

# Illinois State Water Survey Division

SURFACE WATER SECTION

AT THE  
UNIVERSITY OF ILLINOIS



SWS Contract Report 428

## BASINWIDE FLOW AND AQUATIC HABITAT ASSESSMENT MODEL FOR THE MIDDLE FORK AND SALT FORK OF THE VERMILION RIVER, WABASH BASIN

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Robin B. King, and Michael L. Pubentz*

Prepared for the  
Energy and Environmental Affairs Division  
Illinois Department of Energy and Natural Resources

Champaign, Illinois  
August 1987

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(Part of the joint project, "Landscape-Scale Interactions  
in the River Basin," conducted by the Illinois State  
Geological Survey, Natural History Survey, and State Water Survey)

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Energy and Environmental Affairs Division  
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## ABSTRACT

Protecting the ecological integrity of streams and rivers is a key factor in proper management of Illinois water resources. Land use, water withdrawals, streamflow regulation, drainage modifications, and the discharge of effluents all have a significant and generally detrimental impact on the biological integrity of streams and rivers. Avoiding adverse impacts while continuing to serve increasing societal water needs requires an understanding of the factors that influence the quality of the aquatic habitat. The basins of the Middle Fork and Salt Fork of the Vermilion River in Illinois share the same history of glaciation and are hydrologically homogeneous. However, activities such as extensive stream channel modifications and urban development have significantly altered physical and hydrologic conditions in the Salt Fork Basin. These two basins provide a unique setting for studying differences in aquatic habitat quality.

The physical characteristics, geomorphology, and hydrology of both basins are discussed. Data from USGS measurements are used to evaluate hydraulic geometry relations for both basins. A field study was conducted to gather information on the distributions of local depths and velocities in the basin streams as well as on substrate types and dissolved oxygen concentrations. Hydraulic geometry relations were combined with probabilistic distributions for depth and velocity to form flow models for both basins. These models are used to simulate flow hydraulics for streams throughout the basins. The flow simulations provide the information on local depths and velocities needed to evaluate the suitability of the stream aquatic habitat with the incremental methodology developed by the Instream Flow Group of the U.S. Fish and Wildlife Service. Habitat response curves are presented for two fish species for both basins.

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BASINWIDE FLOW AND AQUATIC HABITAT ASSESSMENT MODEL FOR THE MIDDLE FORK AND SALT FORK OF THE VERMILION RIVER, WABASH BASIN--Project Completion Report to the Energy and Environmental Affairs Division, Illinois Department of Energy and Natural Resources, August 1987, Champaign, Illinois, 110 p.

KEYWORDS--instream flow/ aquatic habitats/ stream fisheries/ channel morphology/ physical models/ simulation/ habitat suitability/ incremental methodology/ hydraulic geometry

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INTRODUCTION

Protection of the ecological integrity of streams and rivers has been explicitly recognized in the State Water Plan (Illinois State Water Plan Task Force, 1984) as a key factor in proper management of Illinois water resources. In addition to providing natural aquatic habitats, streams and rivers serve as a significant source of water supply for public, industrial, and agricultural uses and are an important link in the transport and assimilation of wastewater. Land use, water withdrawals, streamflow regulation, drainage modifications, and the discharge of effluents all have a significant and generally detrimental impact on the biological integrity of streams and rivers. Protecting the ecology of Illinois surface waters, while continuing to serve increasing societal water needs, requires an understanding of the factors that influence the quality of the aquatic environment. Implementation of broad-based management plans that protect streams and rivers requires quantitative assessment of instream flow needs.

The Middle Fork Vermilion River and the Salt Fork Vermilion River join to form the Vermilion River in Vermilion County, Illinois. The basins of these two rivers share the same history of glaciation and have a common drainage divide. Over the past 100 years activities within these basins have altered the physical and hydrologic conditions. The smaller tributaries of both basins have been channelized; however, channel modifications have been much more extensive in the Salt Fork Basin than in the Middle Fork Basin. Nearly all of the land in the Middle Fork Basin is used for agriculture. Along the river, the area is forested and known for its scenic beauty. There are two sizable urban areas (Rantoul and Urbana-Champaign) within the Salt Fork Basin. The streams in this basin receive large effluent discharges from the wastewater treatment plants serving



these communities. The dissimilarity between these two basins offers a unique opportunity to study the ensuing differences in the aquatic habitat quality.

This report describes research conducted by investigators at the Illinois State Water Survey (ISWS) as part of a joint project with the Illinois Natural History Survey and the Illinois State Geological Survey. This combined effort has two objectives: 1) to study the ways in which basin geomorphology, hydrology, and cultural development influence the quality and quantity of aquatic habitat in a basin, and 2) to incorporate the information gathered into analytical procedures and models for assessing instream flow needs and ecological impacts of changes in land and water use in a basin. The procedures and models developed give insight into the ecological response of a stream system to human activities, and provide analyses germane to making watershed management decisions.

#### Objectives and Scope

The primary objective of the ISWS portion of this project is the development of a flow and habitat assessment model for each of the two basins. Together the flow and aquatic habitat models relate the quantity of useful habitat to the flow rate in a stream. The flow model is based on the principles of hydraulic geometry which relate flow characteristics such as flow width, depth, and velocity along a stream to drainage area and flow duration. The methodology used was developed by Singh and Broeren (1985) and Singh et al. (1986) in a pilot study of the Sangamon River Basin. The flow model is specifically designed for use with the instream flow incremental methodology (IFIM) developed by the Cooperative Instream Flow Service Group (IFG) of the U.S. Fish and Wildlife Service. The IFIM links habitat quality and quantity to flow characteristics.

This report discusses: 1) background information and related research; 2) the geology and morphology of the basins and their present-day physical configurations (e.g., major stream channel modifications, effects of urbanization, channel slope, and bank conditions); 3) regional flow-duration and basin hydraulic geometry relations; 4) a field study of channel forms, substrate, and dissolved oxygen concentrations, and the development of depth and velocity distributions; 5) adjustment factors for

hydraulic parameters; 6) the flow and aquatic habitat assessment model developed for the two basins; and 7) results for two target fish species.

#### Acknowledgments

This study was supported by the Energy and Environmental Affairs Division and the State Water Survey Division of the Illinois Department of Energy and Natural Resources. Thomas Heavisides of the Research and Planning Section of the Energy and Environmental Affairs Division served in a liaison capacity during the course of this study. The help of the staff of the U.S. Geological Survey, Urbana office, in providing historical flow measurement information collected at various gaging stations in the study area is deeply appreciated.

Becky Howard typed the draft and camera-ready copy of the report. Linda Riggins and Lynn Weiss prepared the final graphics, and Gail Taylor edited the report.

### BACKGROUND INFORMATION AND RELATED RESEARCH

#### IFG Incremental Methodology

Numerous case studies have been conducted to assess the environmental impact of completed or proposed alterations of streamflow characteristics and to evaluate instream flow needs of selected stream reaches. The most widely recognized means of investigating instream flow needs is to relate the quantity of suitable habitat to discharge, using the instream flow incremental methodology (IFIM) developed by the IFG (Stalnaker, 1979). The incremental methodology is compatible for use with optimization models for water resources allocations and can be applied to the design and operation of water projects for water supply, power generation, flood protection, and economic efficiency (Loar and Sale, 1981; Milhous and Grenney, 1980).

The most significant flow parameters related to aquatic habitat suitability are depth and velocity. Variations in depth and velocity throughout a stream reach create a continuum of conditions essential to meeting the diverse needs of a variety of fish species at different life stages and of other riverine life forming the food chain. The IFG incremental methodology relates these critical streamflow parameters to the quantity of suitable habitat. The basis of the IFG approach is a

tabulation of fish habitat preference curves for depth and velocity as well as substrate, temperature, and cover. All preference curves vary between 0.0 and 1.0, based on the preference of a given species (at its different life stages) for various depths, velocities, substrates, etc. A source file of digitized preference curves for more than 500 warm and cold water fish species is maintained by the IFG (Loar and Sale, 1981). Typical life stages are adult, juvenile, fry, and spawning.

The aquatic habitat of a stream reach is analyzed on an incremental flow basis. A stream reach is conceptually segmented into an array of individual cells by partitions transverse and parallel to the flow. Each cell is defined by its flow surface area and by characteristic depth, velocity, substrate, etc., for each measured (or simulated) discharge. The habitat suitability for each cell, as defined by these parameters, is independently evaluated by using the preference curves for the given fish species and life stages. Through segmentation of a stream reach into a number of cells, the local variations in habitat suitability created by local flow conditions, such as those in riffles and pools, can be accounted for.

The quantity of suitable habitat or the weighted usable area, WUA, is calculated from:

$$WUA = \sum_{i=1}^N S(d_i) \cdot S(v_i) \cdot \dots \cdot a_i \quad (1)$$

in which  $S(d_i)$ ,  $S(v_i)$ ....are the preference indices for depth,  $d_i$ , velocity,  $V_i$ , ..., characteristic of a portion of the stream having a flow surface area  $a_i$ , and  $a_i$  is the total surface area of the study reach. Joint preference indices for depth and velocity,  $S(d,v)$ , have been proposed (Bovee, 1982). The joint preference,  $S(d,v)$ , is substituted for the product  $(S(d) \cdot S(v))$  in equation 1. This procedure approximates the total water surface area in a simulated reach as an equivalent area of preferred habitat for a given flow condition. The values of WUA computed for different discharges may be compared to assess the relative quantity of suitable habitat expected under various flow scenarios.

A stream habitat study yields the habitat response curves (WUA versus discharge relations) for various fish species and their life stages. The

impact of altering the streamflow regime can be assessed from the habitat response curves. The impact of channel alteration can be assessed by developing a new habitat response curve for the altered condition and comparing it with that for the unaltered condition. Critical low-flow limits for sustenance of the stream fishery can be evaluated.

The local variations in depth and velocity throughout the stream reach must be known to evaluate the WUA for each discharge. The flow models developed by the IFG for simulation of stream hydraulics are calibrated from measurements of flow velocities and depths in a representative stream reach across about 6 to 10 transects for two or more discharges. In order to evaluate WUA at other discharges, a relationship between discharge and local values of velocity and depth must be established.

#### Hydraulic Modeling

Hydraulic modeling of study reaches is a critical aspect of an instream flow needs study. Reliable flow modeling is essential for extrapolation of results beyond the discharges physically measured. Currently the IFG supports two basic approaches to flow modeling for habitat evaluation, each of which is available as a computer algorithm. One approach is based on Manning's equation and performs a modified step-backwater calculation. This is commonly referred to as the water surface profile (WSP) program or IFG-2. The second modeling approach (IFG-4) relies on developing log-log linear relationships between stage and discharge at each transect and between individual cell discharge and associated average velocity (Milhous et al., 1984).

The IFG-2 and IFG-4 models are designed to simulate flows for a specific reach. Each requires extensive field work to collect calibration data. Typically, the IFG-2 model is used, as it requires somewhat less calibration data than the IFG-4 model. The models do not adequately simulate low-flow hydraulics. The limited scope of the IFG-2 model has been demonstrated in applications where a successful calibration could not be accomplished for low flows, and the validity of the relations used in the IFG-4 model is not well established (Bovee and Milhous, 1978; Milhous et al., 1984).

Reach-specific calibrated models such as IFG-2 and IFG-4 cannot be used to reliably predict flow conditions in other unmeasured stream reaches in a basin. Typically, two or three representative reaches in a basin are selected for detailed hydraulic modeling. The results of the model for the study reaches may be extended to other reaches with similar drainage areas through the principles of hydraulic geometry. However, relative differences in pool and riffle depths vary with drainage area, and the analysis described provides no empirical or theoretical basis for interpolating the local variations in depths and velocities between streams of different orders.

The IFG-2 and IFG-4 models are not appropriate or practical for basinwide instream flow analyses because of the extensive fieldwork required to gather calibration data, the limited range of flows which can be modeled, and the lack of reliable means of extrapolating results to unmeasured stream reaches.

Details of the modeling assumptions and procedures may be found in Bovee and Milhous (1978), Bovee (1982), and Milhous et al. (1984). The limitations of the models are discussed by Bovee and Milhous (1978) and Singh et al. (1986).

A methodology for basinwide flow modeling was derived by Singh and Broeren (1985) and Singh et al. (1986) in a study of the Sangamon River Basin in Illinois. A portion of the area draining to the Sangamon River lies in Champaign County, Illinois, adjacent to the uplands of the Salt Fork River. The northern half of the Sangamon watershed has undergone the same glacial advances as the study area.

The flow model employs generalized relationships for discharge and streamflow characteristics which apply to streams throughout a basin. Hydrologic and hydraulic geometry relations are derived from historical data collected by the USGS at streamgaging stations. This information is augmented by field measurements of discharge, local depths, and velocities as well as riffle-pool forms and substrate. Functions relating patterns of local depths and velocities to drainage area and flow duration are developed from the field data. The simulation results are compatible for use with the habitat model created by the IFG. The flow model is interfaced with the suitability indices (IFG habitat model) to form a basinwide flow and aquatic habitat model.

### Stream Network Relations

Leopold and Maddock (1953) first stated the concept of hydraulic geometry by relating width (W), depth (D), and velocity (V) to discharge (Q) at a particular stream cross section (e.g., gaging station):

$$\begin{aligned} W &= aQ^b \\ D &= cQ^f \\ V &= kQ^m \end{aligned} \tag{2}$$

in which  $b + f + m = 1.0$  and  $a \cdot c \cdot k = 1.0$ , and D is the average depth of flow and equals  $Q/(W \cdot V)$ . This form of the equation plots as a straight line on log-log scale. Dunne and Leopold (1978) observed that a curvilinear relation may be closer to reality. Singh et al. (1986) found that a third-order polynomial provides a better approximation of the trend displayed by the data collected near gaging stations in the Sangamon River Basin in Illinois.

Leopold and Maddock (1953) used power functions similar to the station equations listed as equation 2 to express the trend of increasing W, D, and V with drainage area for a constant frequency of discharge. Relations linking flow parameters throughout the basin also may be constructed as functions of drainage area and flow duration. Stall and Fok (1968), expanding on the original concepts of hydraulic geometry, defined basin relations for hydraulic parameters in the form:

$$\ln (\text{parameter}) = a + bF + c(\ln A_d) \tag{3}$$

in which a, b, and c are regression coefficients for a basin, F is the decimal flow duration, and  $A_d$  is the drainage area. These general relations were confirmed for Illinois streams and for selected basins in the United States (Stall and Yang, 1970). The form of the relationship remains constant for different basins regardless of the physiographic setting. Hydraulic geometry relations illustrate an orderly progression of change in a stream system.

Numerous researchers have observed that stream networks show a consistent, interdependent pattern of formation. The consistency in the nature of stream channel formation is evidenced in recurring stream

geometry patterns such as pool-riffle sequences. The pool-riffle sequence forms in a fairly predictable pattern, repeating on the average every 5 to 7 times the stream width; and the width increases with drainage area (Leopold and Wolman, 1957; Harvey, 1975; Nunnally and Keller, 1979). The average pool depth will also increase with increasing drainage area. In an extensive review of river patterns in Russia, Rzhanitsyn (1960) reported that the maximum pool depth-to-width ratio and riffle depth-to-width ratio maintain similar relationships when plotted against drainage area for a given discharge frequency such as average annual discharge. The distribution of depths throughout riffles and pools in different reaches may be linked by relating the standard deviation of depth to drainage area and flow duration for similar channel forms. The distribution of velocities may be related to the channel characteristics and the bulk flow velocity.

