RIVERBED FORMATION

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Abstract

The general fluvial processes that work to form a riverbed and produce the characteristic pattern of either meandering, braided, or straight are reviewed. A method for quantification of river pattern and correlation, with the basic hydraulic characteristics of discharge and slope, is presented. Additional characteristics of a river system may be deduced from high-quality photography and imagery obtained from either aircraft or space platforms.

Introduction

Since the establishment of Colorado State University as the land-grant college for the State of Colorado in 1870, one of the main emphases of both basic and applied research has been in the broad subject category of water use. Consequently, subjects concerning rivers and river behavior have been of prime concern, particularly as they relate to river control, navigation, pollution, and water resource management. In connection with these endeavors, engineering staff members of Colorado State University have long maintained a considerable amount of direct working relationships with Federal and State agencies, and private corporations both here in the U.S. and abroad.

In more recent years, an obvious need has emerged for studying a particular river problem from a broader systems approach. The amount of sediment being carried in a river at a particular location, proposed for a water supply intake for a major city, for example, may be the combined result of a heavy rainfall on some new timbering operation hundreds of miles upstream. River behavior is a complex reaction often resulting from a variety of manmade and/or natural inputs.

As a result of the need for a broader overview of a river, certain remote sensing procedures have been utilized by engineers at Colorade State University during the past 10 years in order to provide supplemental information about larger and larger parts of a given river system. An aircraft platform, with altitude limitations of about 30 000 ft above the mean sea level, has provided good overviews of many important characteristics of rivers. Three basic sensors have been used: a Wild RC-8 precision mapping camera (with a variety of film-filter combinations), a multiband camera and regular aerial cameras with selected film-filter combinations, and thermal infrared line scanners. Rivers located in the Rocky Mountain areas of Colorado, Wyoming, and Montana, to the mighty muddy Mississippi in the lower Gulf region, have been investigated.

During the course of these investigations a great deal of experience has been gained as to what characteristics of a river system can be evaluated using certain sensors from an aircraft. Now with observations from an orbital platform a practical reality, one will finally be able to obtain the vital, additional dimensions of synoptic, sequential overviews of total river systems. An extension of our understanding of the use and analysis of remote sensor output from an aircraft platform can now be immediately applicable to orbital survey data. This paper will discuss certain characteristics of river systems that are amenable to determination from orbital altitudes.

Scope

A riverbed is the result of a long-term process of transport and deposition of sediments by the flowing water. The total riverbed is often characterized by an impermeable or semipermeable boundary filled with layers of cobbles, gravel, sand, silt, clay, and organic material. The live stream may only occupy a small portion of the total width of the riverbed. The overbank area or flood plain is often covered with dense growths of vegetation and may extend for considerable distances on either side of the main river.

The river and total flood plain, as a unit, is the target of interest. Viewed in this total context using a variety of sensors, one can extract valuable information as to the geologic development of the riverbed, determine the present fluvial processes at work, and make certain predictions as to what the river behavior will be in the near future.

The pattern (planimetric shape) of the flowing stream may be generally classified as either meandering, braided, or straight (Fig. 1). Streams have a natural tendency to meander, but many streams have a braided pattern, and a very few have straight patterns. Each of these patterns indicate a particular set of circumstances regarding the flowing water and the riverbed conditions. The main subject emphasis of this paper, and something that is particularly feasible from orbital altitudes, is: (1) the general identification of stream pattern, and (2) the use of certain pattern characteristics from meandering streams for both river-flow and river-slope predictions.

These predictions (estimates) of flow and slope are tremendously important for water resource planning purposes. A comparison of relative water yields from adjacent basins, for example, should be immediately apparent to a trained interpreter from a cursory observation of either the corresponding photograph or imagery. Recent work at Colorado State University for determining the correlation between meander river pattern characteristics and river flow and slope has been accomplished [1]. Results of these studies clearly indicate the potential of satellite observations for this purpose.

A considerable amount of additional qualitative information about the river-system environment may be obtained from satellite observations. Examples of each of these characteristics will also be illustrated in the following text.

General Discussion of River Patterns: Braided, Meandering, or Straight

River channel patterns have been generally classified into three categories as braided, meandering, and straight [2]. These categories are neither all encompassing nor mutually exclusive; the stream pattern may change from one type to another over relatively short stretches or may consist of combinations [3]. However, river-channel patterns can be divided into two broader main categories: (1) single channel, and (2) multiple channel. Single-channel pattern can be either meandering, straight, or braided. The multiple channel does not necessarily imply braided, and can be branching channels formed in the process of alluvial fan building.

Meanders have also been classified as regular or irregular, single or compound, acute or flat, and sine, parabolic, circular, or sine-generated curves [4].

Straight channels over any sizable distance are a rarity, although steep channels in fairly uniform bed material may develop broad, shallow cross sections and can maintain relatively straight alignment for considerable distances [4].

