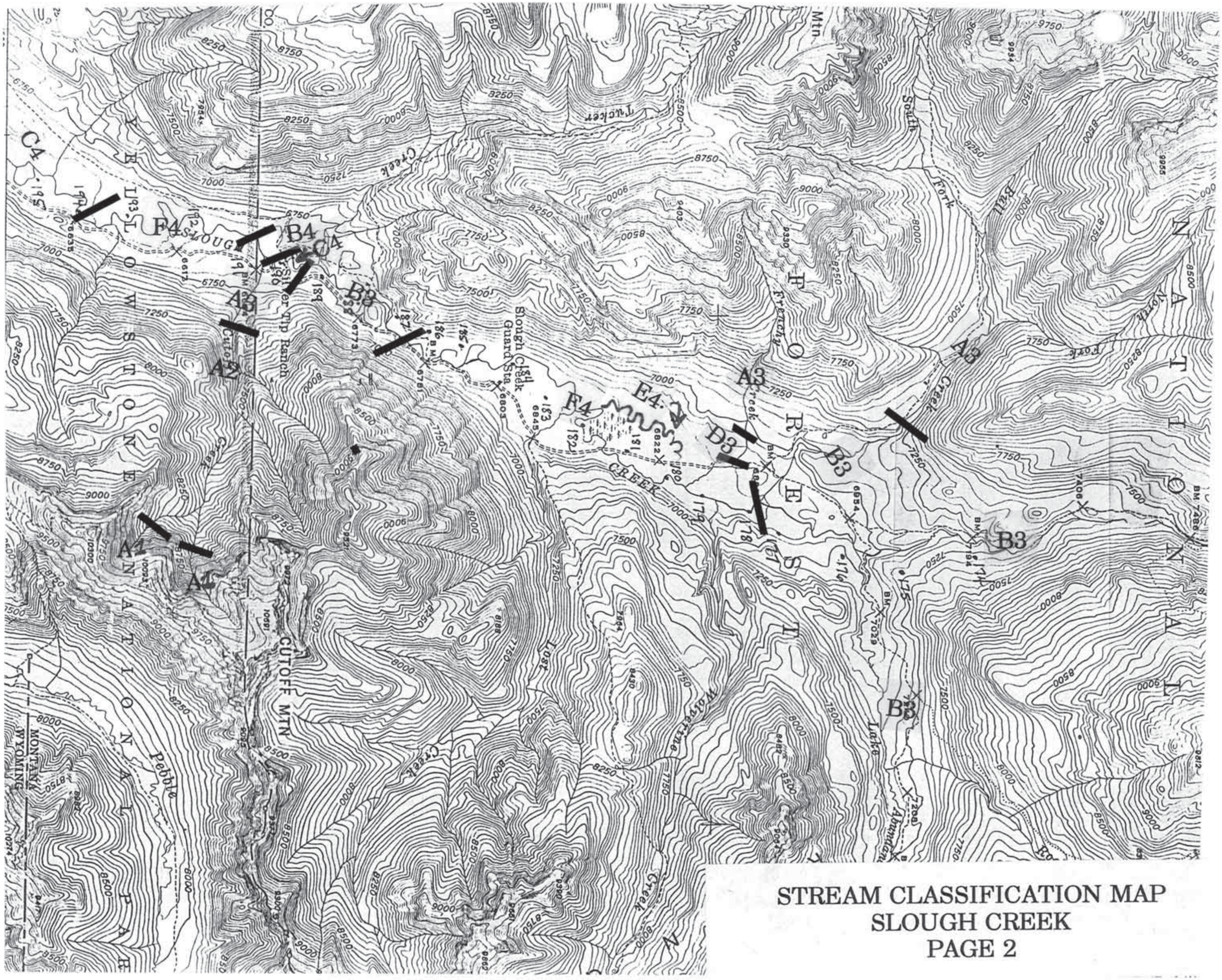
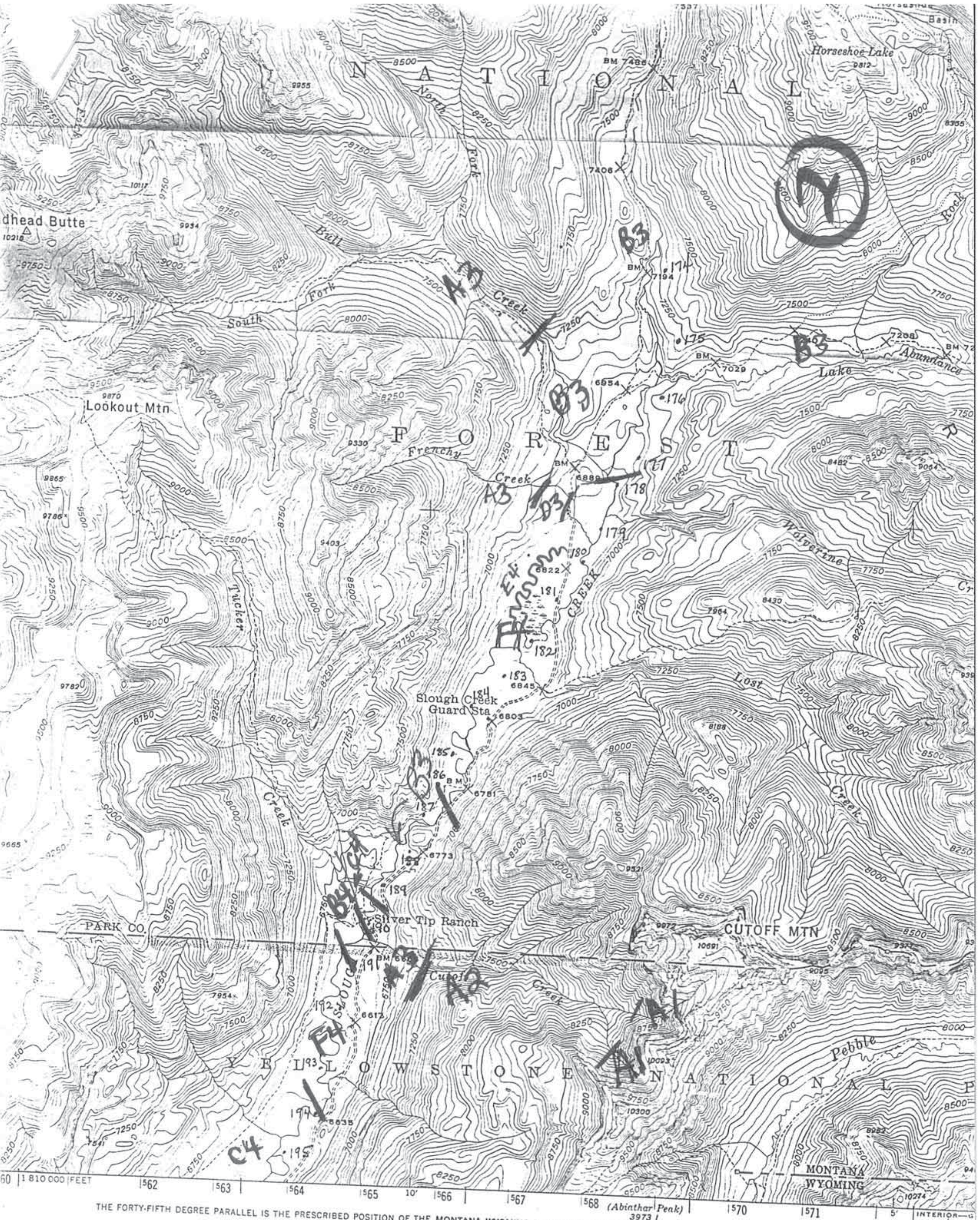
# MAINSTEM LAMAR RIVER
# PAGE 5