#### **VERMILION RIVER WATERSHED: MIDDLE FORK AND SALT FORK BASINS**

The Vermilion River is tributary to the Wabash River in Indiana. The watershed lies primarily in Ford, Champaign, and Vermilion Counties in Illinois and Warren and Vermillion Counties in Indiana. The three main branches of the Vermilion River are the Middle Fork, the Salt Fork, and the North Fork. The Vermilion River stream network is shown in Figure 1. The Middle Fork and Salt Fork Basins lie entirely within Illinois.

The Middle Fork River has its headwaters in Ford County. After leaving Ford County the Middle Fork flows southeast through Vermilion County, where it joins the Salt Fork River. The Middle Fork River has a drainage area of 449 sq mi at its mouth. The Salt Fork Basin covers the eastern half of Champaign County. The Salt Fork River flows generally north to south in Champaign County, then east to its confluence with the Middle Fork River in Vermilion County. The Salt Fork River has a drainage area of 509 sq mi at its mouth. The geomorphology of the two basins is similar; however, the present drainage networks differ considerably as a result of human intervention. The hydrology of the two basins is influenced by unique geological features as well as by urbanization.





### Basin Geomorphology

The Vermilion River Basin lies in a region of extensive glacial history. During the "Great Ice Age," or Pleistocene Epoch, at least three glacial advances invaded the present-day basin (Willman and Frye, 1970). The resulting glacial deposits altered the drainage network and buried virtually all the original bedrock surface under drift layers up to 400 feet thick. Thus, the present surficial material is quite young, geologically speaking, and is Wisconsinan in origin. Wisconsinan drift deposits are distinctly less compact and lighter in color than the older underlying glacial drift. They consist largely of pebbles, sandy clay, and clayey silt interspersed with boulders, sand, and gravelly sand.

Basin topography is essentially broad and hummocky throughout most of the area but becomes gently rolling along the morainal ridges. Steep slopes occur mainly at the valley walls of the larger streams in the lower end of the basin. The steep slopes are probably associated with the erosional work of Wisconsinan glacial meltwater.

The retreat of the Wisconsinan glacier was marked by numerous readvances (Willman and Frye, 1970) of sufficient duration to construct terminal moraines. The moraines exerted a strong influence on the development of the drainage system by acting as drainage divides. For example, the northern boundary of the basin is defined by the Chatsworth Moraine, and the Gifford Moraine separates the Middle Fork Vermilion from the Salt Fork Vermilion. Other moraines in the basin played an equally important role in the development of the drainage patterns.

The parent materials of soils in the Vermilion River Basin are almost exclusively glacial in origin, and usually consist of thin to moderately thick loess deposits overlying Wisconsinan till, outwash, and lakebed sediments (Fehrenbacher et al., 1984). The only soils of non-glacial origin are the alluvial, silty loams found in the bottomlands of the larger streams.

The Vermilion River Basin lies entirely within the Bloomington Ridged Plain physiographical region identified by Leighton et al. (1948). Drainage development in this region is generally in the initial stage. Low flow is highly variable because of variations in soils (Wangness et al., 1983). Streams cut in clayey deposits will have lower sustained flows than

those flowing through more permeable deposits. Natural drainage is rated from poor to moderately good or good.

#### Streambed Profiles and Equilibrium Profiles

When a stream has reached the point where it is neither aggrading nor degrading its own bed, it is said to be mature and in a condition of equilibrium. Yang (1971) and Leopold et al. (1964) have shown that the profile of a mature alluvial stream appears concave up. In such a stream, the headslope is relatively steep, but slope tends to become less steep, or flatten out, in the downstream direction.

The probable equilibrium profiles for the Middle Fork, Salt Fork, Saline Branch, and Jordan Creek are compared to the present bed profiles in Figures 2 and 3. The relative immaturity of these streams is clearly seen by the significant difference in present-bed and equilibrium profiles. The present-bed profiles are closely associated with the geology of the area. The vast quantity of glacial drift deposits and the presence of relatively resistant bedrock at or near the surface in the lower portions of the basin contribute to the present shape of the bed profiles.

As the Middle Fork (mainstem) approaches the equilibrium profile, the Salt Fork bed profile will degrade further to meet its new base level (endpoint a, Figure 2b). Jordan Creek and the Saline Branch will in turn work to meet their new base levels as the Salt Fork approaches its equilibrium profile (endpoints b and c, Figures 2a and 3). Ultimately the entire Vermilion system may enter an equilibrium condition as the geologic controls imposed on the basin are removed through many years of stream action.

The average basin divide profiles for the Salt Fork and Middle Fork are also plotted in Figures 2a and 2b. The divide profile is noticeably wavy and uneven, although there is a general decrease in elevation toward the downstream direction. As pointed out earlier, the drainage divides of the Vermilion River Basin are not strictly conventional compared to those of a more mature and developed landscape. The Vermilion drainage divides are generally morainal features left by Wisconsinan glaciation. Consequently the average basin divide profile can also be thought of as a longitudinal cross section of glacial end moraines, and this accounts for the rugged appearance of the divide profile.

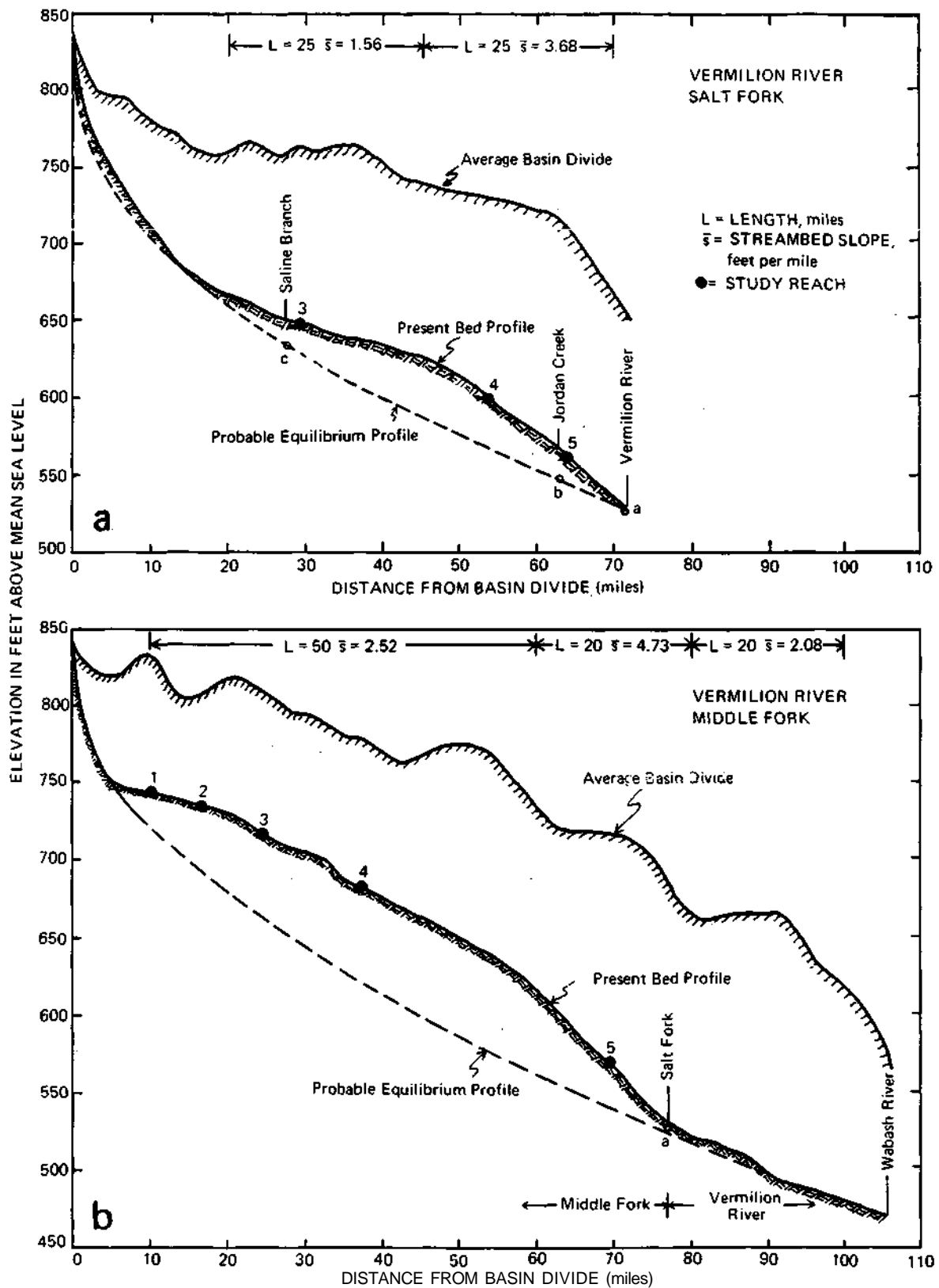


Figure 2. Present streambed profiles and probable equilibrium profiles  
 a) Salt Fork and b) Middle Fork Vermilion Rivers

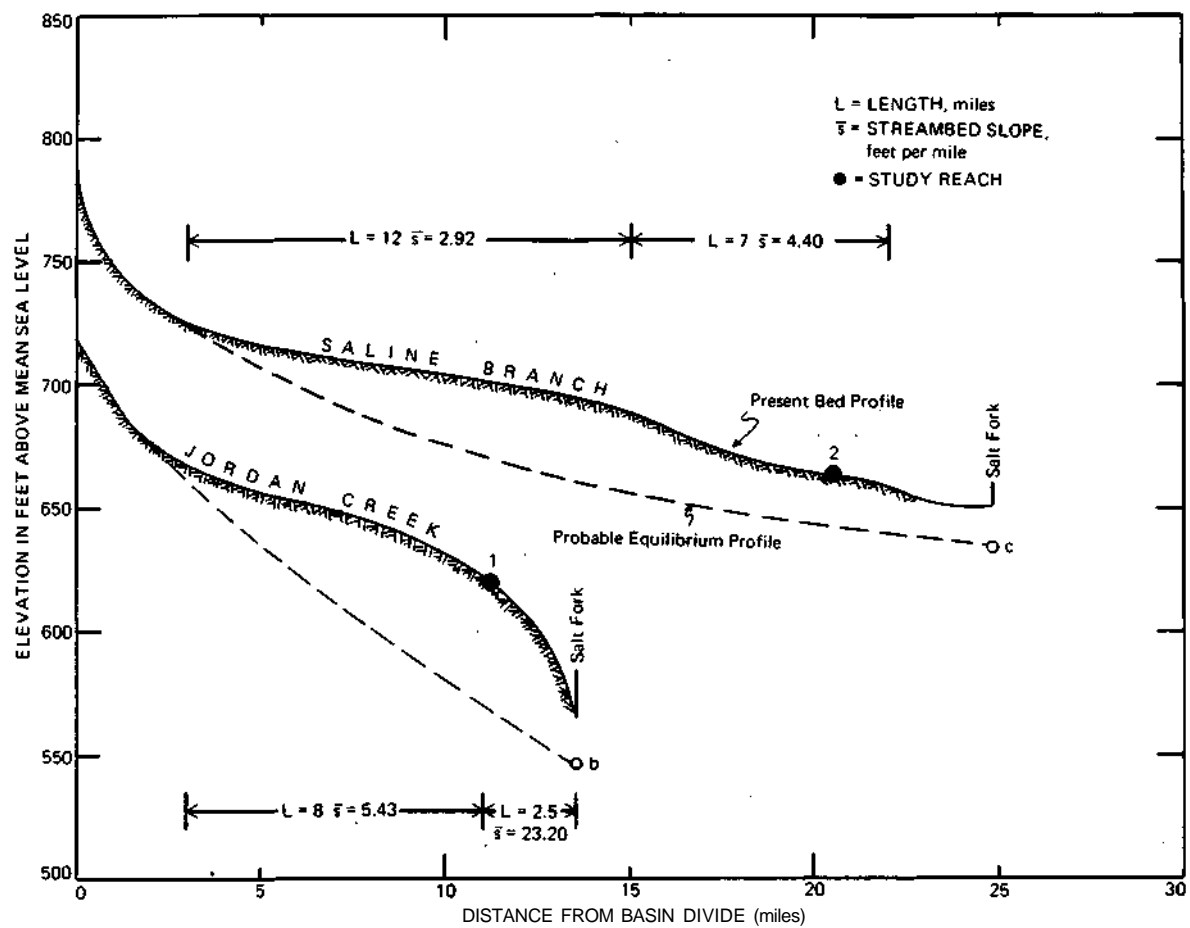


Figure 3. Present streambed profiles and probable equilibrium profiles: Saline Branch and Jordan Creek

### Drainage Improvements

The upland drainage networks of both the Middle Fork and Salt Fork Basins have been extensively modified. The topography of the area is generally flat and drainage is poor. Miles of ditches have been constructed to drain the originally swampy land. Many naturally occurring channels have been widened, deepened, and straightened to improve drainage. Most of the streams up to the main channels of the Middle Fork and Salt Fork Rivers throughout the watershed have been channelized as illustrated in Figure 4. The main channels of the Middle Fork and Salt Fork are naturally occurring stream channels. In addition to the surface drainage improvements, sub-surface drain tiles have been installed to accelerate drainage in many of the cultivated fields. Hay and Stall (1974) conducted an extensive investigation of drainage channel improvements in the Vermilion River, and much of the information in this section is drawn from their report.

The two main upland tributaries of the Middle Fork shown in Figure 1 -- the Wall Town Drainage Ditch (East Branch of the Middle Fork), and the Big Four Drainage Ditch (West Branch of the Middle Fork) -- are almost entirely man-made. One exception is an approximately 2-mile segment of the Wall Town Drainage Ditch extending upstream from its confluence with the Big Four Drainage Ditch. The historical evidence shows the existence of a naturally occurring stream up to this point. Approximately 25 miles of the Big Four Drainage Ditch main channel in Ford County was widened to 50 feet in 1937. The channel modifications in the Big Four Drainage Ditch end just above the Ford-Champaign County line. The drainage area at this point is approximately 180 sq mi. The last clean out and removal of accumulated sediment was performed around 1975.

Drainage modifications in the Salt Fork Basin have been more extensive than those in the Middle Fork Basin. Surface drainage of the upper 300 sq mi of the Salt Fork Basin is conducted through a network of artificially constructed ditches and channelized streams. The northern extreme of what is now the Saline Branch drains an area originally known as Beaver Lake, so named because of standing water during rainy seasons. The existing channels were deepened by 4 feet in 1908.