Braided Pattern. The braided stream pattern has been attributed to steep slopes and/or high bedload concentration [5]. Although a steep stream may tend to develop a braided pattern, the general direction of the channel as a whole tends to be relatively straight. The channel is generally quite wide, relative to the depth, and ordinarily has a fairly flat bottom. Braiding generally occurs in channels carrying sand or coarser material as bedload.

Braided streams have a very characteristic pattern on an aerial photograph. Color infrared photography can enhance the intricate pattern and detail and often help identify the age of the particular braided channel; that is, to discriminate between vegetated and nonvegetated islands, and also to render the location of channel remnants.

The engineering significance of braided channels and the associated design problems to be considered for bridge construction, for example, are very important. Considerable bedload is in motion, and streambed and bank scour can be easily induced.

The reasoning for straight sections of braided channels was discussed by Chitale [4]. He noted that: (1) the continuity of the transverse bed profile was broken by numerous islands and/or submerged bars and (2) the range of bed material sizes was greater than in straight channels with no braiding.

These two factors tended to disrupt the homogeneity of the flow and dampen the tendency for transverse velocity components. Curvilinear flow, such as found in a meandering channel, was inhibited and therefore alignment was relatively straight except for the possible effect of channel boundaries.

For shallow streams of uniform depth and flowing with banks full, Brice [6] found that the growth of bars and/or islands in the channel not only divided the flow into braids but also reduced the water width to a value less than the bank-full width.

For a given discharge and bed material size, Brice found that braided sections of a river had steeper channel slopes and greater effective widths than meandering sections of the same river [6]. He cautioned, however, that no general statement about relation of valley slope to channel pattern can be made unless the other significant variables are specified, that is to say, bank erodibility, bed material, and discharge.

Large braided rivers, observed by Leopold and Maddock were to be characterized by wide channels, rapid shifting of bed material, and continuous shifting of the river course [7]. Reaches within a single-channel river having steeper slopes tended to be braided. The close relationship between meandering and braided patterns could be recognized in a braided stream; the individual branches of a braided stream definitely meandered. In plan view, however, the overall channel course of a braided stream was less sinuous than a meandering course with similar discharge. Sediment transport and deposition were found to be the essential ingredients for braiding [8].

The author has observed, on the North and South Platte Rivers of western Nebraska, relatively clear water with high rates of bedload movement in braided patterns. A braided pattern does not necessarily imply that a channel is overloaded, since "poised" or "degrading" channels have been recognized as braided [6, 8].

Rivers have been found to tend to braid where: (1) bank caving is active, (2) the slope is steep and sediments are easily erodible, or (3) the slope is excessively low and the total sediment load is great [9].

Fahnestock observed that glacial streams changed in pattern from meandering to braided with high summer discharges and returned to meandering with the advent of lower late-summer discharges. He found that both braided and meandering sections can occur where the stream is aggrading, poised, or degrading. The pattern does not conclusively define river regime. Fahnestock emphasized that the braided pattern cannot develop without bedload. He considered, in his investigation of the White River, the braided pattern to be caused by basically the following conditions: (1) erodible banks, (2) rapid and large variation in discharge, (3) steep slope or excessively low slope, (4) abundant load, and (5) local incompetence for sediment transport [10].

Meander Pattern. Meandering channels are a most common pattern found in a variety of situations from steep mountain slopes providing an alluvial cone to the deltaic environment. Meandering rivers can have bed material ranging from large cobbles to fine-grained silt. A gradual reduction of tortuosity ratio was found with an increase in slope [5]. Dominant discharge, which controls meander wavelengths, is a range of flows (possibly falling stage flows) somewhere between mean discharge for the month of maximum discharge to the annual mean discharge. There was some evidence of the effect of valley slope on meander wavelength. In cases of bank-full and overbank floods, the main current of the river takes on a valley-axial direction of flow, and during very large floods the flood plain acts as a river channel [11].

Wide, shallow channels are generally associated with lesser tortuosity. Also, since valley slope provides the force which tends to straighten the channel alignment, the higher the mean velocity the flatter the curvature required [4].

The values of tortuosity ratio (ratio of thalweg length to valley length) greater than 5.5 are rarely found in the field. This was the limiting value for idealized circular meanders. The reasoning for rivers ordinarily developing meanders in narrow, deep sections, but not in wide and shallow ones are listed:

1. Narrow, deep channels with low velocities allow easy adjustment of channel section conducive to flow concentrations at one bank or another and create conditions favorable to meandering. Wide, shallow channels with high flow velocities limit any nonuniformity of flow to a local effect, which dissipates in a short length without affecting the channel as a whole.

2. For very tortuous channels, the centerlines of the bends become close to each other, and consequently, the width of the channel must be small, or, alternately, the meander shape dictates that width of channel increase with decrease in tortuosity.

3. Flow curvature creates superelevation and transverse velocity components. In wide, shallow channels the relative height of roughness elements

to flow depth is greater than in deep channels. Consequently, such transverse components are minimized because of friction on the boundary [4].