STREAM CLASSIFICATION MAP
SLOUGH CREEK
PAGE 1

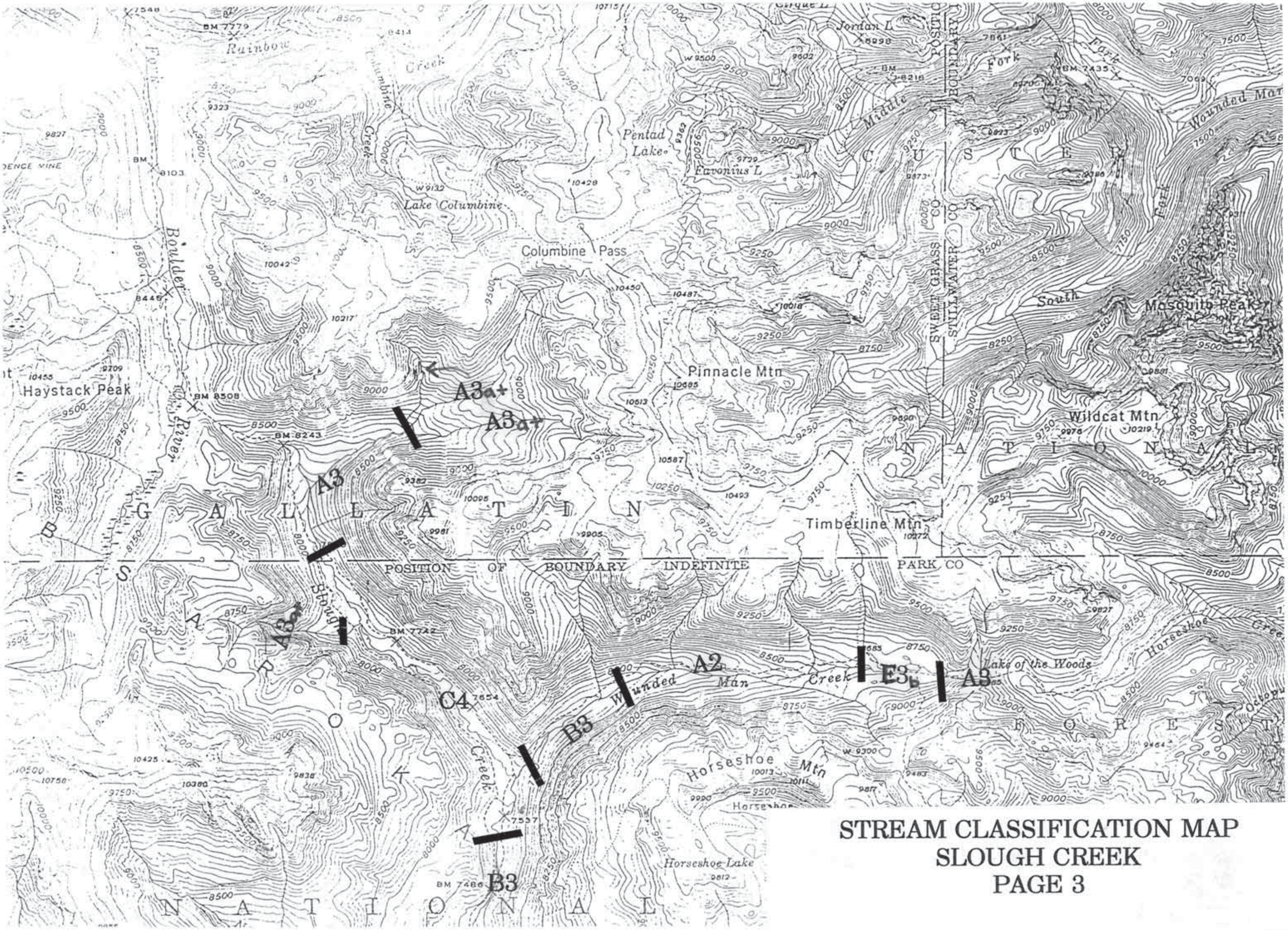



STREAM CLASSIFICATION MAP
SLOUGH CREEK
PAGE 2



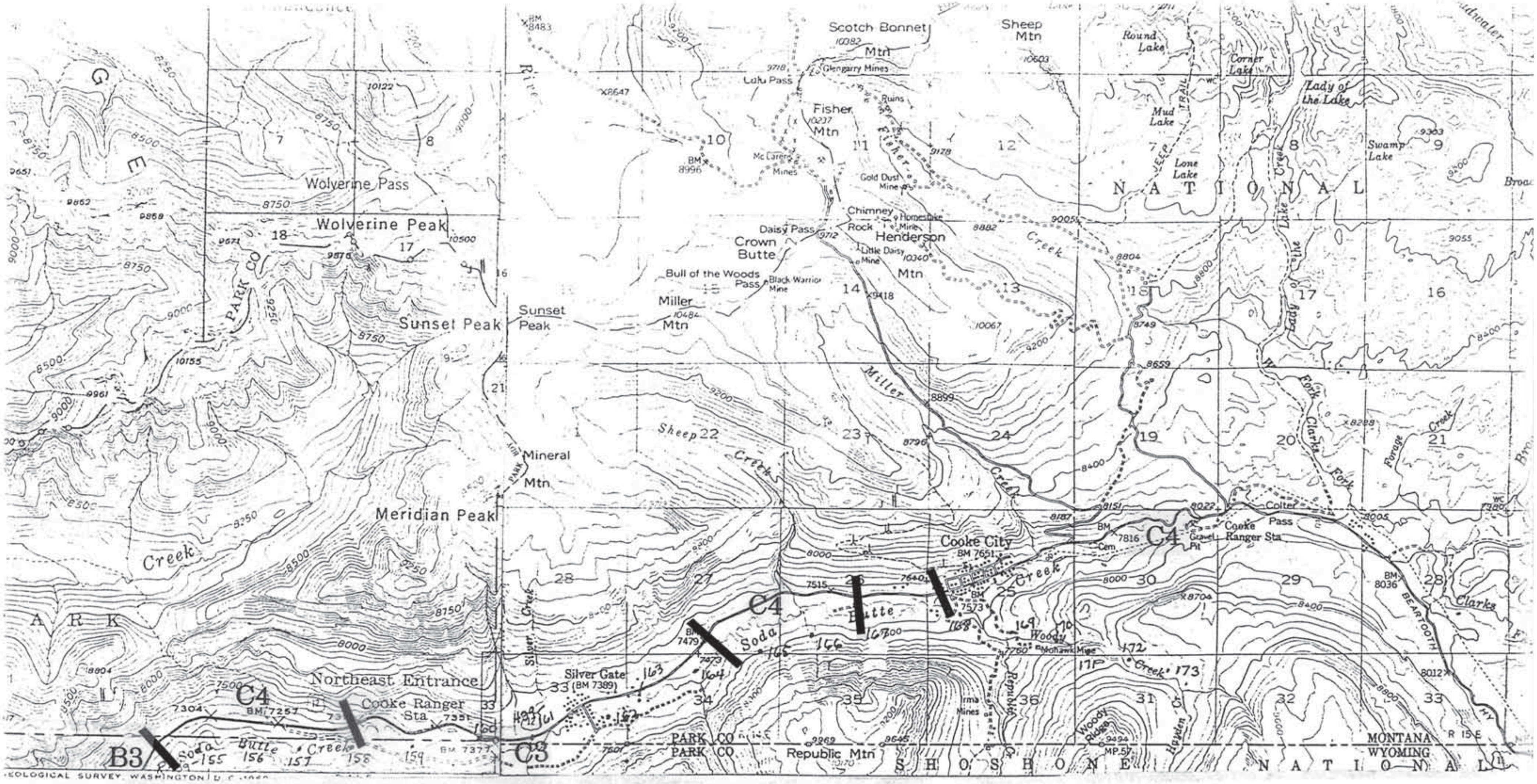

THE FORTY-FIFTH DEGREE PARALLEL IS THE PRESCRIBED POSITION OF THE MONTANA-WYOMING BOUNDARY. WITHIN THIS QUADRANGLE IT HAS BEEN OMITTED WHERE ITS ACTUAL POSITION, AS O