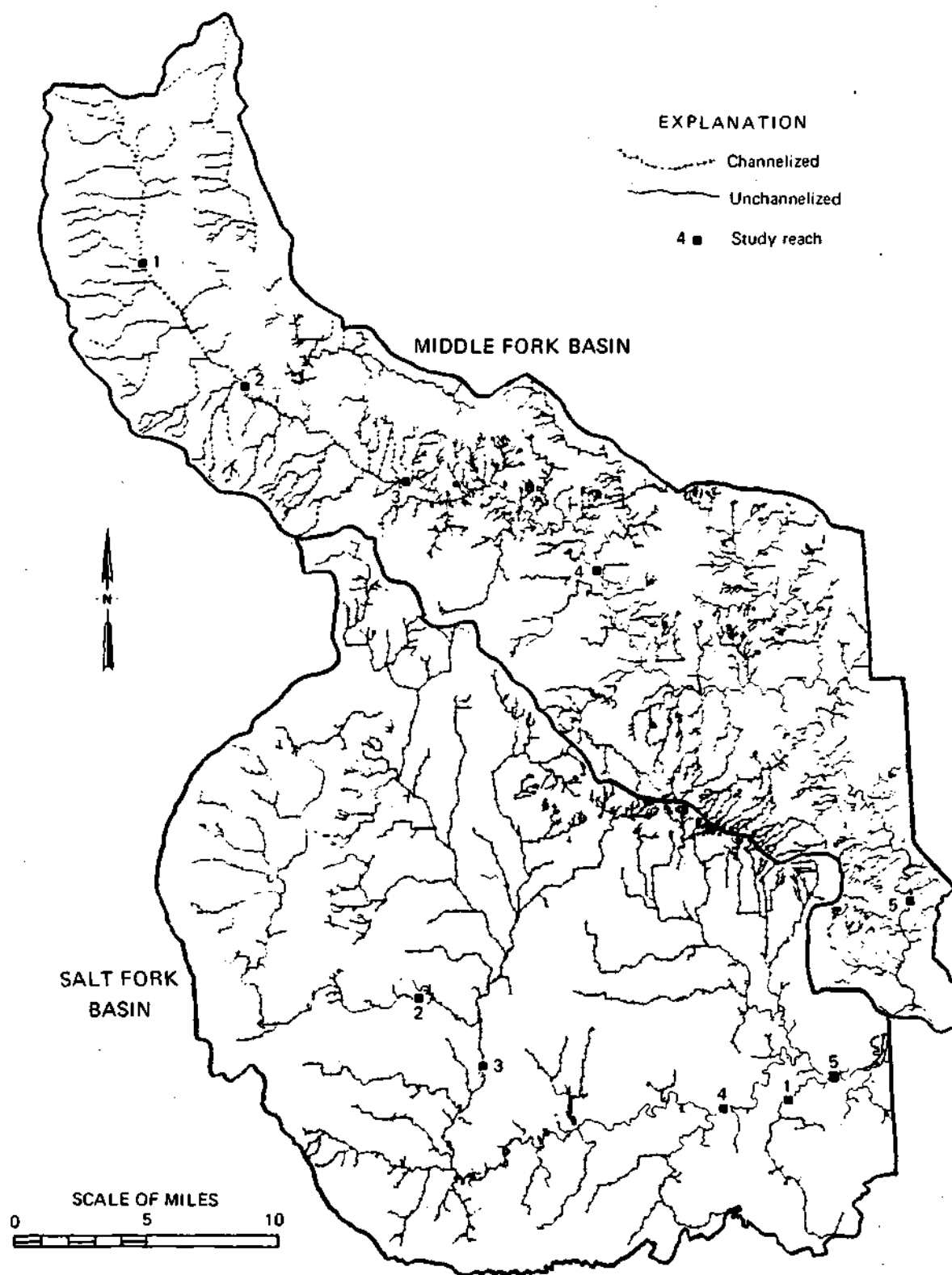


Figure 4. Stream channelization: Middle Fork and Salt Fork Vermilion Rivers (after Riley et al., 1985a and b)

Boneyard Creek is the only major urban drainage channel in the watershed. It drains parts of Champaign and Urbana and flows into the Saline Branch near north Urbana. It has been extensively modified over the years.

The Saline Branch has been shortened by 5 miles, widened to a 30-foot bottom width, and deepened by several feet. These modifications were performed on the reach from north of Urbana to the confluence with the Salt Fork River near St. Joseph.

The Upper Salt Fork Drainage Ditch was constructed with a 60-foot bottom width, tapering upstream to a 20-foot bottom width near Rantoul. The channel was constructed with an 80-foot bottom width for 4-1/2 miles downstream from St. Joseph. The constructed channel lies within the Upper Salt Fork Drainage District and is the largest constructed channel in the Vermilion Basin. Records dated as early as 1939 show problems with drift and sandbar formation in the Upper Salt Fork channel.

Typical engineering practice at the time of most of the channel construction was to achieve the highest gradient possible. The bed profile of the Upper Salt Fork in Figure 2a illustrates that the constructed channel slope resembles the theoretical equilibrium profile. The radical decrease in channel slope near the Saline Branch confluence suggests a subsequent reduction in sediment-carrying capacity and probably contributes to the problem of sediment deposition.

Most of the channel construction work was performed between 1880 and 1934. Since that time drainage improvement has consisted of maintaining the channels.

### Urbanization

Urbanization of an area tends to increase peak runoffs because of the efficient delivery of rainwater to streams through sewer systems and the decrease in losses to infiltration because of large expanses of impervious areas. Over time, channel cross-sectional area tends to increase downstream of urban areas (Hammer, 1972). The Urbana-Champaign area is the largest urban development in the two basins. The long-term effects of urbanization on channel size are not readily discernible because of the artificial construction of Boneyard Creek and the Saline Branch.

Another consequence of urbanization is the discharge of treated wastewater to surface water streams. The wastewater is an additive component to the streamflow when communities derive their public water supply from ground water that is independent of the surface water. This is the case in the Salt Fork Basin. These additive effluent discharges tend to sustain flow levels and alter the streamflow regime, particularly at low flows.

In the Middle Fork Basin the wastewater treatment plant serving Paxton is the only facility discharging effluent into the basin network. The average daily discharge in 1985 was 0.71 cfs. This quantity does not appreciably alter the streamflow regime of any major streams in the basin.

Four communities (Gifford, St. Joseph, Rantoul, Urbana-Champaign, and Chanute Air Force Base) discharge effluents to streams in the Salt Fork Basin. Of these effluents, the combined effluents from the Rantoul Sanitary District and Chanute Air Force Base facilities and those from the Urbana-Champaign Sanitary District facilities are sufficiently large to alter the flow regime of the receiving streams. In 1985 the average daily discharge from the Rantoul Sanitary District east plant was 4.1 cfs and the average daily discharge from Chanute Air Force Base was 1.9 cfs. The effluents are discharged to the upper reaches of the Upper Salt Fork Drainage Ditch. The average daily discharge in 1985 from the Urbana-Champaign Sanitary District northeast plant to the Saline Branch was 22.4 cfs.

Outside of the Middle Fork and Salt Fork Basins the wastewater treatment plant serving Danville is the only other facility discharging effluents at a rate sufficient to notably influence streamflow. This plant discharges to the Vermilion River below the two study basins.

The effects of these discharges on basin hydrology are discussed in the next section.

### Hydrology

The hydrology of the Vermilion River Basin was investigated by analyzing historical daily flow data from continuous gaging stations located in the watershed (Figure 1). Data from seven USGS gaging stations were used in the final development of flow-duration equations. These stations, their locations and drainage areas, and the years of record used



are listed in Table 1. Two stations (03336500 and 03336645) are in the Middle Fork Basin; three stations (03337500, 03336900, and 03338000) are in the Salt Fork Basin; and the remaining two stations are on the Vermilion River downstream of the confluence of the Middle Fork and Salt Fork Rivers. A long-term record for USGS gage 03337000 on Boneyard Creek in Urbana is available; however, data from this gage were not used. Flows measured at this gage are influenced by artificial modifications to both drainage pattern and channel character and do not follow trends typical of those at the other gages. The remaining gages in the watershed do not have a sufficient length of record for use in developing flow-duration equations.

Effluents discharged from the four wastewater treatment plants serving Rantoul, Chanute Air Force Base, the Urbana-Champaign area, and Danville (all in Illinois) affect flows measured at four of the gaging stations. The gage near St. Joseph in the Salt Fork River is downstream of the effluent outfalls from the Rantoul and Chanute Air Force Base treatment plants; the gage near Homer is downstream of those two plants and the Urbana-Champaign treatment plant. Flows measured at USGS gage 03338500 on the Vermilion River near Catlin are influenced by the effluents discharged from the above three plants. USGS gage 03339000 on the Vermilion River near Danville is downstream of the discharge points of all four plants.

Effluent discharges have increased over the years as the populations of these communities have increased. These discharges thus introduce a time-varying component to the river flows. The volume of effluents discharged by these plants is large compared to expected natural low flows of the receiving streams.

The daily flows measured at the two Salt Fork stations and the two Vermilion River stations were adjusted to reflect natural flow conditions. This was accomplished by subtracting the estimated effluent discharges from the measured flow. Treatment plant discharge information collected by the Illinois Environmental Protection Agency was used to estimate effluent discharges for previous years. Water use data on file at the Illinois State Water Survey and population data also were used to estimate effluent discharges.

Relations between naturally occurring discharge and drainage area were developed from the daily flow data collected at the two stations in

Table 1. Continuous USGS Gaging Stations Used in Developing  
Flow-Duration Equations

<u>USGS gage number</u>	<u>Location</u>	<u>Drainage area (sq mi)</u>	<u>Years of record used</u>
03336500	Bluegrass Creek at Potomac	35.0	1950-1971
03337500	Saline Branch at Urbana	68.0	1937-1958
03336900	Salt Fork near St. Joseph	134.0	1959-1983
03338000	Salt Fork near Homer	340.0	1945-1958
03336645	Middle Fork River above Oakwood	432.0	1979-1983
03338500	Vermilion River near Catlin	959.0	1940-1958
03339000	Vermilion River near Danville	1290.0	1929-1983

the Middle Fork Basin and the station on the Saline Branch at Urbana, as well as from the adjusted data for the remaining four stations discussed above.

The drainage area of Bluegrass Creek at USGS gage 03336500 is 35.0 sq mi. The drainage area at this location is the smallest of the drainage areas at the seven gaging stations whose daily flow records were used in the development of the flow-duration equations. Low flows measured at this gage do not have the same relationship to drainage area as low flows measured at the other six stations. Low flows measured at this station are less than would be expected on the basis of the trends indicated by the low flows measured at the other stations. Differences in flow regime between this station and other stations may be attributable in part to the extensive alteration of drainage patterns throughout the watershed. The stations with the next two smallest drainage areas are located in the Salt Fork Basin. The drainage area of the Saline Branch at gage 03337500 is 68.0 sq mi and the drainage area of the Salt Fork at gage 03336900 is 134.0 sq mi. Flows measured at these stations may show trends influenced by the accumulated effects of upstream drainage improvements. Another important factor is the interaction between surface flow and subsurface flow, which is governed by soil permeability. As noted previously, low flows in streams throughout the Bloomington Ridged Plain region tend to vary considerably from stream to stream.

Equations defining the relationship between drainage area and discharge were developed for naturally occurring flows for flow durations 10, 20 . . . . 90%. A single relationship between drainage area and discharge was found for all stations for flow durations 10-60%. One equation for each flow duration mathematically defines the relationship. Two sets of equations were developed for flow durations 70-90%. One set of equations applies to streams with drainage areas greater than 60 sq mi, and one set of equations applies to streams with drainage areas less than 60 sq mi. The form of the equation for flow durations 10-60% for all streams, and for flow durations 70-90% for streams with drainage areas greater than 60 sq mi, is:

$$Q_f = C_f \cdot A_d \quad (4)$$

where

$f$  = flow duration

$Q_f$  = discharge in cfs for flow duration  $f$

$C_f$  = coefficient for flow duration  $f$

$A_d$  = drainage area in sq mi

The equation for streams with drainage areas less than 60 sq mi for flow durations 70-90% is:

$$Q_f = B_f + C_f \cdot A_d \quad (5)$$

where  $B_f$  = a constant for flow duration  $f$ . The values of the coefficients evaluated are listed in Table 2.

#### HYDRAULIC GEOMETRY

Station hydraulic geometry relations were developed from USGS data available for four stations in the Middle Fork Basin and seven stations in the Salt Fork Basin. These stations are listed in Table 3. The flow-duration equations presented earlier in this report were used to compute the discharges corresponding to flow durations 10, 20, ..., 90% at each of these 11 gaging stations. By substituting the computed discharges into station relations defining hydraulic parameters in terms of discharge, the values of the hydraulic parameters  $W$ ,  $D$ , and  $V$  were evaluated at each station for each of the nine flow durations. The computed values of  $W$ ,  $D$ , and  $V$  were used to determine the basin relations for  $W$ ,  $D$ , and  $V$  at each of the nine flow durations. The final basin equations define the values of  $W$ ,  $D$ , and  $V$  for any stream in a basin as a function of flow duration and drainage area.

The basin equations are a formalized expression of the relationship between hydraulic conditions throughout a stream network at a similar discharge frequency. Dunne and Leopold (1978) hypothesize that the consistency of the relationship between the various stations in a basin is indicative of the interdependency of streams in the network and the similarity of natural stream channel formation. Leopold and Maddock (1953) in their original work on hydraulic geometry and Dunne and Leopold (1978) in later related studies observed that the station equations should be developed only from data obtained at cross sections representative of the

Table 2. Regression Equations for Discharge

All drainage areas

$$\begin{aligned} Q_{10} &= 1.84195 \cdot A_d \\ Q_{20} &= 1.01391 \cdot A_d \\ Q_{30} &= 0.63179 \cdot A_d \\ Q_{40} &= 0.42056 \cdot A_d \\ Q_{50} &= 0.27892 \cdot A_d \\ Q_{60} &= 0.16671 \cdot A_d \end{aligned}$$

Drainage areas greater than 60 sq mi

$$\begin{aligned} Q_{70} &= 0.09129 \cdot A_d \\ Q_{80} &= 0.04544 \cdot A_d \\ Q_{90} &= 0.02064 \cdot A_d \end{aligned}$$

Drainage areas less than 60 sq mi

$$\begin{aligned} Q_{70} &= -4.06793 + 0.15908 \cdot A_d \\ Q_{80} &= -2.61676 + 0.08905 \cdot A_d \\ Q_{90} &= -1.25344 + 0.04153 \cdot A_d \end{aligned}$$

Note: Subscripts 10, 20, .... 90 denote % annual flow duration;  $A_d$  = drainage area in sq mi

Table 3. USGS Gaging Stations Used in Developing Hydraulic  
Geometry Relations

<u>Gage no.</u>	<u>Description</u>	<u>A<sub>d</sub>* measurements</u>	<u>Number of</u>	<u>Years</u>
				<u>of record</u>
Middle Fork Basin				
03336500	Bluegrass Creek at Potomac	35.0	249	1949-1971
03336090	Wall Town Drainage Ditch near Paxton	49.6	25	1967-1970
03336300	Middle Fork River at Armstrong	280.0	25	1966-1970
03336645	Middle Fork River above Oakwood	432.0	65	1978-1984
Salt Fork Basin				
03336940	Saline Branch near Thomasboro	3.8	23	1972-1974
03336970	Saline Branch near Leverett	47.8	46	1971-1975
03337500	Saline Branch at Urbana	68.0	207	1936-1958
03337700	Saline Branch near Mayview	82.1	50	1966-1974
03336900	Salt Fork River near St. Joseph	134.0	30?	1959-1984
03338000	Salt Fork River near Homer	340.0	148	1944-1958
03338097	Salt Fork River near Oakwood	489.0	57	1975-1985

\*A<sub>d</sub> = drainage area in sq mi

natural channel. The relationship of width, depth, or velocity to discharge at a section with bridge piers or abutments will differ from that at a natural section. On a larger scale, reaches which are dredged or leveed, or where flows are regulated or influenced by a dam or backwater, are typically not representative of the natural stream system.