Most meandering rivers have a ratio of radius of curvature to channel width in the range of 2 to 3. Size of bends appear to be proportional to the size of the river; the repeating distance between bends, width of the channel, and the radius of curvature are the basic dimensions [2].

Discharge was the most important single factor affecting the geometry of a meandering channel. The width of meandering channels is greater than straight channels having no well-developed shoal pattern; and that high sediment loads required steeper slopes and wider channels [12].

Schumm concluded, as did Leopold and Wolman, that meandering is a principal means of dissipating stream energy. A river can develop a meandering course of low gradient without having to transport large quantities of sediment by downcutting. Streams transporting little bed-material loads are relatively narrow, deep, and sinuous. Some rivers transporting only very fine sediment are very straight (low sinuosity) [13].

From an engineering standpoint, the only independent variables that need to be considered for defining channel pattern are: (1) discharge, (2) valley slope, (3) material in the bed and banks, and (4) man's activities [14].

The centrifugal force in the bend causes a transverse water-surface slope and helicoidal flow in the bend. These transverse gradients induce velocity components toward the convex bank having a magnitude of about 15 percent of the average channel velocity; concentrations of bedload are swept toward the convex bank to be deposited as point bars. Scour in the bends causes migration of the entire pattern in a downstream direction and sometimes in a lateral direction. Recorded downstream meander pattern movements have been as great as 2500 ft per year in alluvial rivers. Also, much of the material eroded from the concave bank is deposited in the crossing and on the point bar in the next bend downstream [15].

In steep, confined mountain streams, an alternating series of deeps and shallows, related to bends and crossings in freely meandering channels have been observed. Leopold reported the alternating pools and rapids in the Colorado River through the Grand Canyon [16].

Straight Pattern. Even when the channel appears straight, it is unusual for the thalweg not to wander back and forth in a meandering fashion. Even in straight channels, alternate bars develop [8]. Steep, confined streams, fairly straight in alignment, develop pool and riffle patterns with spacings very comparable to the spacings of pools and crossings in similar-size, freely meandering streams. "Extremely short segments or reaches of the channel may be straight, but it can be stated as a generalization that reaches which are straight for distances exceeding 10 times the channel width are rare" [17].

A straight pattern was defined as one having a sinuousity or tortuosity ratio of less than 1.5. Long reaches (up to 2.5 miles, 30 times river width) on the North Loup and Middle Loup River with a sinuosity index of less than 1.01 are fairly common. The straightness of the Loup River reaches may be exceptions [6].

Streamflow and Slope Prediction

A recent study, completed by the author, has provided prediction equations for average daily discharge and river slope from river pattern characteristics. In the intermountain regions of Colorado, Wyoming, and Montana, 11 freely meandering rivers were selected. The pattern (planimetric shape) characteristics of each river were determined from 7.5 min quadrangle sheets using a coordinatograph and a CDC 6400 computer. The correlation coefficient between average daily discharge and mean radius of curvature was 0.88; the correlation coefficient between river slope and tortuosity was 0.73 [1].

The rivers investigated had average daily discharges ranging from about 30 cfs to about 1000 cfs, slope ranging from 5 ft per mile to 69 ft per mile, and drainage basin areas ranging from about 80 to 4000 square miles.

River pattern is a characteristic that can be easily recognized from almost any form of imagery or photography taken in preferably a near vertical direction (or with known orientation) and with some estimate of imagery or photographic scale. River pattern is a characteristic that could be automated at the sensor output for subsequent use in routine logic decisions. Line scanner output, for example, can be programmed to recognize the water-land interface and subsequently define the river pattern. Studies to date indicate a need for additional work to refine the process of riverflow and slope prediction, preferably in the automated fashion [18].

Other Characteristics of Rivers

Studies to date can provide estimates of riverflow and slope from pattern characteristics of some intermontane regions of the Rocky Mountains. Refined prediction equations of a multivariate nature need to be established between the pattern and the hydraulic characteristics for rivers in a variety of fluvial-geomorphologic environments. Orbital altitude photography will provide an economical way to develop and utilize these relationships.

Many additional characteristics related to the riverbed may be interpreted from high-quality satellite imagery. The author has listed 10 categories of particular importance to river engineers:

1. Sediment transport processes. Relative suspended sediment concentrations in rivers may be interpreted readily from color infrared photography taken from an aircraft platform (Fig. 2). The Gemini photography also demonstrated this distinctive tone change, where dark-colored bodies of water indicate relatively clear water and blue tones in water indicate the presence of suspended sediment. Using this interpretive key, a person acquainted with rivers can determine where erosion is occurring and trace the transport path. Recent remote sensing studies on the lower Mississippi River using color infrared have utilized this technique for identifying areas of erosion, describing flow patterns, and locating sections of the river where flow separation is occurring.