v J. L. Lewis

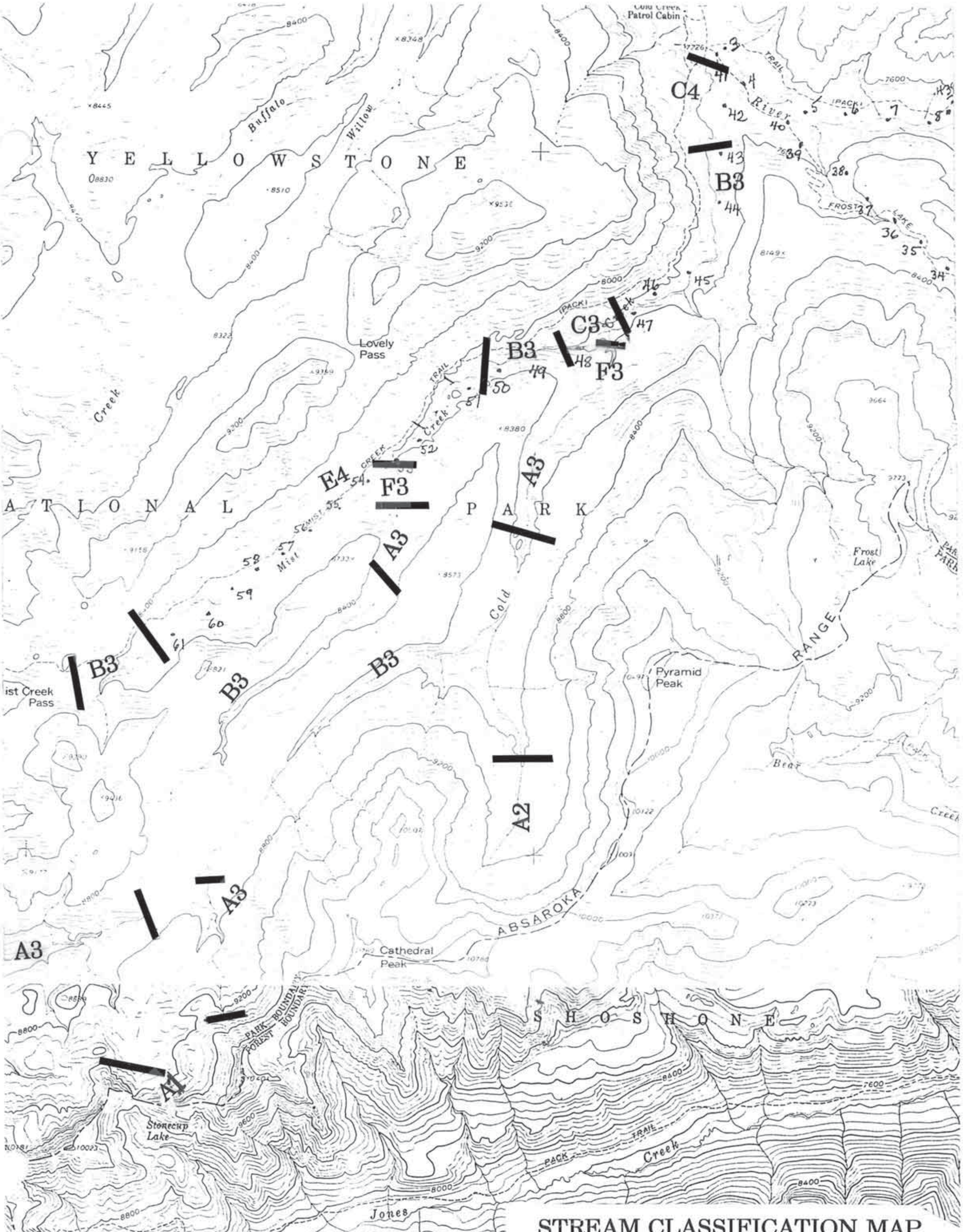



STREAM CLASSIFICATION MAP
SLOUGH CREEK
PAGE 3

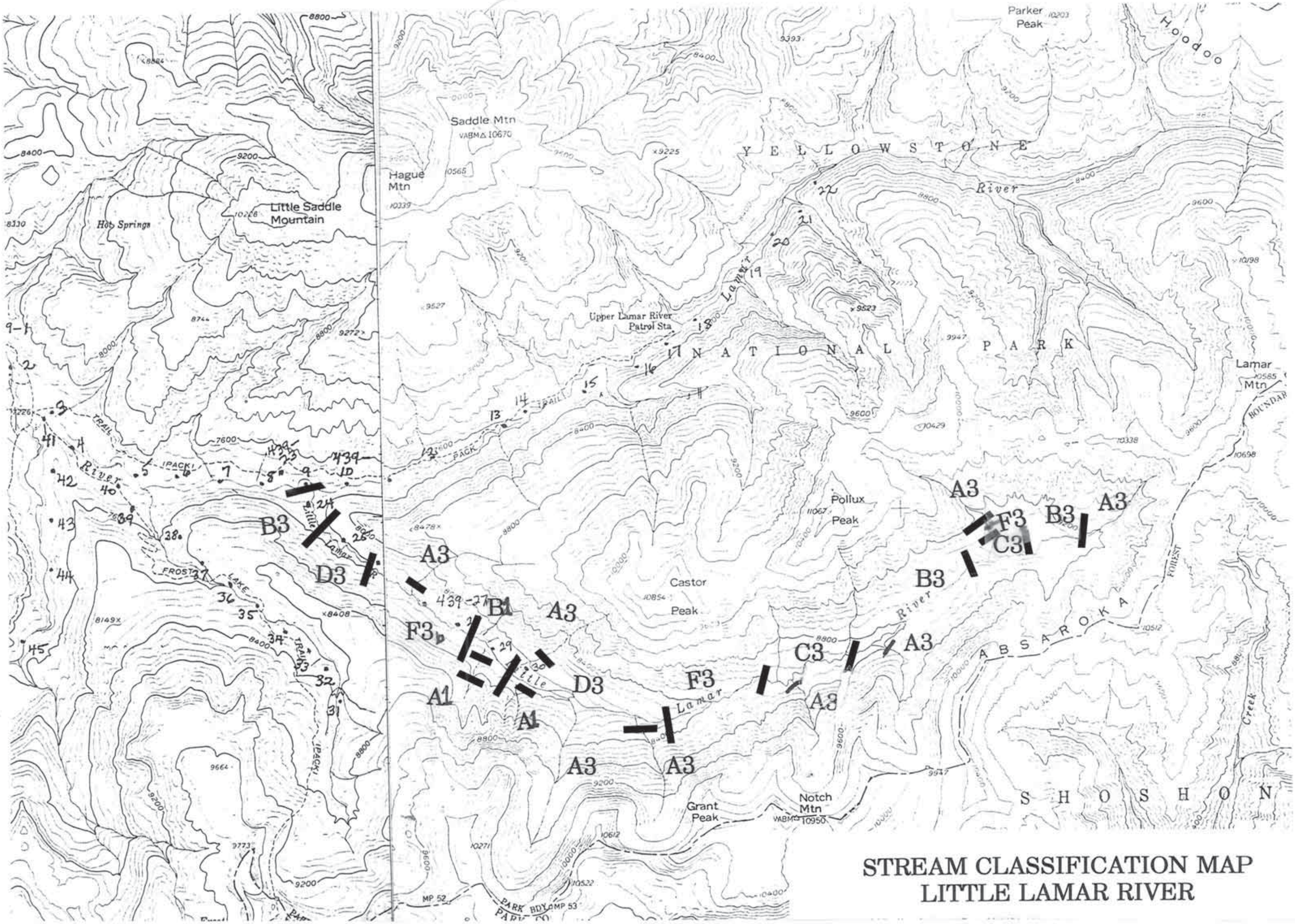

STREAM CLASSIFICATION MAP
SODA BUTTE CREEK
PAGE 1