The four gaging stations on streams in the Middle Fork Basin are all situated in reaches where the stream channel has not been directly modified by deepening or widening. USGS gage 03336090 is located in the 2-mile reach of the Wall Town Drainage Ditch which has not been channelized. However, the entire upstream drainage network is completely channelized. The Middle Fork Basin equations are fairly representative of flow conditions expected for natural stream channels. They do not necessarily represent flow conditions in small, channelized streams.

Five of the seven gaging stations in the Salt Fork Basin are located on streams where the channel and all of the upstream drainage network has been significantly altered from the natural state. Gage 03336940 ( $A_d = 3.8$  sq mi) is located in the Beaver Lake area, and gage 03336970 ( $A_d = 47.8$  sq mi) is located just downstream of the Beaver Lake area. Streams in this area have been widened and deepened. Gages 03337500 and 03337700 (with drainage areas of 68.0 and 82.1 sq mi, respectively) are situated in the reach of the Saline Branch that was extensively reconstructed. The channel of the Upper Salt Fork River upstream of gage 03336900 ( $A_d = 134.0$  sq mi) has likewise been channelized. Only the streams with larger drainage areas have not undergone channel modifications. The two gaging stations located in natural channel streams represent the two largest drainage areas of the seven stations.

The relationship between the values of  $W$ ,  $D$ , and  $V$  (for a given flow duration) at the various stations in the Salt Fork Basin will be highly influenced by the altered channel design and the extent of ongoing maintenance of the altered channels. The basin relations developed from this type of data are less general and without adjustment apply only to streams which have undergone similar channel construction.

All of the 11 gaging stations were inspected to determine the channel conditions, reach plan geometry, pool-riffle definition, and other pertinent features. This information is presented in Table 4. The Middle Fork stations are located in reaches where the channel is meandering. The

Table 4. Summary of Stream Channel Conditions near Gaging Stations

Gage No.	Channelized	Pool-riffle definition	Reach plan geometry	Bank slope	Bank. stability	Local land cover (December)	General substrate size
<b>Middle Fork</b>							
03336500	No	Ice cover during inspection	Meander	1:1	Unstable	Cultivated fields and forested	Unknown
03336090	No	Excellent	Meander	5:1 - vert.	Unstable	Forested	Sand-gravel
03336300	No	None visible	Meander	<1:1	Stable	Forested	Silt-sand
03336645	No	Excellent	Meander	1:1 - 3:1, some ~ vert.	Unstable	Forested	Gravel up to 3-ft boulders
<b>Salt Fork</b>							
03336940	Yes	Good	Straight	1:1	Stable	Cultivated fields	Sand
03336970	Yes	None visible	Straight	1:1	Stable	Cultivated fields	Sand
03337500	Yes	None visible	Straight	1:1	Stable	Urban	Sand, gravel, small cobbles
03337700	Yes	Excellent	Straight	1:1 - 3:1	Unstable	Cultivated fields	Sand, gravel, small cobbles
03336900	Yes	None visible	Straight	1:1	Stable	Cultivated fields	Silt, sand
03338000	No	Excellent	Meander	1:1	Moderately stable	Forested	Sand, gravel cobbles, boulders
03338097	No	Excellent	Meander	<1:1	Unstable	Forested	Sand, gravel



stream banks are for the most part unstable. The five Salt Fork stations in channelized streams are located in straight reaches and the banks are typically stable. The two stations with larger drainage areas are in meander reaches with somewhat unstable banks.

#### Data

The U.S. Geological Survey conducts an extensive program of streamflow measurements. As part of the continuing program, between 10 and 20 detailed current meter flow measurements are made every year at each active gaging station. This effort makes available a mass of data on streamflow and associated velocities, depths, and geometry of flow sections. For each measurement, velocities and depths are sampled at a stream cross section, the top width (W) is measured, and gage height is recorded. The flow cross-sectional area (A), the average velocity (V), and discharge (Q) are computed. The average depth (D), defined as the hydraulic depth, may be computed from  $D = A/W$  (Chow, 1959). Low to medium flows are typically measured by wading along a stream cross section. High flows with depths exceeding approximately 3 feet are usually measured from a bridge near the gage installation, from a cable car if available, or from a boat. The flow measurement data are not published but are available at USGS district offices.

Data collected near 15 streamgaging or water quality stations in the Middle Fork and Salt Fork Basins were obtained from the USGS district office in Urbana, Illinois. Data for three of the stations were insufficient to develop station relations. Station relations for USGS gage 03337000 on Boneyard Creek at Urbana were not used in the basin equation analysis as the station data exhibit atypical trends. Hydraulic geometry equations were developed from data collected near the 11 stations listed in Table 3. The basin name, station name, drainage area, number of measurements, and years of record used are included in Table 3.

The hydraulic consistency and accuracy of the flow data were checked by examining the stage-discharge relationship for the period of record and also by verifying that the continuity equation  $Q = W \cdot D \cdot V$  was satisfied by the recorded information. Gage height versus discharge was plotted on log-log scale from the available data. In a few cases multiple rating curves were evident. Only data forming a single curve were retained. This

elimination process reduced data scatter in the plots of flow parameter versus discharge to some extent. Measurements were omitted if  $W \cdot D \cdot V$  was not within 5% of the reported discharge. Usually from 1 to 5% of the measurements were omitted from the final data set because of these considerations.

The original field notes for each measurement were reviewed to identify it as a wading measurement (information collected by field personnel traversing the stream on foot, by boat, or from a cable car installation) or bridge measurement (measurement made by lowering equipment into the stream from a bridge or at a bridge site). The approximate location of the measured section relative to the gage was noted if reported.

#### Station Relations

Plots of the station hydraulic data are shown in Figures 5 through 15. There are three log-log plots for each station: width  $W$ , depth  $D$ , and velocity  $V$  versus discharge  $Q$ . The plots for each station show only the final data sets. Data collected at a wading section are plotted with a  $\circ$  symbol, and data obtained at a bridge section are plotted with a  $+$  symbol. The two vertical dashed lines in each graph are plotted at discharges equal to the 90% flow duration and 1.5 times the 10% flow duration. An exception to this is gage 03336940 in the Saline Branch near Thomasboro (Figure 9), for which the vertical dashed line at the lower limit marks the 60% flow duration discharge. The relationships developed in this project were limited to flows at or between these limits. Flows less than the higher discharge limit may be expected to be contained within the channel banks.

The discontinuity between the wading section data and the bridge section data at many of the stations demonstrates the difference in hydraulic conditions between the two channel configurations. The differences between trends exhibited by wading and bridge section data are site-specific. Only the wading station data were used to evaluate the station hydraulic geometry relations, as these sections are clearly more representative of most of the stream length.

Ideally, station hydraulic geometry plots show the correspondence of flow parameters to discharge at a single cross section. The scatter in the data in Figures 5 through 15, particularly at very low discharges, is

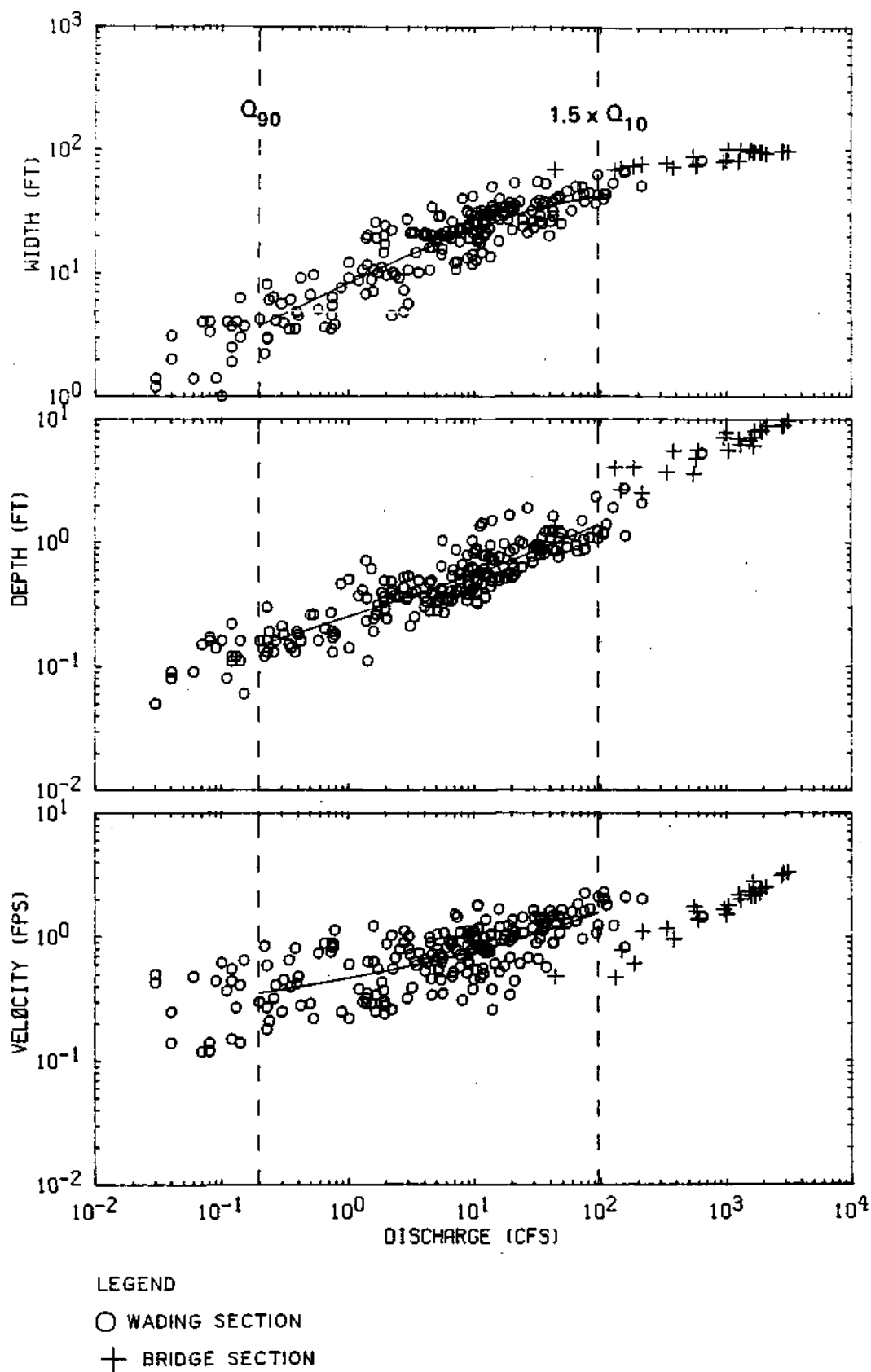
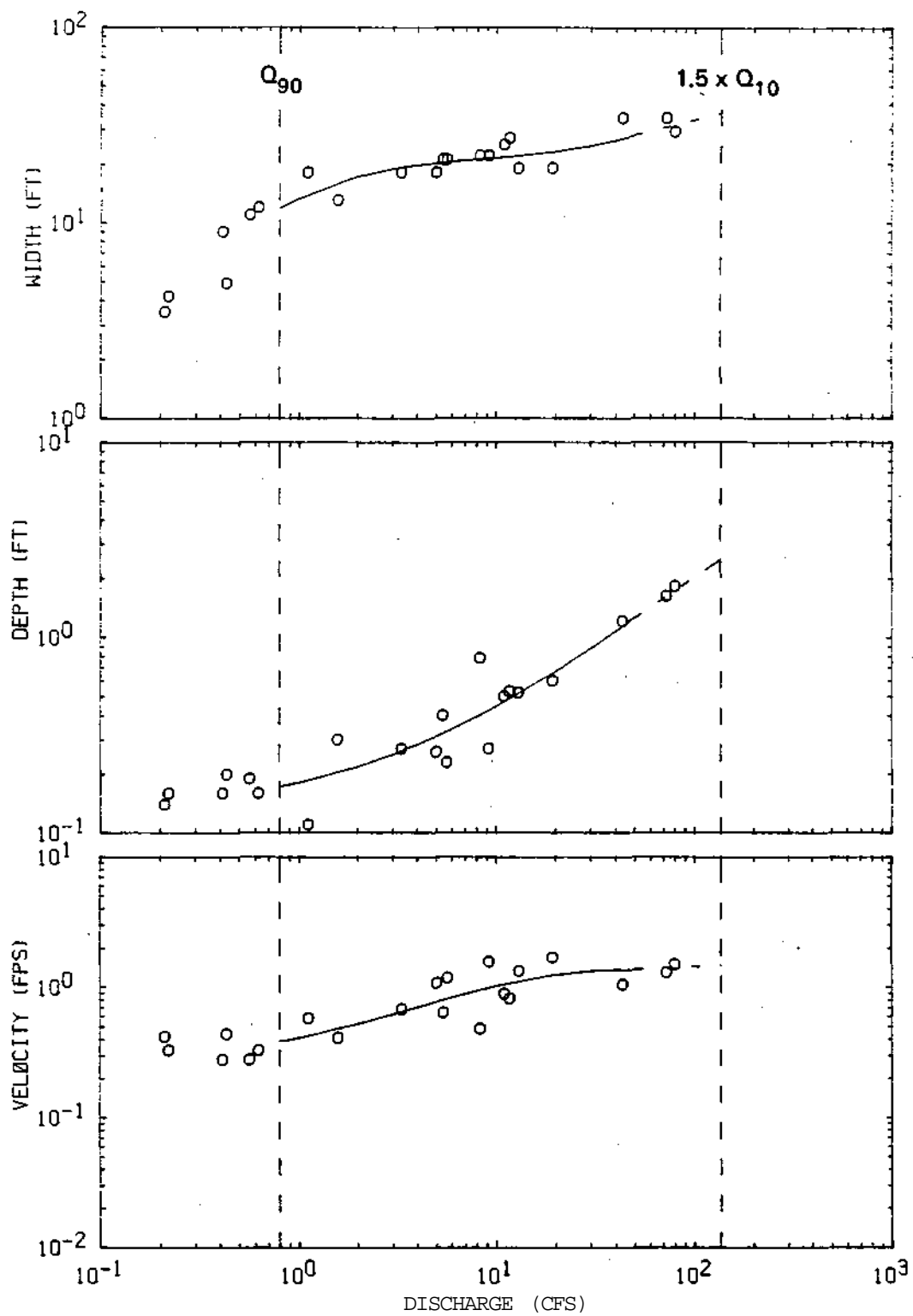