2. Flood plain vegetation surveys. The flood plain soils are generally very fertile and consequently, much agriculture is practiced on flood plains, particularly in the arid and semiarid parts of the world. Vegetation of a variety of types, including beneficial and nonbeneficial vegetation, consumes a considerable amount of the ground water located in the underground reservoir immediately beneath the flood-plain areas.

Particular attention must be paid to the encroachment of salinity problems induced by the proximity of the water table, poor drainage characteristics, and reuse of the water itself. Phreatophytes, that is, nonbeneficial plant life, can consume considerable amounts of ground water. In the western part of the U.S. there have been programs to attempt to eliminate this undesirable type of vegetation and consequently save some water in the process. Color infrared photography again has proven quite beneficial for evaluating plant species, and identifying certain types of plant stress (Fig. 3). The plant vigor is often related to the proximity of the water table.

3. Flood prediction and damage evaluation. Throughout the entire world excess volumes of water cause considerable damage to life and property. The ability to track a flood crest via the satellite observations would be tremendously beneficial. A large proportion of the population both here in the U.S. and abroad live immediately adjacent to large rivers and are particularly vulnerable to unexpected high flows in a river (Fig. 4).

4. Soil classification. The ability to classify soils for agricultural purposes and to locate gravel deposits commonly found in the flood-plain areas is of considerable importance. Procedures have been developed in terms of photointerpretation for these applications but a good amount more must be done and would be very practical with more sophisticated sensors and procedures. Gravel deposits, for example, are becoming a rather scarce commodity, and they are often classified as valuable mineral resources in certain areas (Fig. 5).

5. River navigation. A considerable amount of our commerce here in the U.S. depends on very economical transportation on our major river systems. A continuing ongoing process is the maintenance of these navigation channels (Fig. 6). An improved procedure for locating the thalweg (or the position of the deepest part of the stream) would be very worthwhile. A person acquainted with rivers and fluid mechanics can interpret the location of this thalweg from color infrared photography, for example. Recent studies at Colorado State University also indicate that thermal infrared imagery may be used, in some cases, to indicate the major channel in the river. In addition, space photography can provide an excellent monitoring technique for managing river traffic.

6. Water depths in clear water. Certain films are now available which allow one to record the bottom detail of near-coastal areas or of clear, inland streams to considerable depths. Studies completed in Montana this past year, using color infrared

photography, allowed perception of the detail of the channel bottom and bars for a particular clear-water river.

7. Drainage net pattern. This is another planimetric feature that can be quite easily extracted from either good quality imagery or photography from space (Fig. 7). Information about the drainage net pattern can help one to better understand discharge characteristics of streams. Work is currently being undertaken at Colorado State University in this respect.

8. Water resource management. The ability to observe very large areas can be helpful in connection with recording precipitation patterns, including both rainfall and snowfall, and for the subsequent use of flow prediction in streams (Fig. 8). Historically, flow prediction, at least in the western part of the U.S., has been based on snow surveys taken periodically during the winter months. Ordinarily these historical statistical procedures have provided a fair prediction for use in planning for reservoir fillings and withdrawals. However, this spring on the North Platte River Basin in eastern Wyoming and western Nebraska, considerable damage was done to the flood-plain areas. This was because of the fact that excess runoff from the high mountains forced unusually high releases from the impounding reservoirs in order to accommodate the new runoff from the snowfields.

It has been evident for some time that improved methods for flow prediction are necessary for optimum management of our water resources. In connection with the normal irrigation practices, the water resource managers need information about water use patterns in order to make appropriate releases to satisfy demands. Satellite observation could provide this valuable mapping of water use patterns. In addition, from the appearance of certain crops, the water use manager can estimate irrigation scheduling.

Another factor in water resource management, of course, is the aspect of pollution. Large pollution spills can be very hazardous to downstream users. Oftentimes these spills are noticed before they become a part of some organization's consumption, but certainly an early warning system concerning pollution spills would be very important. During excessive rainfall periods streams may become polluted because of runoff from bordering feedlots (Fig. 9).

9. Channel changes. The Gemini photos of the lower Mississippi River are of particular interest to the people concerned with the maintenance of navigation and flood control in this major river. Certain portions of the river have been longtime problem areas and, in the case of several colleagues familiar with river mechanics, a glance at some of these photographs can quickly indicate why these particular areas are causing difficulty. A river tends to meander, and wherever man has affected this normal meandering pattern he can expect considerable difficulty in maintenance of the channel.

10. Increased knowledge to mankind about river systems. Man knows very little about the behavior of the total river system primarily because he has had only a chance to look at pieces of any particular river system. Observations from an orbital platform using a variety of sensors can materially increase man's understanding of this complex system. It is prohibitive from the data magnitude standpoint to try to record everything about all river systems. On the other hand, orbital altitude imagery and photography can pinpoint those areas where additional investigations can be most economically achieved. Certainly aircraft and in some cases extensive ground data collections are a vital part of this overall look [19, 20].