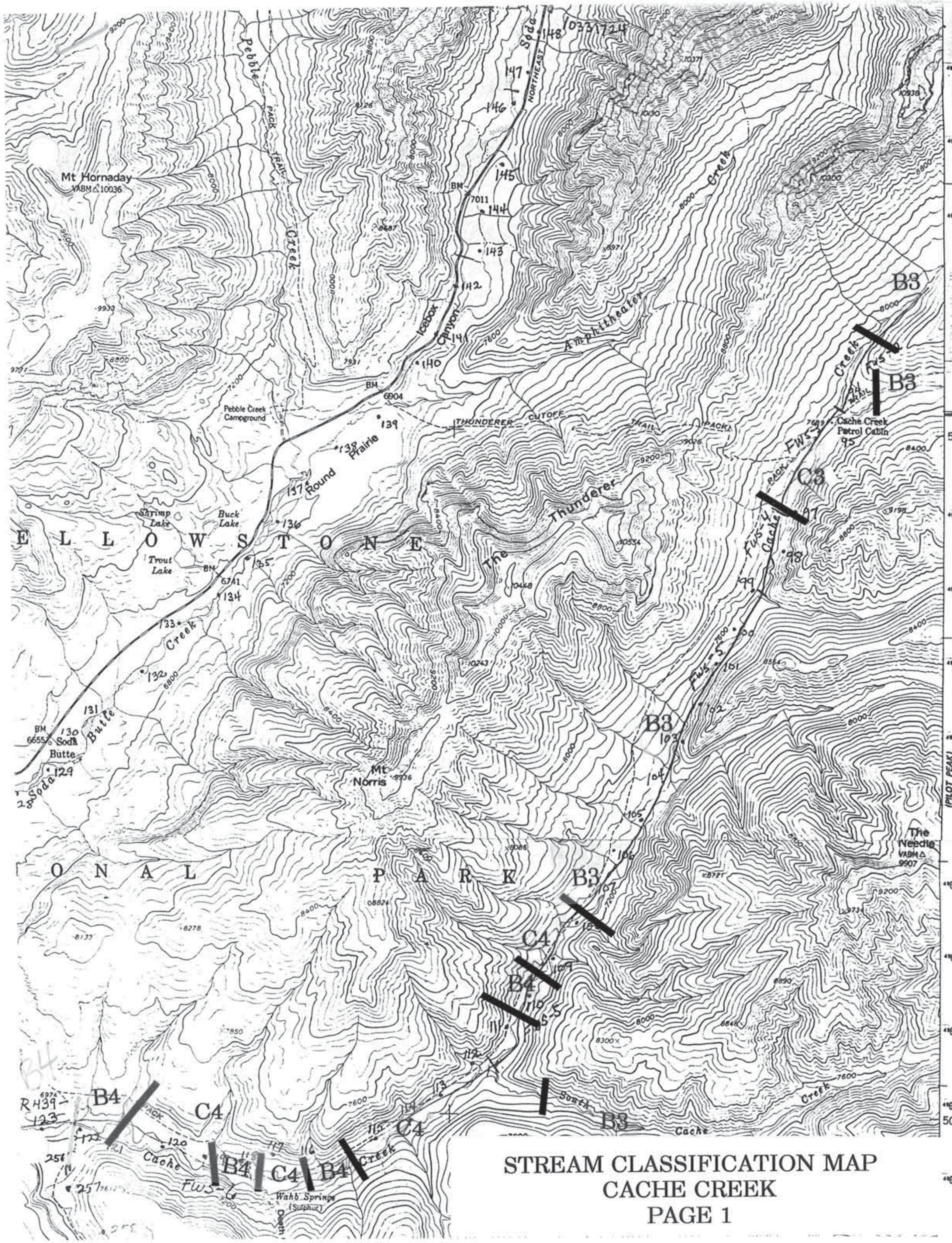

STREAM CLASSIFICATION MAP
SODA BUTTE CREEK
PAGE 2



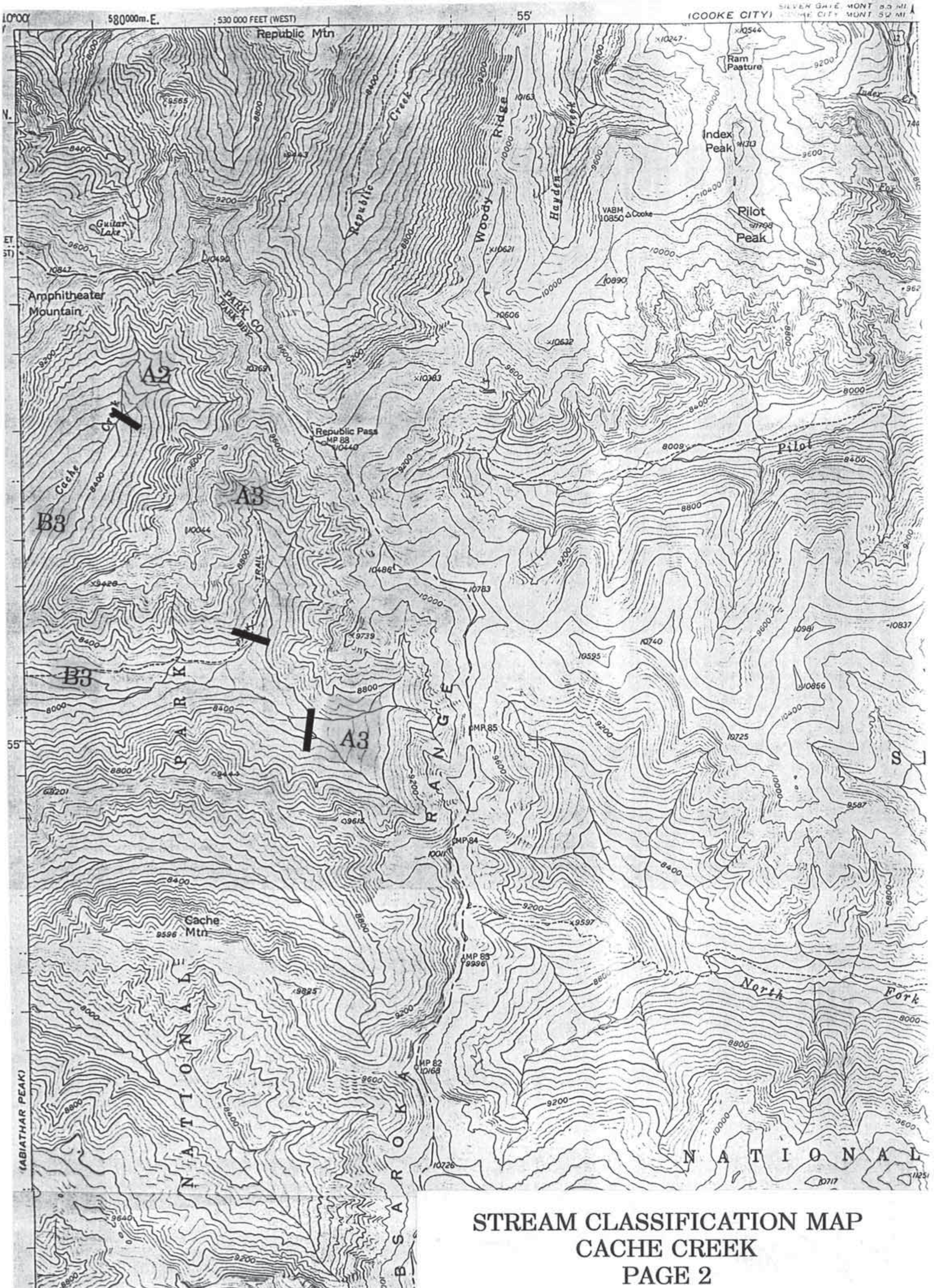

# STREAM CLASSIFICATION MAP
# MIST/COLD CREEKS



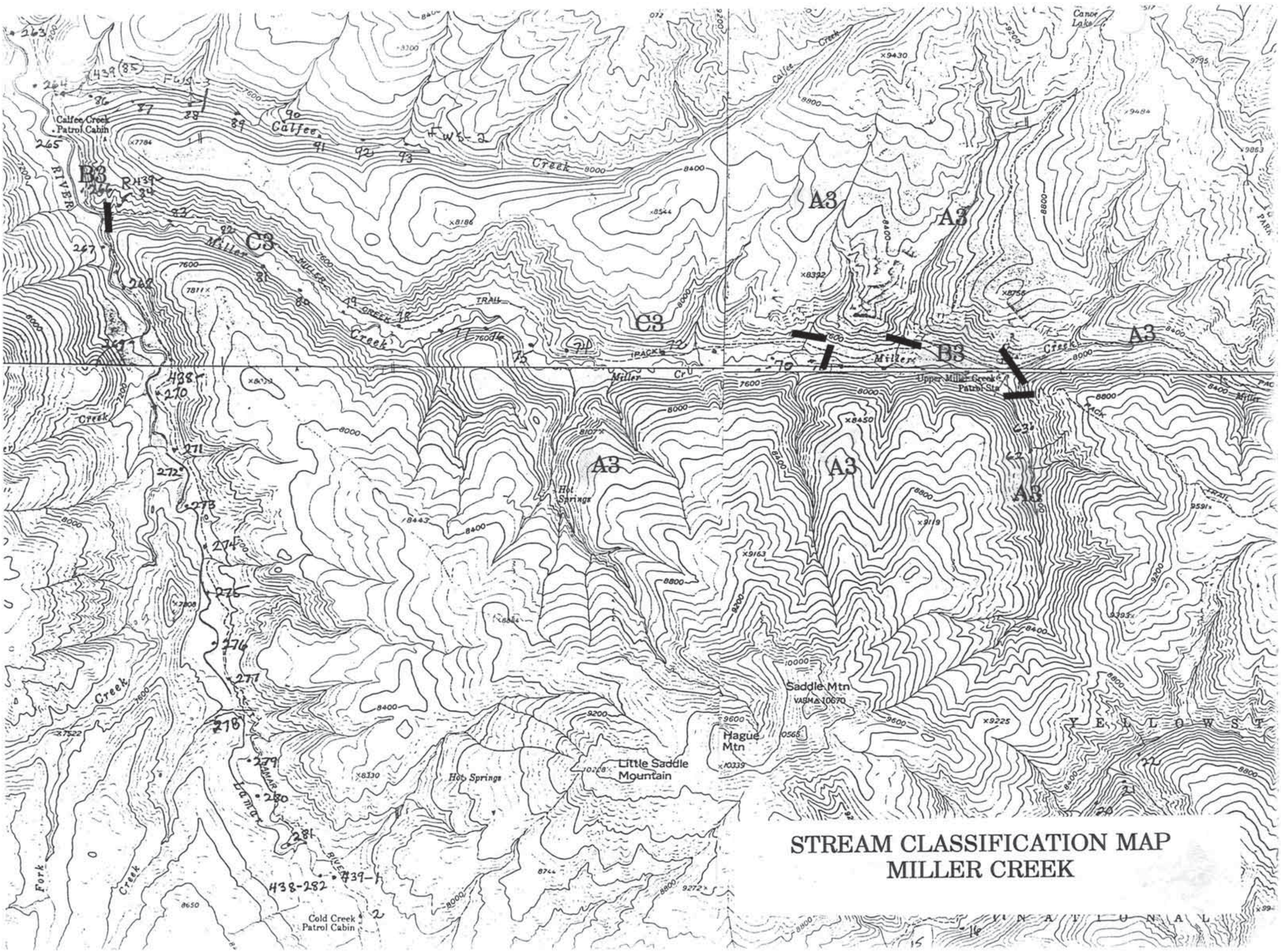