Figure 5. Station hydraulic geometry: Bluegrass Creek at Potomac

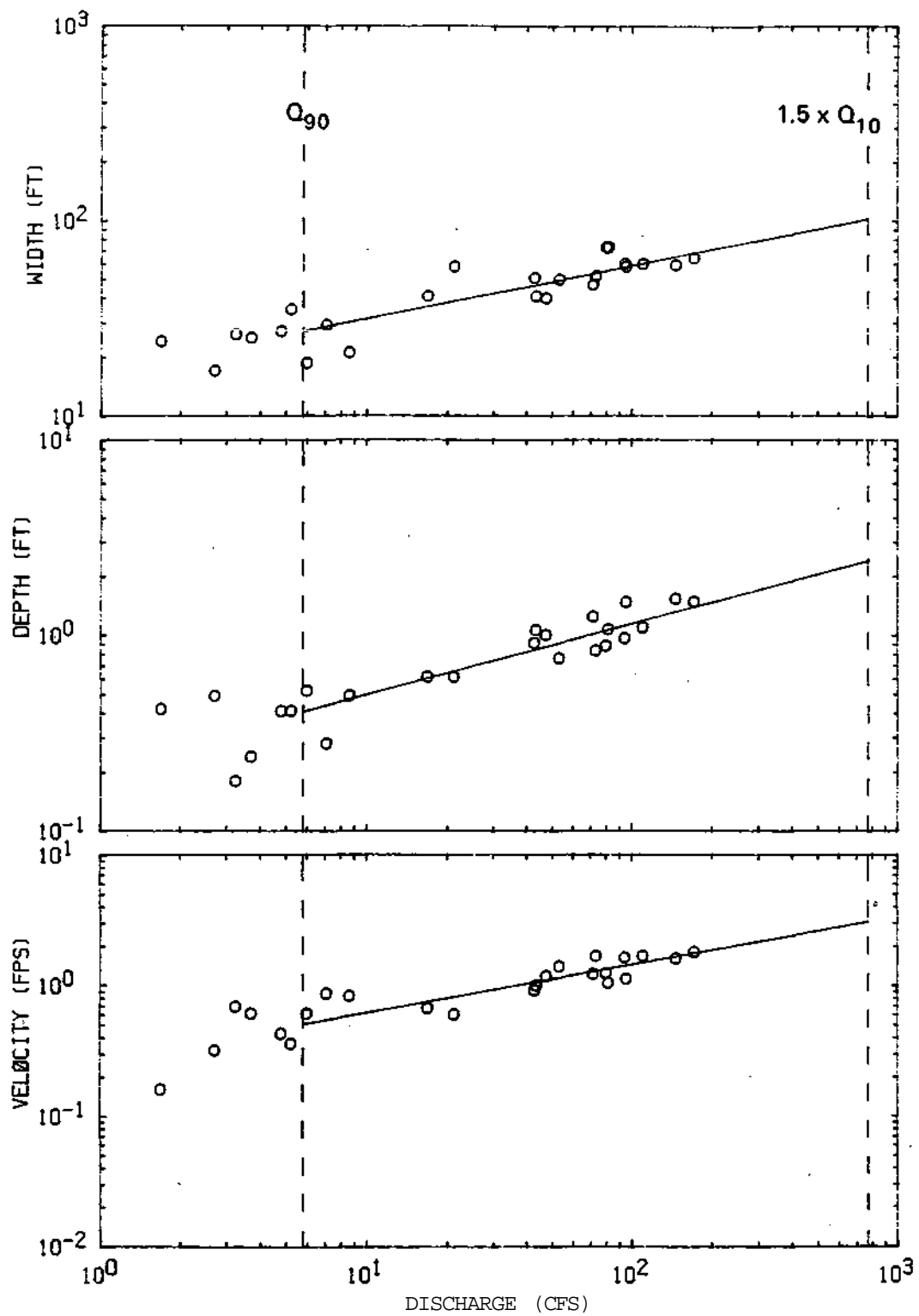


LEGEND

○ WADING SECTION

+ BRIDGE SECTION

Figure 6. Station hydraulic geometry: Wall Town Drainage Ditch near Paxton



LEGEND

- WADING SECTION
- + BRIDGE SECTION

Figure 7. Station hydraulic geometry: Middle Fork Vermilion River at Armstrong

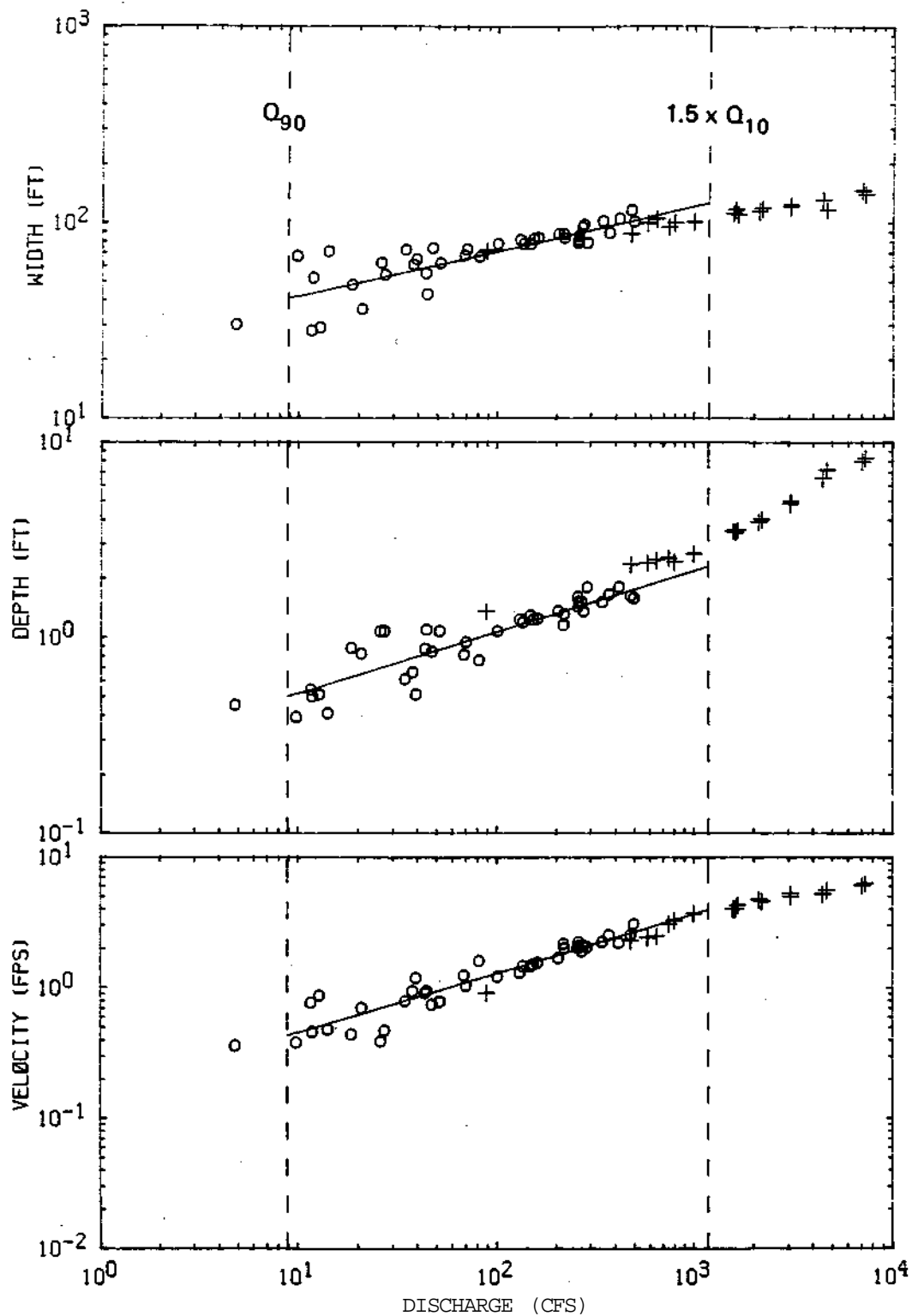
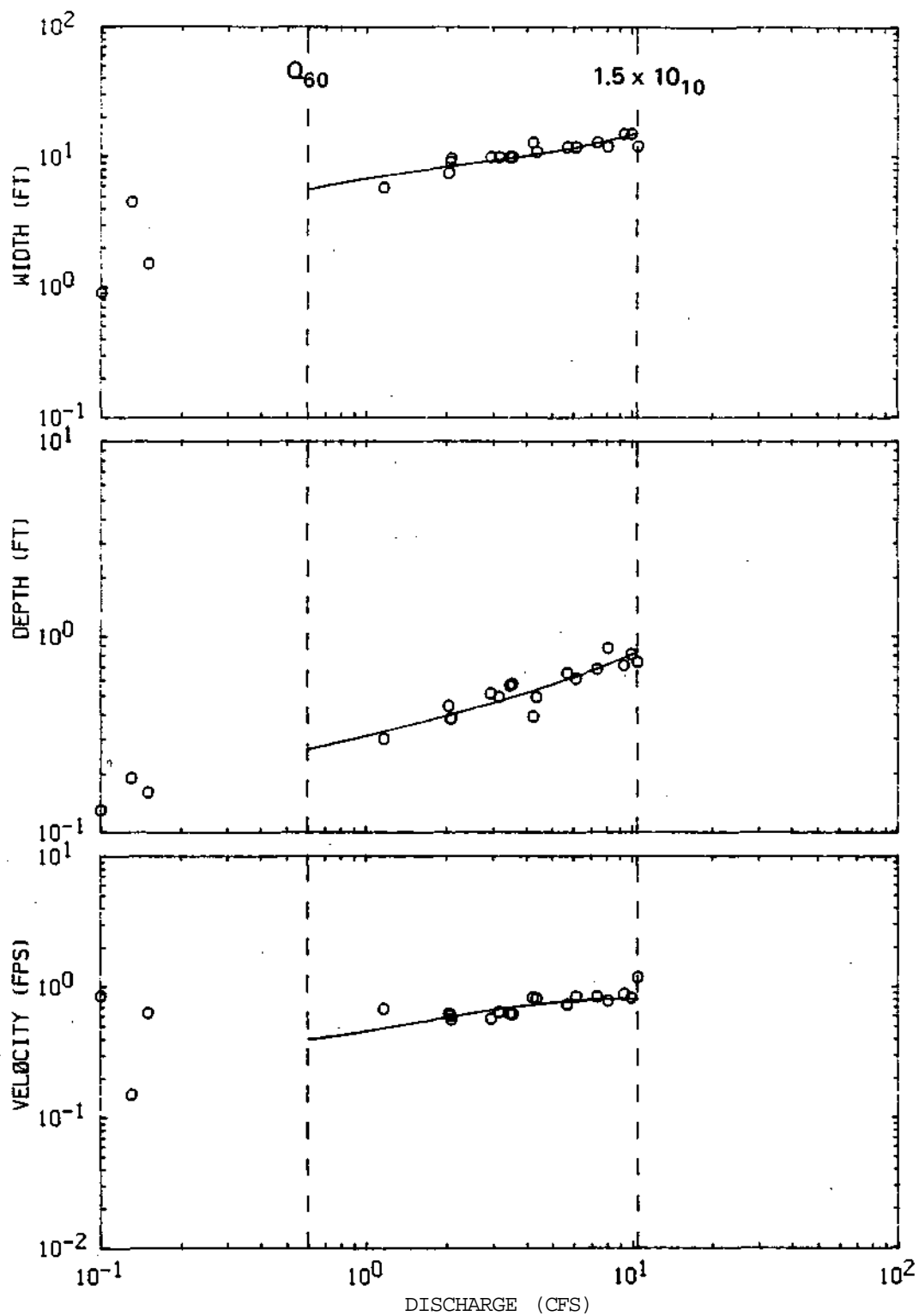