Conclusion

River pattern definition from orbital altitudes can materially increase mankind's understanding of river systems throughout the world. Quantification of river pattern can be accomplished for estimating discharge and river slope. High-quality imagery and photography can provide a unique, overall view of sediment transport and deposition processes in streams, delineate flood plains and provide vegetation surveys, help predict and evaluate flood damages, monitor and identify river traffic, and aid materially in precipitation surveys for optimum water resource management.

References

1. Skinner, M.M.: Free Meander Pattern in Intermontane Rivers. In Preparation for Submission to American Society of Civil Engineers (ASCE), CEP71-72MMS14.

2. Leopold, Luna B., and Wolman, M. Gordon: River Channel Patterns: Braided, Meandering,

and Straight. Geological Survey Professional Paper 282-B, 1957, p. 772.

3. Russell, Richard Joel: Louisiana Stream Patterns. Bulletin of the American Association of Petroleum Geologists, vol. 23, no. 8, Aug. 1939, p. 1200.

4. Chitale, Shrikrishna V.: River Channel Patterns. Journal of the Hydraulics Div., ASCE, vol. 96, no. HY1, Jan. 1970, pp. 207, 218, 219.

5. Lane, E.S.: A Study of the Shape of Channels Formed by Natural Streams Flowing in Erodible Material. U.S. Army Engineer Division Missouri River, Corps of Engineers, Omaha, Neb., M.R.D. Sediment Series, no. 9, 1957, p. 33.

6. Brice, James C.: Channel Patterns and Terraces of the Loup Rivers in Nebraska. Geological Survey Professional Paper 422-D, 1964, pp. D31, D39.

7. Leopold, Luna B., and Maddock, Thomas, Jr.: The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. Geological Survey Professional Paper 252, 1953, p. 29.

8. Leopold, Luna B., Wolman, M. Gordon, and Miller, John P.: Fluvial Processes in Geomorphology. W.H. Freeman and Company, San Francisco, Calif., pp. 282, 294.

9. Shen, H.W.: Stability of Alluvial Channels. Preprint of Paper presented at the Institute of River Mechanics, Colorado State University, Fort Collins, Colo., June 15-26, 1970, p. 22.

10. Fahnestock, Robert K.: Morphology and Hydrology of a Glacial Stream-White River, Mount Rainier. U.S. Geological Survey Professional Paper 422-A, 1963.

11. Carlston, Charles W.: The Relation of Free Meander Geometry to Stream Discharge and Its Geomorphic Implications. American Journal of Science, vol. 263, Dec. 1965, p. 885.

12. Charlton, F.G.: Meandering Channels in Alluvium. Channel, A Current Information Guide, vol. 2, no. 10, Oct. 1969, p. 305.

13. Schumm, S.A.: Fluvial Geomorphology (The Historical Perspective). Preprint of Paper presented at the Institute of River Mechanics, Colorado State University, Fort Collins, Colo., June 15-26, 1970.

14. Winkley, B.R.: Practical Aspects of River Regulation and Control. Preprint of Paper presented at the Institute of River Mechanics, Colorado State University, Fort Collins, Colo., June 15-26, 1970.

15. Simons, D.B.: River and Canal Morphology. Preprint of Paper presented at the Institute of River Mechanics, Colorado State University, Fort Collins, Colo., June 15-26, 1970.

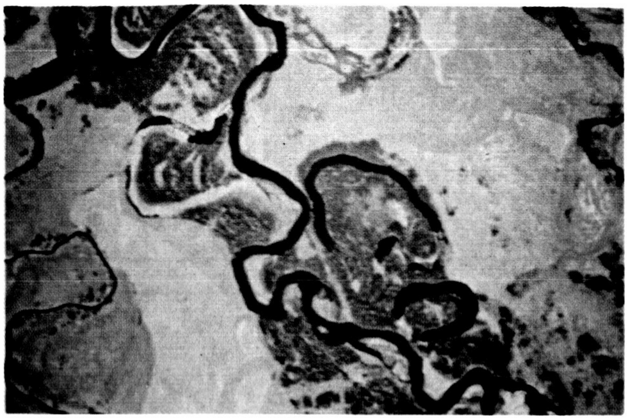
16. Rabbitt, Mary C., McKee, Edwin D., Hunt, Charles B., and Leopold, Luna B.: The Colorado River Region and John Wesley Powell. U.S. Geological Survey Professional Paper 669, 1969, p. 131.

17. Skinner, M.M.: Remote Sensing for Applied River Studies. In preparation for submission to American Society of Civil Engineers (ASCE), CEP71-72MMS16.