STREAM CLASSIFICATION MAP
LITTLE LAMAR RIVER



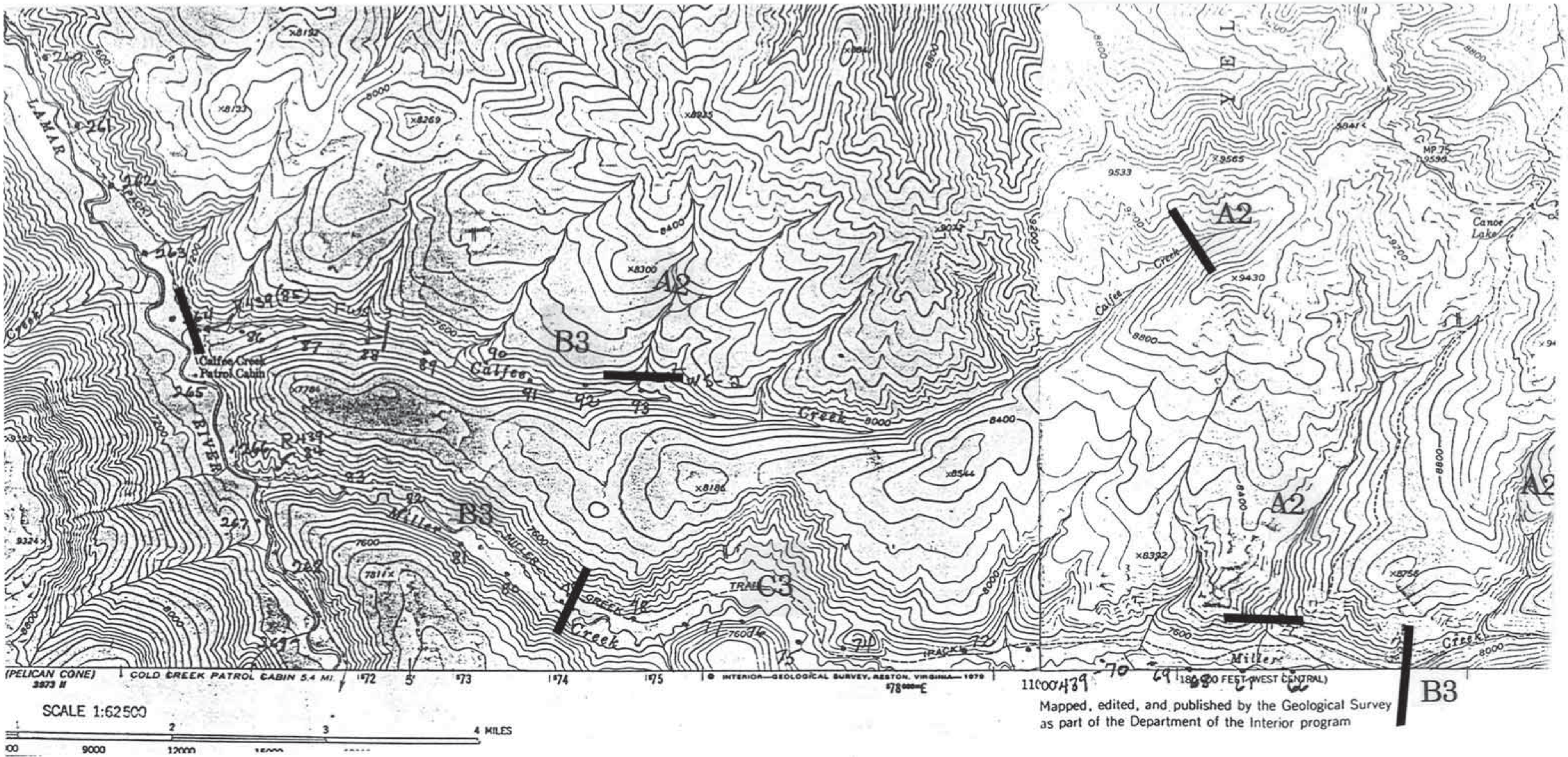

# STREAM CLASSIFICATION MAP
# CACHE CREEK
# PAGE 1



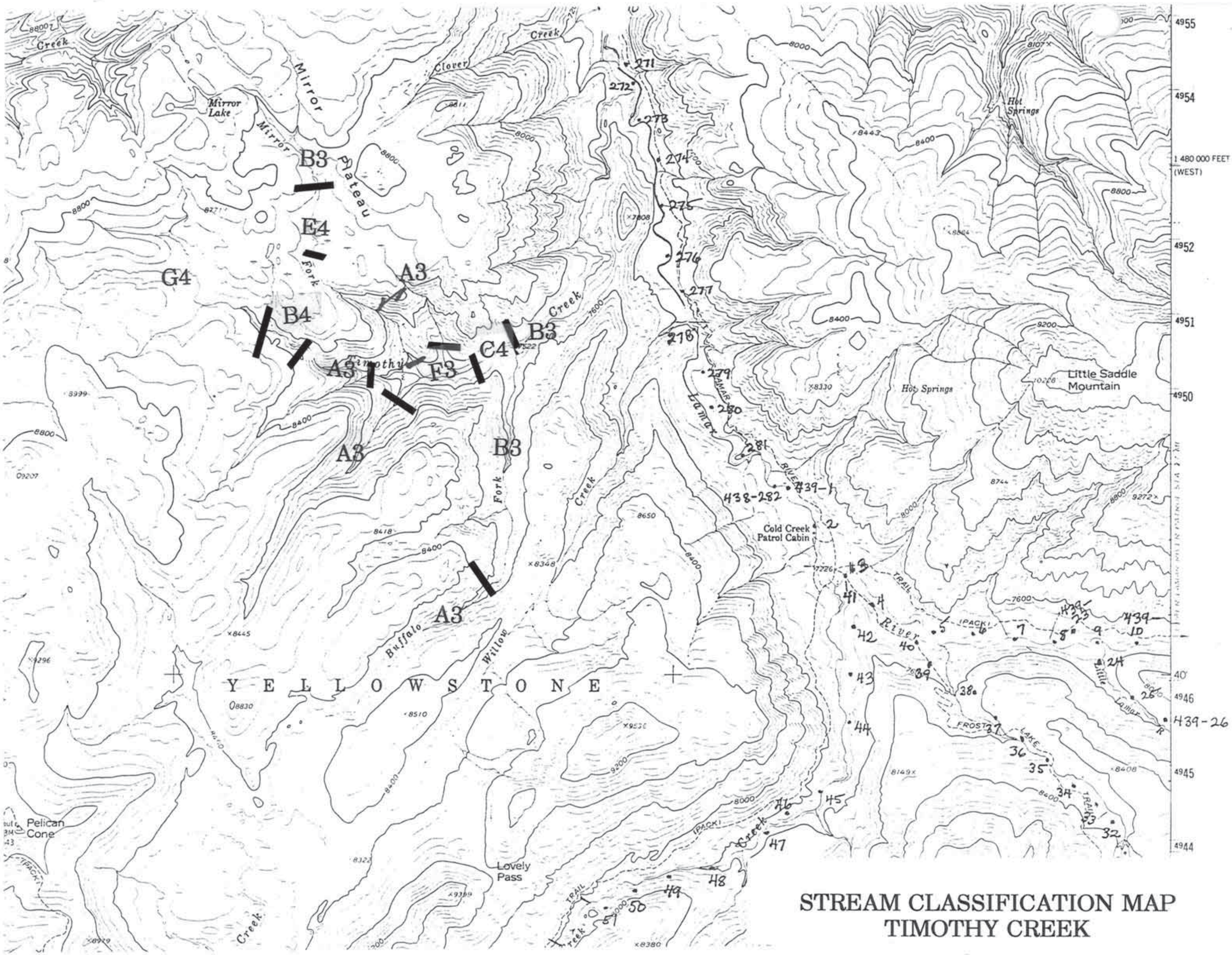