Figure 8. Station hydraulic geometry: Middle Fork Vermilion River above Oakwood

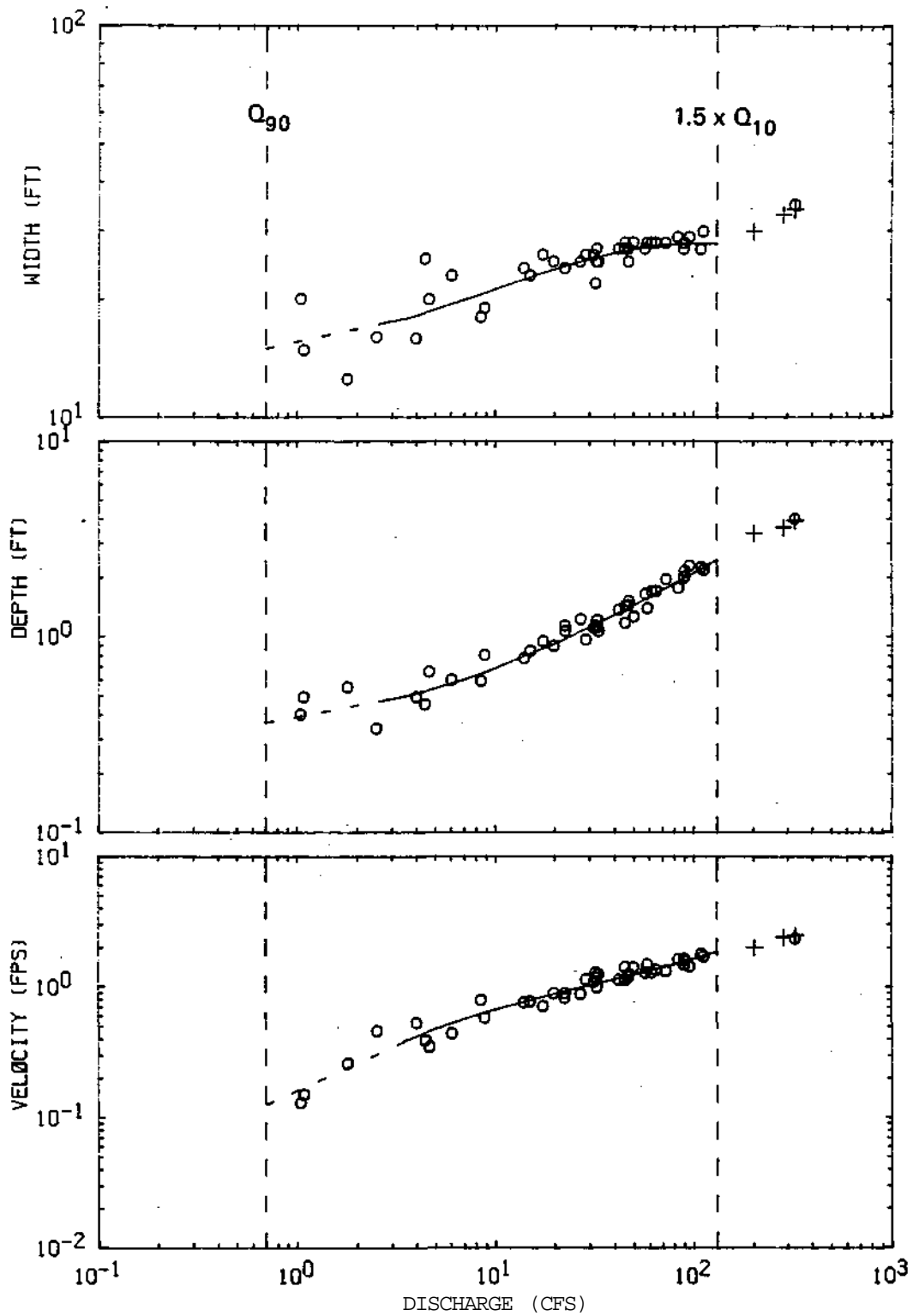


LEGEND

○ WADING SECTION

+ BRIDGE SECTION

Figure 9. Station hydraulic geometry: Saline Branch near Thomasboro



LEGEND

- WADING SECTION
- + BRIDGE SECTION

Figure 10. Station hydraulic geometry: Saline Branch near Leverett



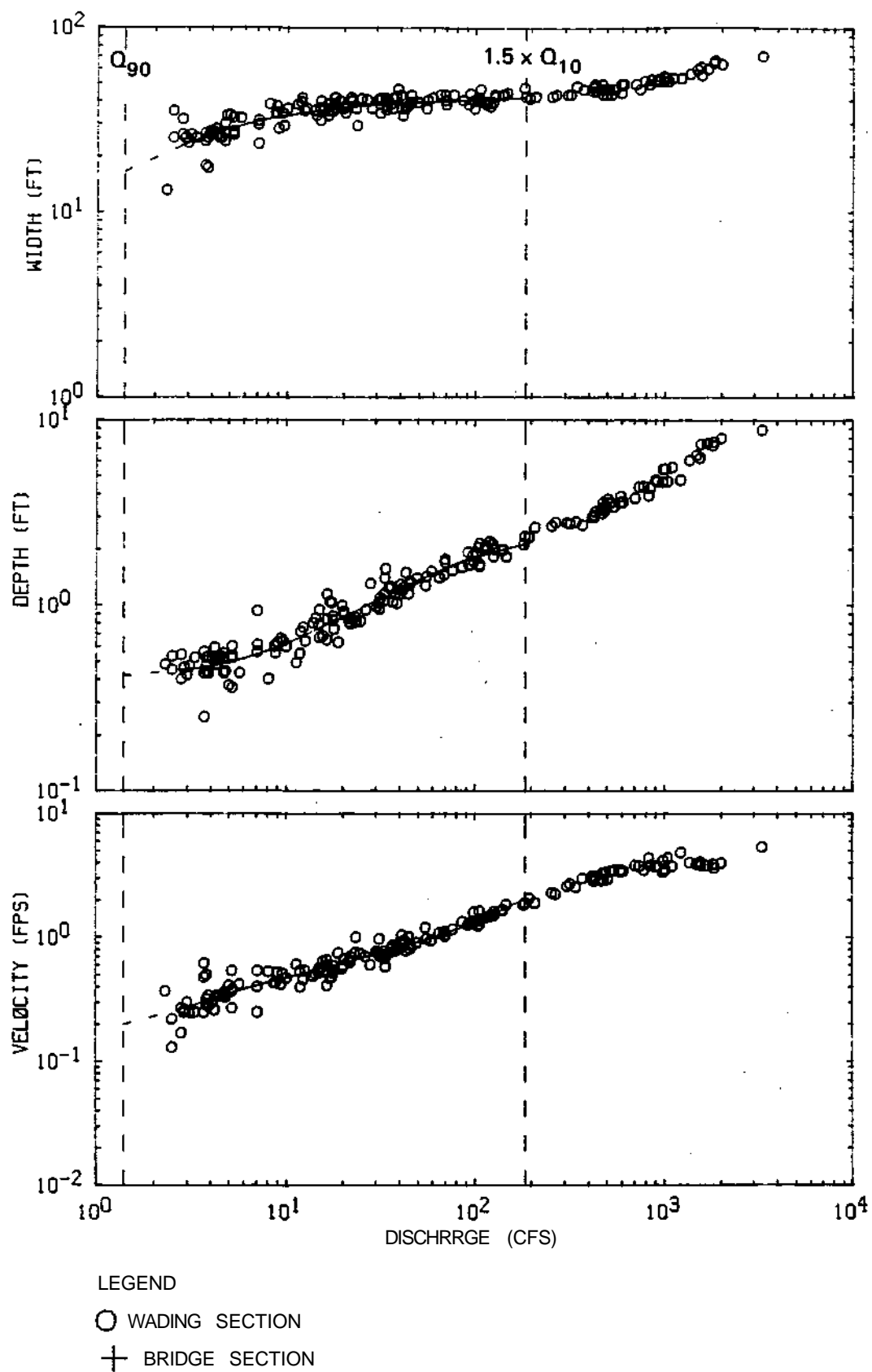
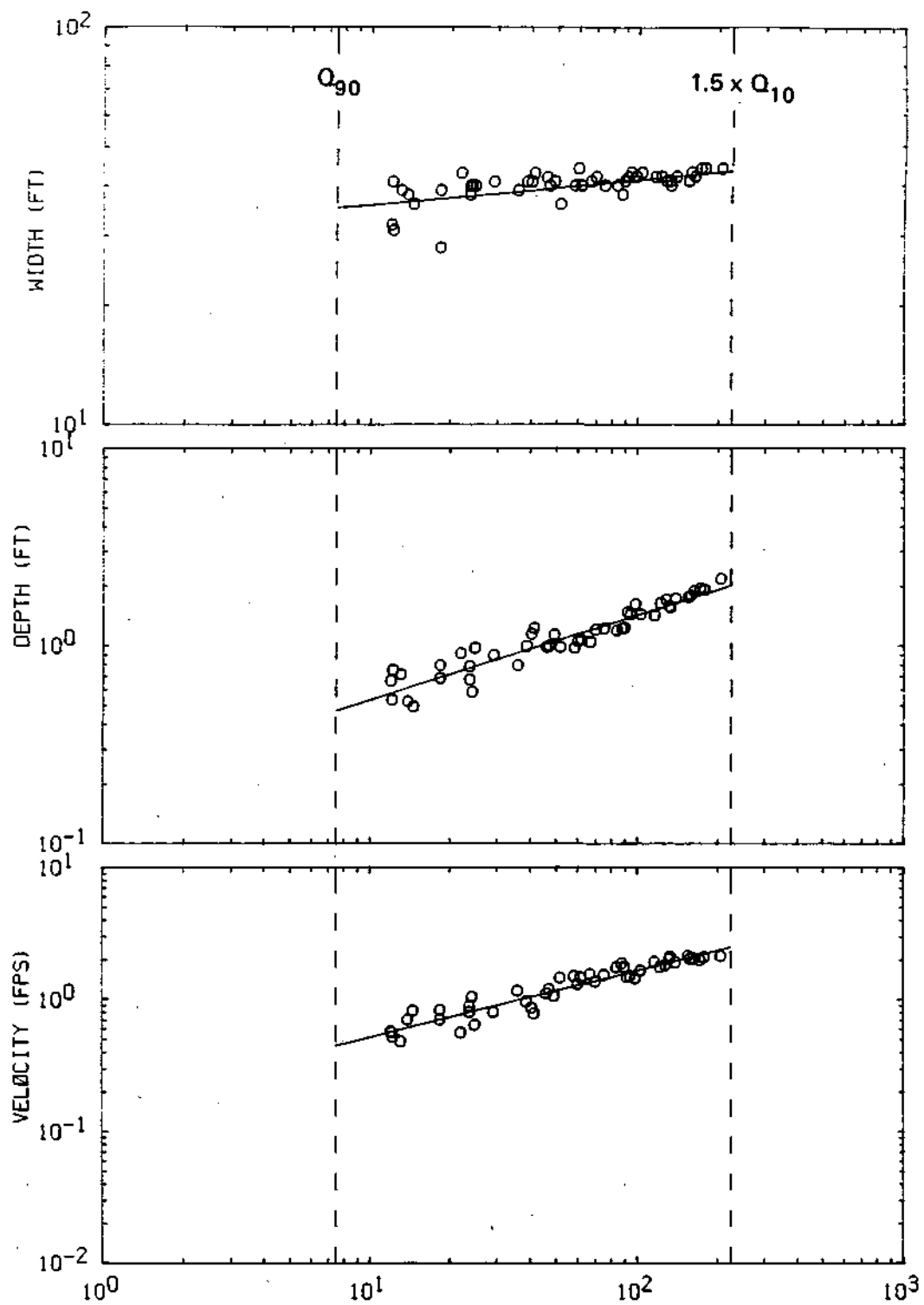


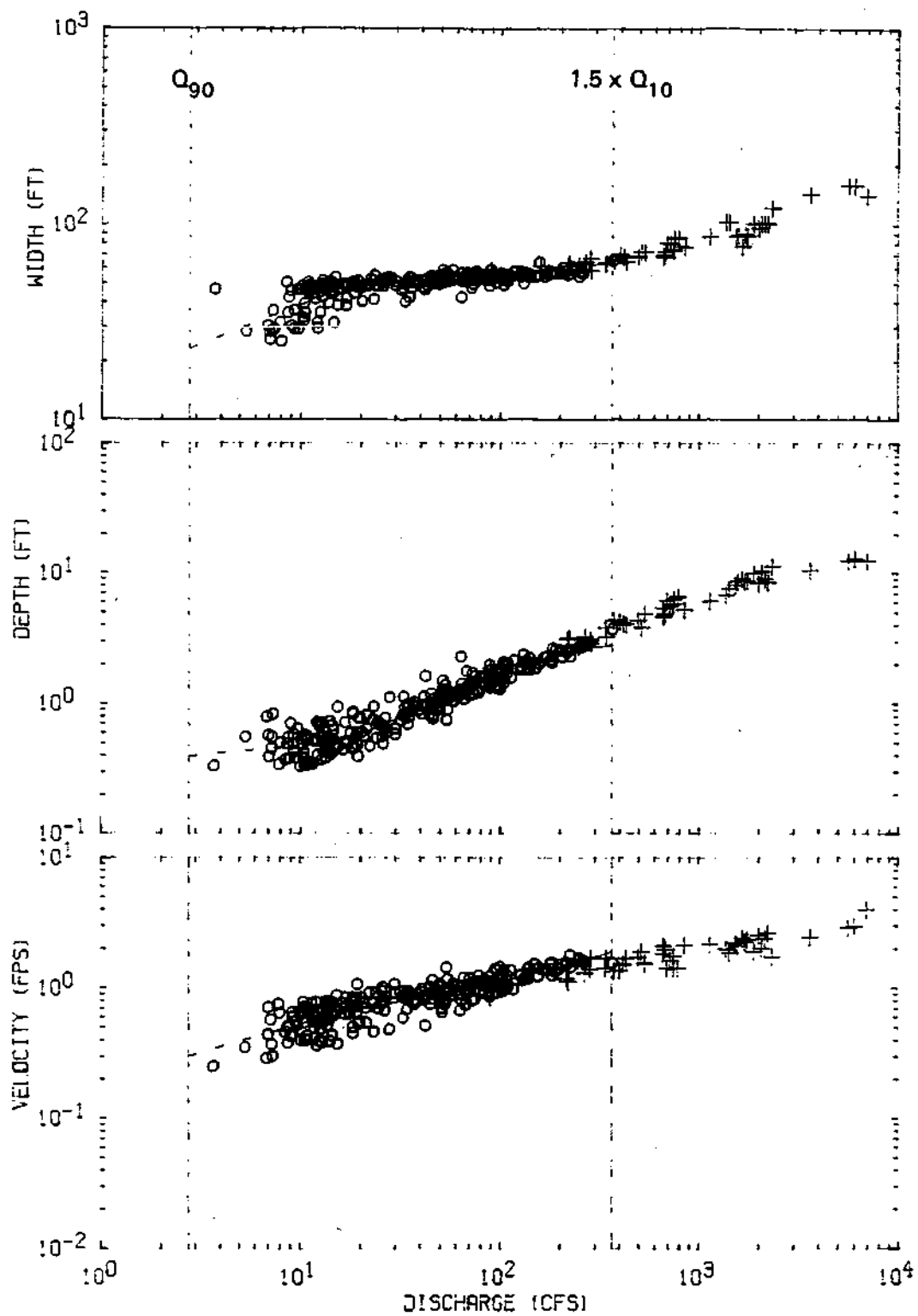
Figure 11. Station hydraulic geometry: Saline Branch at Urbana