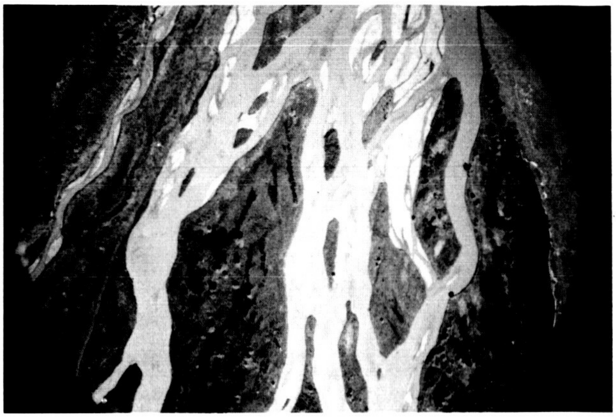
18. Leopold, Luna B., and Wolman, M. Gordon: River Meanders. Bulletin of the Geological Society of America, vol. 71, June 1960, p. 53.

19. Garner, H.F.: Rivers in the Making. Scientific American, April 1967.

20. Drury, G.H., ed.: Rivers and River Terraces. Praeger Publishers, New York, 1970.



Meander pattern/cutoff oxbows



Braided pattern

Figure 1. River patterns.

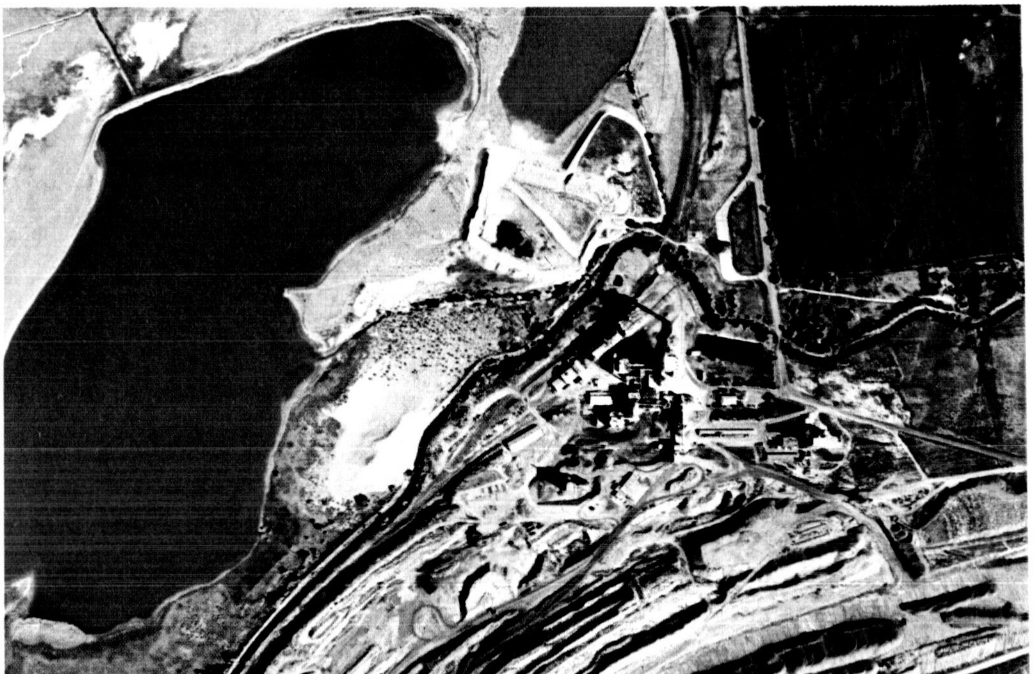


Figure 2. Internegative print from Kodak Aerochrome infrared film 2443 (cement plant near Fort Collins, Colorado).

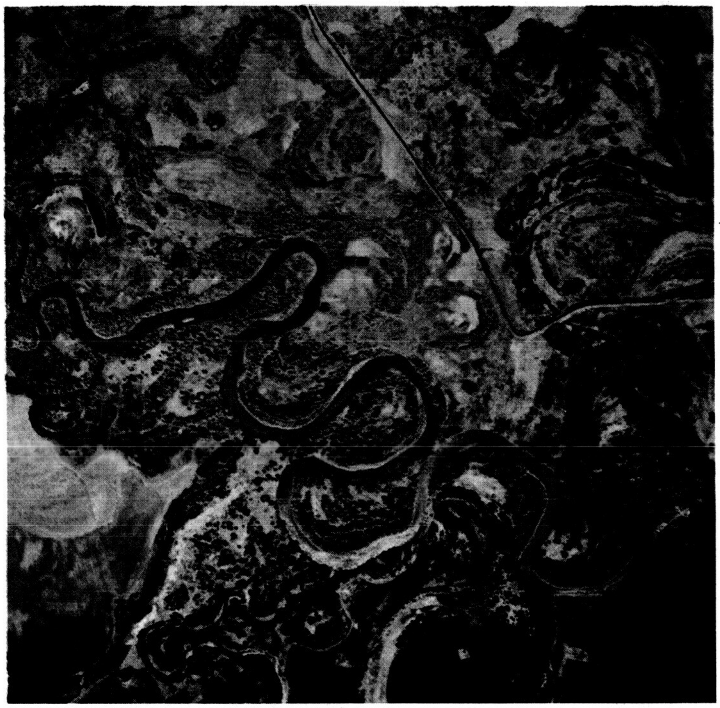


Figure 3. Internegative print from Kodak Aerochrome infrared film 2443 (cement plant near Fort Collins, Colorado).