STREAM CLASSIFICATION MAP
CACHE CREEK
PAGE 2



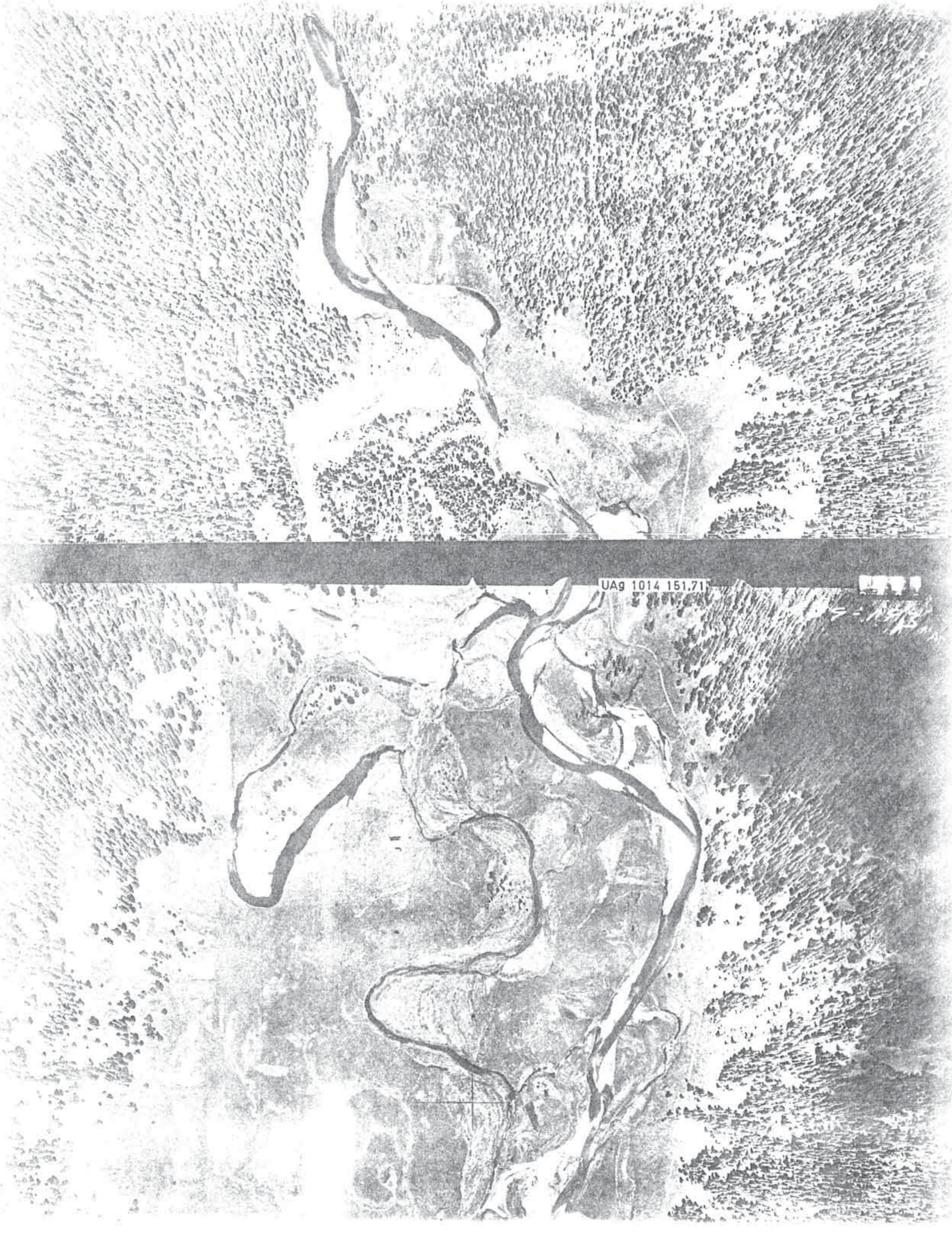
STREAM CLASSIFICATION MAP
MILLER CREEK
Calfee Creek Patrol Cabin
Calfee Creek
Miller Creek
Upper Miller Creek Patrol Sta
Saddle Mtn
Hague Mtn
Little Saddle Mountain
Hot Springs
Cold Creek Patrol Cabin
Canoe Lake
Lamar River
B3
C3
A3
Y E L L O W S T
N A T I O N A L




# STREAM CLASSIFICATION MAP
# CALFEE CREEK




# STREAM CLASSIFICATION MAP
# TIMOTHY CREEK


UAg 1014 151.71

# APPENDIX II

## PHOTOGRAPHS OF REPRESENTATIVE STREAM TYPES - LAMAR RIVER DRAINAGE

A3

A3

B2

A3

A3


G4

G4


F3


F4


F4


F3

B3

B3

E4

E4

F3

F4

F4

F3