LEGEND

- WADING SECTION
- + BRIDGE SECTION

Figure 12. Station hydraulic geometry: Saline Branch near Mayview

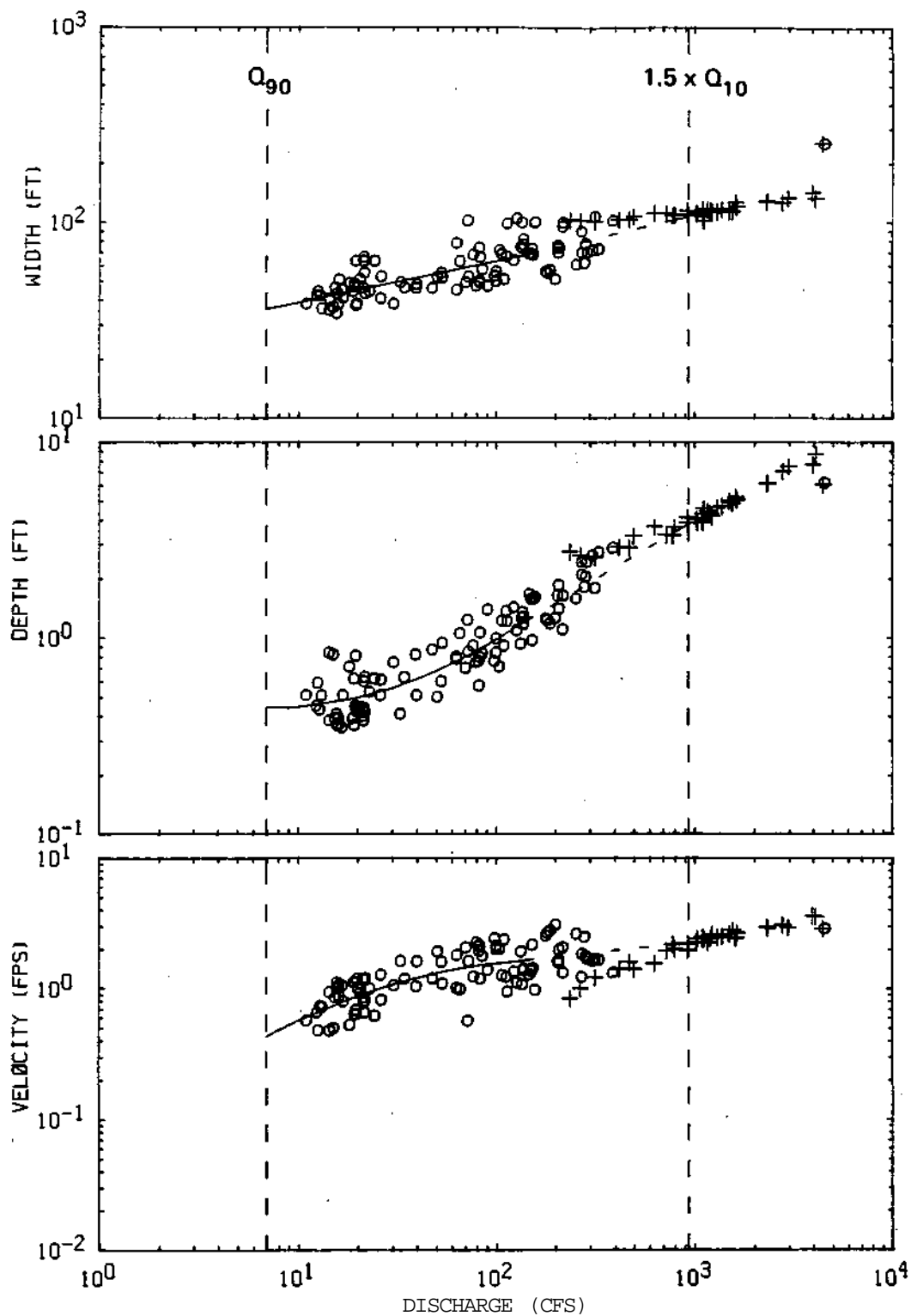


LEGEND

○ WADING SECTION

+ BRIDGE SECTION

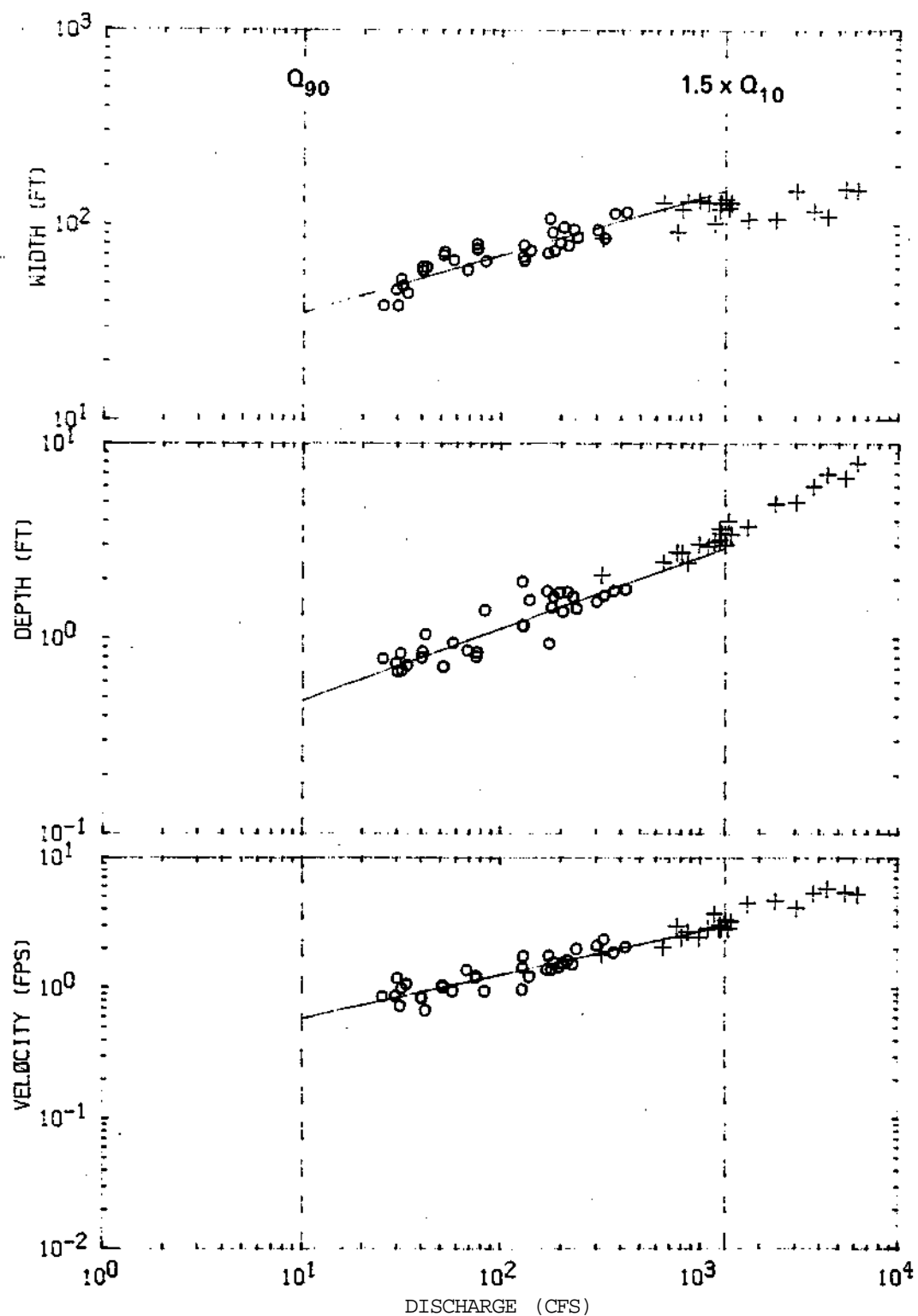
Figure 13. Station hydraulic geometry: Salt Fork Vermilion River near St. Joseph



LEGEND

- WADING SECTION
- + BRIDGE SECTION

Figure 14. Station hydraulic geometry: Salt Fork Vermilion River near Homer



LEGEND

○ WADING SECTION

+ BRIDGE SECTION

Figure 15. Station hydraulic geometry: Salt Fork Vermilion River near Oakwood

attributed to the fact that wading measurements are not made at the same place each time (Dunne and Leopold, 1978) . This was further confirmed by review of the hydrographer's field notes.

Examination of the station plots for the Middle Fork Basin (Figures 5 through 8) shows that flows at and below the 90% flow-duration limit have been measured. Little or no data are available for flows below about the 70% flow duration for the stations located in the Salt Fork Basin (Figures 9 through 15). Effluent discharges from the various municipal wastewater treatment plants noted earlier increase flows substantially, maintaining the lowest flows well above the expected natural flows. Effects of the altered flow regime on the channel formation are masked by the artificial construction and maintenance of the stream channels throughout most of the Salt Fork Basin. The flow durations and associated discharges noted (shown on the plots) represent the natural flow regime and serve as a datum to illustrate the impact of effluent discharges on flow levels.

The station equations were determined by fitting a polynomial function of  $\log Q$  to the log of the measured parameters from the USGS data. The coefficients of the expression were evaluated by using regression analysis. In cases where insufficient data existed to reliably fit an equation, a straight line approximation was extrapolated. The fitted regression equations are plotted with solid lines and the extrapolated functions are plotted with dashed lines in Figures 5 through 15.

The form of the polynomial equation used, the values of the coefficients for each station, and the range of applicable discharges are listed in Tables 5 and 6 for the Middle Fork and Salt Fork Basins, respectively. The multiple correlation coefficient  $R$  and the standard error,  $S_e$ , are also given in Tables 5 and 6 where available.

At seven stations a third-order polynomial had the best correlation . with the data. A third-order polynomial function was also used to approximate the station relations for the Sangamon Basin (Singh and Broeren, 1985). A linear relation between the logs of the parameters and the logs of discharge was selected for four stations. The station hydraulic geometry equations are consistent with the physical law  $Q = W \cdot D \cdot V$ . The summations of the  **$a_0$ ,  $a_1$ ,  $a_2$ , and  $a_3$**  coefficients for  $W$ ,  $D$ , and  $V$  are close to zero and the summations of  $a_1$  are close to 1.0. Thus the product of  $W$ ,  $D$ , and  $V$  (determined from the regression equations)

Table 5. Middle Fork Basin Station Equations

$$\log (\text{VAR}) = a_0 + a_1(\log Q) + a_2(\log Q)^2 + a_3(\log Q)^3$$

Station	VAR	<u>a<sub>0</sub></u>	<u>a<sub>1</sub></u>	<u>a<sub>2</sub></u>	<u>a<sub>3</sub></u>	R	S <sub>e</sub>	Range of discharges (cfs)	
								<u>Q<sub>min</sub></u>	<u>Q<sub>max</sub></u>
Potomac 03336500	W	0.921	0.487	-0.021	-0.022	0.916	0.158	0.2	96.8
	D	-0.593	0.330	-0.001	0.012	0.899	0.144		
	V	-0.328	0.184	0.022	0.010	0.695	0.191		
Paxton 03336090	W	1.129	0.480	-0.412	0.142	0.964	0.074	0.8	50.3
	D	-0.738	0.218	0.176	-0.007	0.948	0.112		
	V	-0.384	0.304	0.220	-0.128	0.887	0.121		
	W	1.023	0.252					50.3	137.1
	D	-1.068	0.688						
	V	0.045	0.060						
Armstrong 03336300	W	1.229	0.273			0.895	0.085	5.8	773.6
	D	-0.662	0.362			0.897	0.111		
	V	-0.574	0.369			0.888	0.119		
Oakwood 03336645	W	1.397	0.231			0.847	0.079	8.9	1193.6
	D	-0.598	0.314			0.907	0.079		
	V	-0.796	0.454			0.943	0.087		

Note: R = multiple correlation coefficient; S<sub>e</sub> = standard error; W = flow width in ft; D = hydraulic depth in ft; and V = flow velocity in fps. Extrapolated W, D, and V curves for higher or lower flows than observed have a<sub>2</sub> = a<sub>3</sub> = 0 and R and S<sub>e</sub> do not apply.

Table 6. Salt Fork Basin Station Equations

$$\log (\text{VAR}) = a_0 + a_1 (\log Q) + a_2 (\log Q)^2 + a_3 (\log Q)^3$$

Station	VAR	$a_0$	$a_1$	$a_2$	$a_3$	R	$S_e$	Range of discharges (cfs)	
								$Q_{\min}$	$Q_{\max}$
Thomasboro 03336940	W	0.842	0.343	-0.181	0.176	0.940	0.111	0.6	10.5
	D	-0.503	0.320	0.037	0.058	0.974	0.052		
	V	-0.336	0.327	0.140	-0.220	0.604	0.134		
Leverett 03336970	W	1.195	0.112					0.7	3.5
	D	-0.405	0.192						
	V	-0.790	0.696						
	W	1.203	0.024	0.157	-0.054	0.880	0.042	3.5	132.0
	D	-0.357	-0.022	0.257	-0.037	0.977	0.047		
	V	-0.845	1.013	-0.435	0.097	0.979	0.056		
Urbana 03337500	W	1.155	0.460					1.4	3.1
	D	-0.394	0.115						
	V	-0.761	0.425						
	W	1.125	0.671	-0.328	0.057	0.844	0.051	3.1	188.0
	D	-0.237	-0.514	0.713	-0.166	0.961	0.063		
	V	-0.890	0.846	-0.385	0.108	0.954	0.075		
Mayview 03337700	W	1.495	0.062			0.601	0.030	7.5	226.8
	D	-0.702	0.430			0.948	0.053		
	V	-0.793	0.508			0.954	0.058		
St. Joseph 03336900	W	1.184	0.406					2.8	12.2
	D	-0.465	0.150						
	V	-0.719	0.444						
	W	0.328	2.284	-1.256	0.232	0.812	0.043	12.2	370.2
	D	0.662	-2.403	1.759	-0.333	0.947	0.081		
	V	-0.990	1.122	-0.505	0.102	0.862	0.081		
Homer 03338000	W	1.373	0.221	-0.002	0.0	0.758	0.082	7.0	143.0
	D	-0.115	-0.554	0.336	-0.016	0.916	0.097		
	V	-1.265	1.345	-0.340	0.017	0.747	0.127		
	W	1.317	0.242					143.0	939.5
	D	-1.212	0.604						
	V	-0.105	0.154						
Oakwood 03338097	W	1.252	0.298			0.886	0.057	10.1	1351.1
	D	-0.685	0.368			0.874	0.074		
	V	-0.569	0.336			0.875	0.067		

Note: R - multiple correlation coefficient;  $S_e$  = standard error; W = flow width in ft; D - hydraulic depth in ft; and V - flow velocity in fps. Extrapolated W, D, and V curves for higher or lower flows than observed have  $a_2 = a_3 = 0$  and R and  $S_e$  do not apply.



practically equals  $Q$ . For the four stations where a log-linear function was found to adequately approximate the data, this function was used for the entire range of discharges (corresponding to the 10% through 90% flow durations).

For five of the stations where a third-order function was selected, linear extrapolations were developed for flow ranges for which no data were available. This was necessary at USGS gage 03338000 in the Salt Fork near Homer, as flows in the higher range must be measured from a bridge. Extrapolations for low flows were necessary for stations in the Salt Fork Basin. However, there is no information available to confirm the low-flow values. At the smaller-drainage-area stations conditions may vary considerably depending on the erosion potential of the bottom deposits and the regularity of clearance maintenance. Meandering thalwegs were observed within some of the channelized sections, and this and other features may greatly affect low-flow hydraulics. The extrapolated lines were constructed to follow the trend indicated by the wading data. Values of  $W$ ,  $D$ , and  $V$  computed from the extrapolations were compared to other station values. If values computed from the extrapolations were inconsistent with trends at the other stations, the extrapolations were adjusted as indicated. The coefficients of the equations and ranges of discharges to which these relations apply are listed in Tables 5 and 6.

#### Basin Relations

Basin hydraulic geometry relations define the average values of width  $W$ , depth  $D$ , and velocity  $V$  for a given flow duration and drainage area. These parameters increase in a consistent manner with drainage area when compared at the same flow duration. Thus each parameter varies with drainage area and flow duration.

Basin equations were developed for the Middle Fork and Salt Fork Basins. The parameter values used in the analysis were calculated from the station equations. For each station, discharges for flow durations 10, 20, 30, 40, 50, 60, 70, 80, and 90% were computed from the flow-duration relationships (Table 2). Nine values each of  $W$ ,  $D$ , and  $V$  were then computed for each station from the relevant station equations.

Different methodologies for developing the basin relations were investigated. Two mathematical formulations for the basin equations were initially tested:

$$\log \text{Var} = a + bF + c \log A_d \quad (6)$$

and

$$\log \text{Var} = A_f + B_f \log A_d \quad (7)$$

where

Var = W, D, or V (W and D in feet and V in fps)

F = decimal flow duration

A<sub>d</sub> = drainage area in sq mi

a, b, and c = constant regression coefficients

A<sub>f</sub> and B<sub>f</sub> = regression coefficients which vary with flow duration f

The first expression was used by Stall and Fok (1968) and Stall and Yang (1970) in their studies of hydraulic geometry of streams in Illinois and throughout the continental United States. The second expression was suggested by Singh and Broeren (1985) and is similar to Leopold and Maddock's (1953) original work in that the coefficients are evaluated independently for a given discharge frequency.

Multiple regression analysis was performed to evaluate the coefficients in equation 6 for W, D, and V. The data used were the computed values of the parameters at each station for all nine flow durations. The coefficient values for equation 7 were independently evaluated for each of the nine flow durations by using linear regression analysis.

According to Singh and Broeren (1985), the underlying assumption in using equation 6 is that the value of a parameter increases with increase in drainage area at the same rate (given by c in equation 6) over the entire range of flow durations, or that this rate of increase is independent of flow duration. The validity of the constant-c assumption was tested by examining the variation of the coefficients A<sub>f</sub> and B<sub>f</sub> with respect to F for each parameter. An examination of equations 6 and 7 shows that A<sub>f</sub> in equation 7 replaces a + bF in equation 6 and is thus expected to vary linearly with flow duration if B<sub>f</sub> is constant and practically the same as c.

The values of  $A_f$  and  $B_f$  determined for each parameter ( $W$ ,  $D$ , and  $V$ ) for the Middle Fork and Salt Fork Basins are plotted versus decimal flow duration ( $F$ ) in Figures 16 and 17, respectively. These plots show a distinct change in the variation of these coefficients when flows decrease below the 60% flow duration discharge. Thus, the basinwide relationship between hydraulic parameters is not the same for high flows and for low flows. Equation 6 does not adequately represent the basin relations for these two basins for the full range of flow durations.