Figure 4. Print from Kodak Aerocolor negative film 2445 (South Platte River in Denver, Colorado).

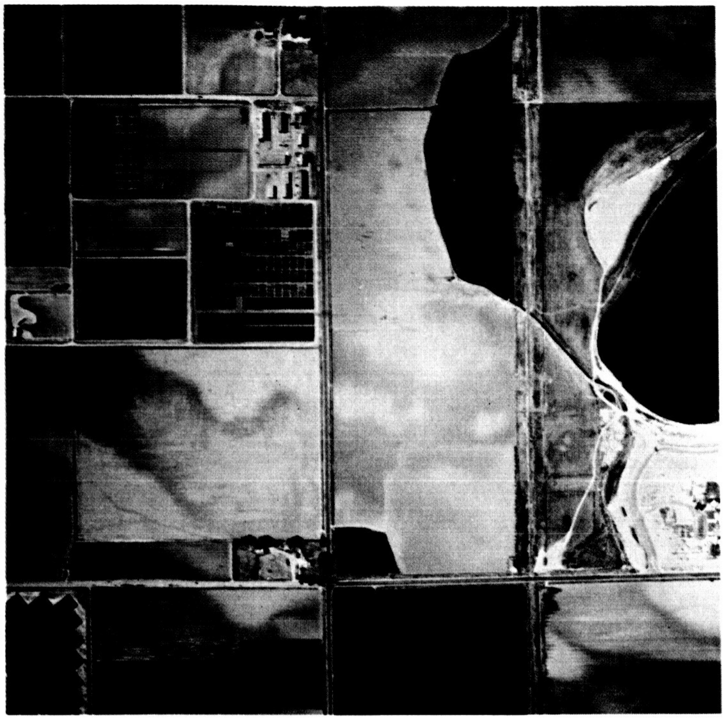


Figure 5. Ektachrome RC print from Kodak Aerochrome infrared film 2443 (area near Fort Collins, Colorado).

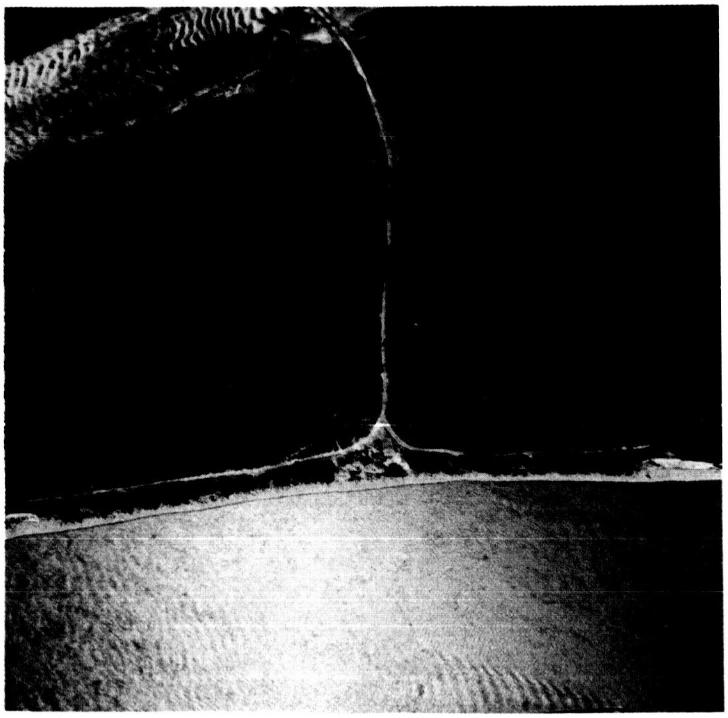


Figure 6. Ektachrome RC print from Kodak Aerochrome infrared film 2443 (Mississippi River near Vicksburg, Mississippi).

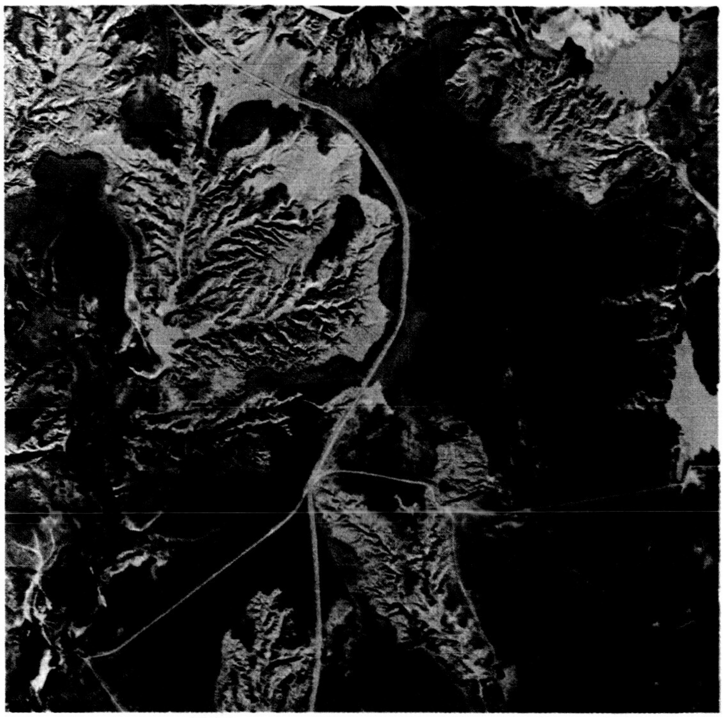


Figure 7. Special process print from Kodak Aerocolor negative film 2445 (area near Lusk, Wyoming).

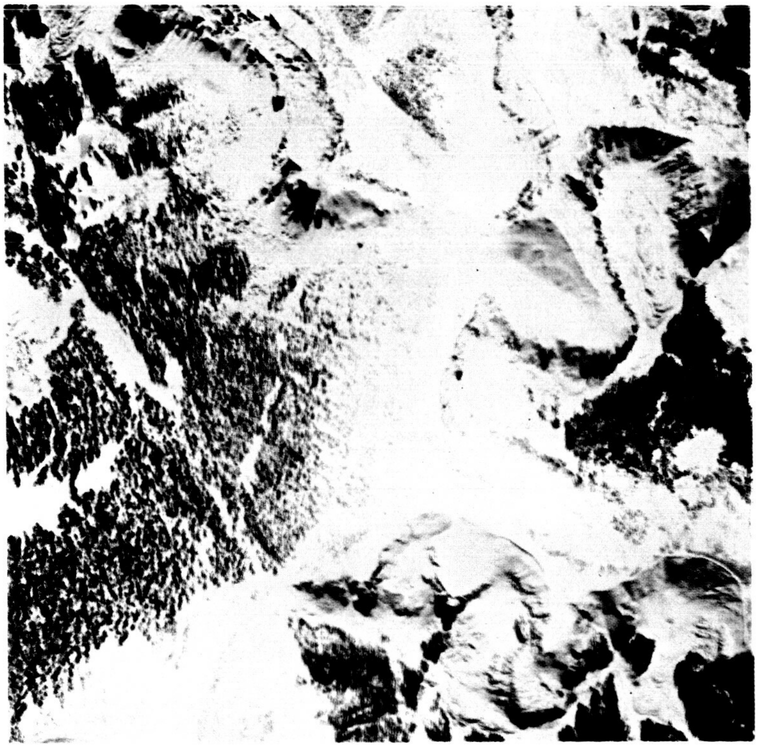


Figure 8. Ektachrome RC print from Kodak Aerochrome infrared film 2443 (Wolf Creek Pass area, Colorado; photography obtained in conjunction with Marshall Space Flight Center).

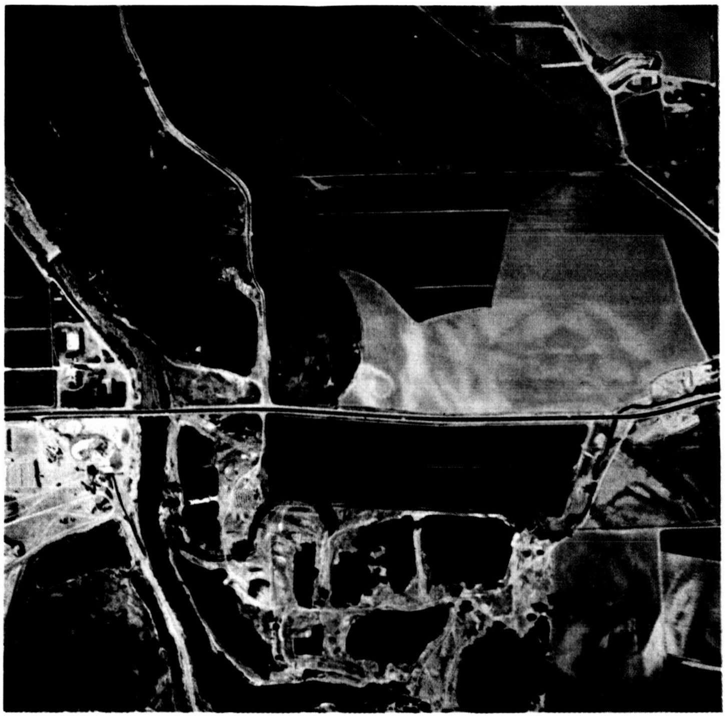


Figure 9. Ektachrome RC print from Kodak Aerochrome infrared film 2443 (area near Fort Collins, Colorado; note feedlot adjacent to stream).