An alternative formulation of the basin equations was derived by fitting a line to the values of  $A_f$  and  $B_f$  plotted in Figures 16 and 17. This procedure defines a functional relationship for the  $A_f$  and  $B_f$  coefficients with  $F$  and is equivalent to expressing the basin equation for a parameter as:

$$\log \text{Var} = a_1 + b_1 F + (c_1 + c_2 F) \log A_d \quad (8)$$

The term  $a_1 + b_1 F$  defines the variation of  $A_f$  with flow duration and the term  $C_1 + C_2 F$  defines the variation of  $B_f$  with flow duration. Because of the discontinuity in the trends for  $A_f$  and  $B_f$  which occurs between the 60 and 70% flow durations, two independent expressions for  $A_f$  and  $B_f$  were derived for each parameter, one for  $F = 0.1 - 0.6$  and one for  $F = 0.7 - 0.9$ . The expressions for  $A_f$  and  $B_f$  values are plotted in Figures 16 and 17.

The values of  $A_f$  and  $B_f$  determined for each parameter are listed in Table 7 for the Middle Fork and Salt Fork Basins. The values of  $a_1$ ,  $b_1$ ,  $C_1$ , and  $C_2$  in equation 8 were computed and are listed in Table 8 for both basins. For flow durations between 60 and 70% the value of a parameter may be linearly interpolated between the values corresponding to 60 and 70%. Equation 8 and the coefficients listed in the table were used for the calculations and results presented in this report.

#### Continuity

Continuity,  $Q = W \cdot D \cdot V$ , may be indirectly checked by comparing the coefficients of the expressions for  $W$ ,  $D$ , and  $V$  with the coefficients of the flow-duration equations for  $Q$  listed in Table 2. Taking the logs on both sides of the continuity equation, we have  $\log Q = \log W + \log D + \log V$ . The most general form of the flow-duration equation is  $Q_f = C_f A_d$ .

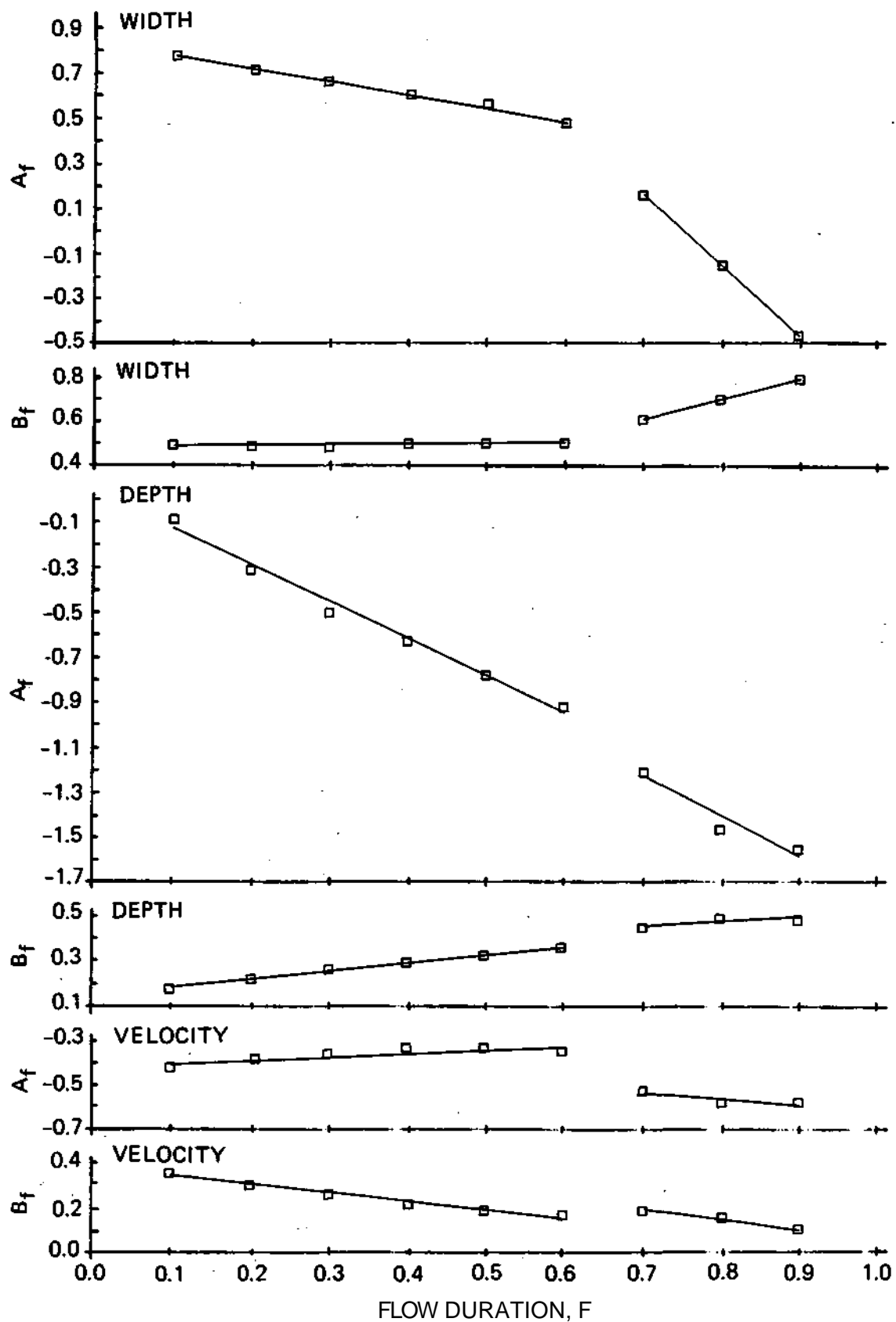


Figure 16. Regression coefficients  $A_f$  and  $B_f$  versus flow duration,  $F$   
Middle Fork Vermilion River system

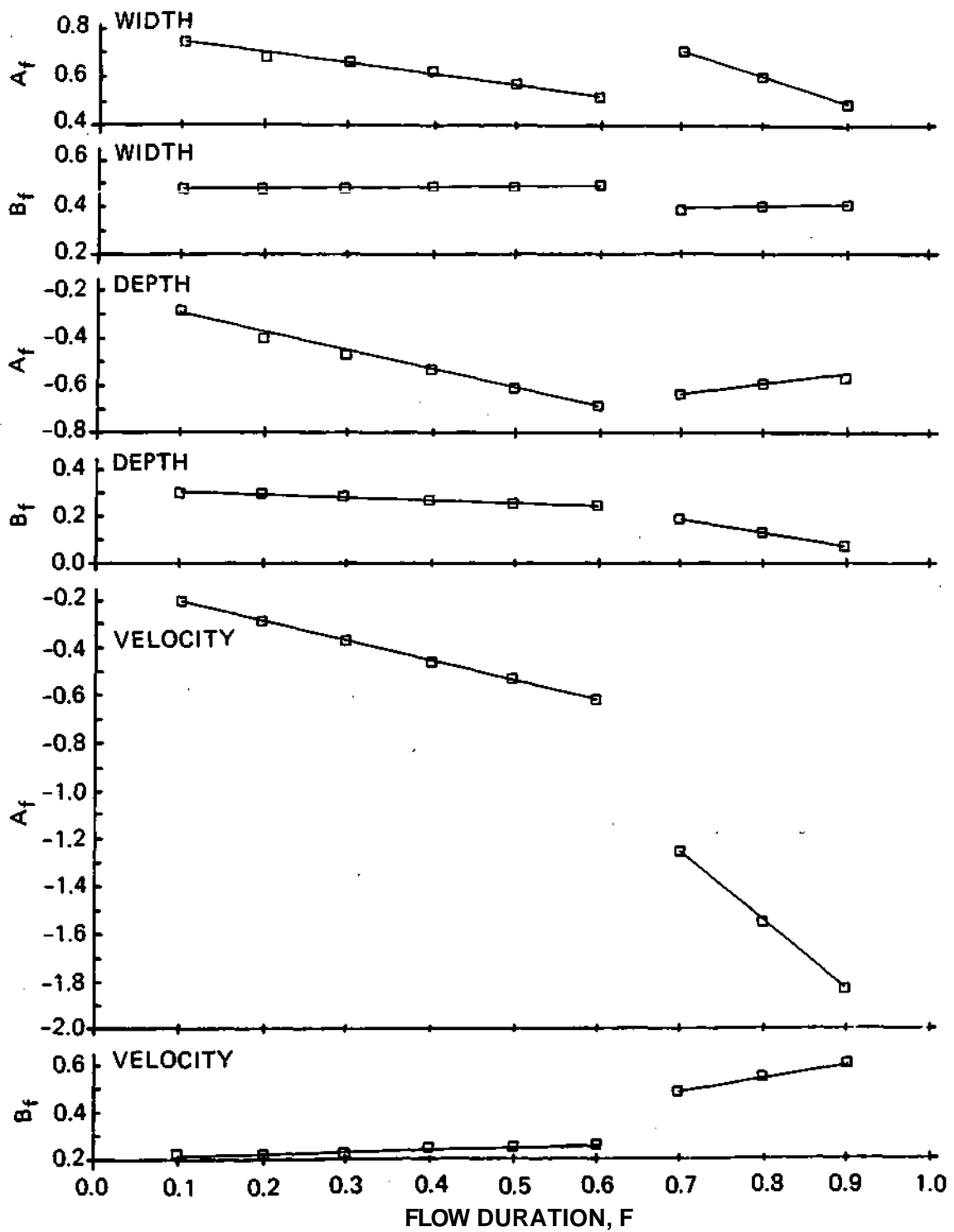


Figure 17. Regression coefficients  $A_f$  and  $B_f$  versus flow duration,  $F$ :  
Salt Fork Vermilion River system

Table 7. Basin Relations with Variable Coefficients

$$\log (\text{VAR}) = A_f + B_f (\log A_d); \text{VAR} = W, D, \text{ or } V$$

<u>F(%)</u>	<u>W</u>		<u>D</u>		<u>V</u>	
	<u>A<sub>f</sub></u>	<u>B<sub>f</sub></u>	<u>A<sub>f</sub></u>	<u>B<sub>f</sub></u>	<u>A<sub>f</sub></u>	<u>B<sub>f</sub></u>
<b>Salt Fork Basin</b>						
10	.751	.483	-.284	.295	-.205	.224
20	.693	.490	-.402	.295	-.291	.219
30	.657	.491	-.487	.287	-.373	.224
40	.625	.493	-.542	.272	-.458	.236
50	.585	.498	-.602	.257	-.537	.244
60	.517	<b>.511</b>	-.672	.242	-.624	.248
70	.715	.396	-.641	.182	-1.249	.479
80	.601	.404	-.588	.127	-1.547	.547
90	.497	.404	-.564	.086	-1.831	.595
<b>Middle Fork Basin</b>						
10	.780	.485	-.096	.165	-.423	.353
20	.722	.482	-.326	.219	-.395	.301
30	.657	.487	-.510	.264	-.359	.254
40	.609	.490	-.643	.291	-.338	.218
50	.561	.491	-.779	.321	-.337	.189
60	.496	.496	-.927	.349	-.353	.158
70	.160	.606	-1.261	.445	-.515	.179
80	-.150	.700	-1.484	.493	-.588	.157
90	-.474	.794	-1.558	.478	-.579	.097

Note:  $A_d$  = drainage area in sq mi; F = flow duration in %; W = flow width in ft; D = hydraulic depth in ft; V = flow velocity in fps

Table 8. Basin Hydraulic Geometry Equations

$$\log (\text{VAR}) = a_1 + b_1 F + (c_1 + c_2 F) \log A_d$$

F(%)	VAR	a <sub>1</sub>	b <sub>1</sub>	c <sub>1</sub>	c <sub>2</sub>
Middle Fork Basin					
10-60	W	0.833	-0.557	0.480	0.024
60-70		2.520	-3.368	-0.175	1.116
70-90		2.381	-3.170	-0.052	0.940
10-60	D	0.018	-1.613	0.143	0.358
60-70		1.064	-3.357	-0.228	0.977
70-90		-0.246	-1.485	0.340	0.165
10-60	V	-0.422	0.156	0.380	-0.385
60-70		0.875	-2.006	-0.067	0.360
70-90		-0.305	-0.320	0.472	-0.410
Salt Fork Basin					
10-60	W	0.791	-0.436	0.478	0.047
60-70		-0.572	1.836	1.161	-1.092
70-90		1.476	-1.090	0.369	0.040
10-60	D	-0.239	-0.741	0.314	-0.113
60-70		-0.966	0.471	0.643	-0.662
70-90		-0.906	0.385	0.516	-0.480
10-60	V	-0.123	-0.834	0.212	0.059
60-70		3.142	-6.276	-1.160	2.346
70-90		0.786	-2.910	0.076	0.580

Note: A<sub>d</sub> = drainage area (sq mi); F = decimal flow duration; W = flow width in ft; D = hydraulic depth in ft; and V = flow velocity in fps

Taking the log of this equation,  $\log C_f + \log A_d$  may be substituted for  $\log Q$  in the continuity equation. Using equation 7 (with the f subscripts omitted for convenience),  $\log W = A_W + B_W \log A_d$ ;  $\log D = A_D + B_D \log A_d$ ; and  $\log V = A_V + B_V \log A_d$ . Summing these equations we have:

$$\log W + \log D + \log V = (A_W + A_D + A_V) + (B_W + B_D + B_V) \log A_d$$

Continuity is satisfied if the sum of the A coefficients equals  $\log C_f$  and the sum of the B coefficients equals 1.0 at each flow duration. This condition is closely satisfied for flow durations 10-60% for both basins. There are two equations for discharge for flow durations 70, 80, and 90%, one for streams with drainage areas greater than 60 sq mi and one for streams with drainage areas less than 60 sq mi. Because of this it is difficult to perfectly satisfy the continuity condition by using one set of equations for W, D, and V in this range of flow durations. An explicit approach to guaranteeing continuity is to develop two different sets of basin equations for the two divisions of drainage area in each basin. There are insufficient data to accomplish this.

An indirect approach to satisfying continuity is to adjust the value of F used in the basin hydraulic geometry equations. The value of F may be adjusted in small increments until the product of  $W \cdot D \cdot V$  computed from the basin equations equals the discharge computed from the flow-duration equations for the desired flow duration. This procedure has been used in all the computations presented in this report for all flow durations. In some instances a better agreement with continuity was achieved by adjusting F by 1% for the high-flow range and by not more than 4% for the low-flow range. Full agreement with continuity cannot in general be guaranteed when the basin hydraulic geometry relations are in the form of equation 6 with constant coefficients and the coefficients defining the relationship between discharge and drainage vary with flow duration.

#### Comparison of Middle Fork and Salt Fork Basin Relations

The basin equations for flow durations 20, 50, and 80% are graphically illustrated in Figures 18 through 20. The Middle Fork Basin equations are plotted with solid lines and the Salt Fork Basin equations are plotted with dashed lines. The plots show an increase in the parameter values with increase in drainage area at a constant flow-duration



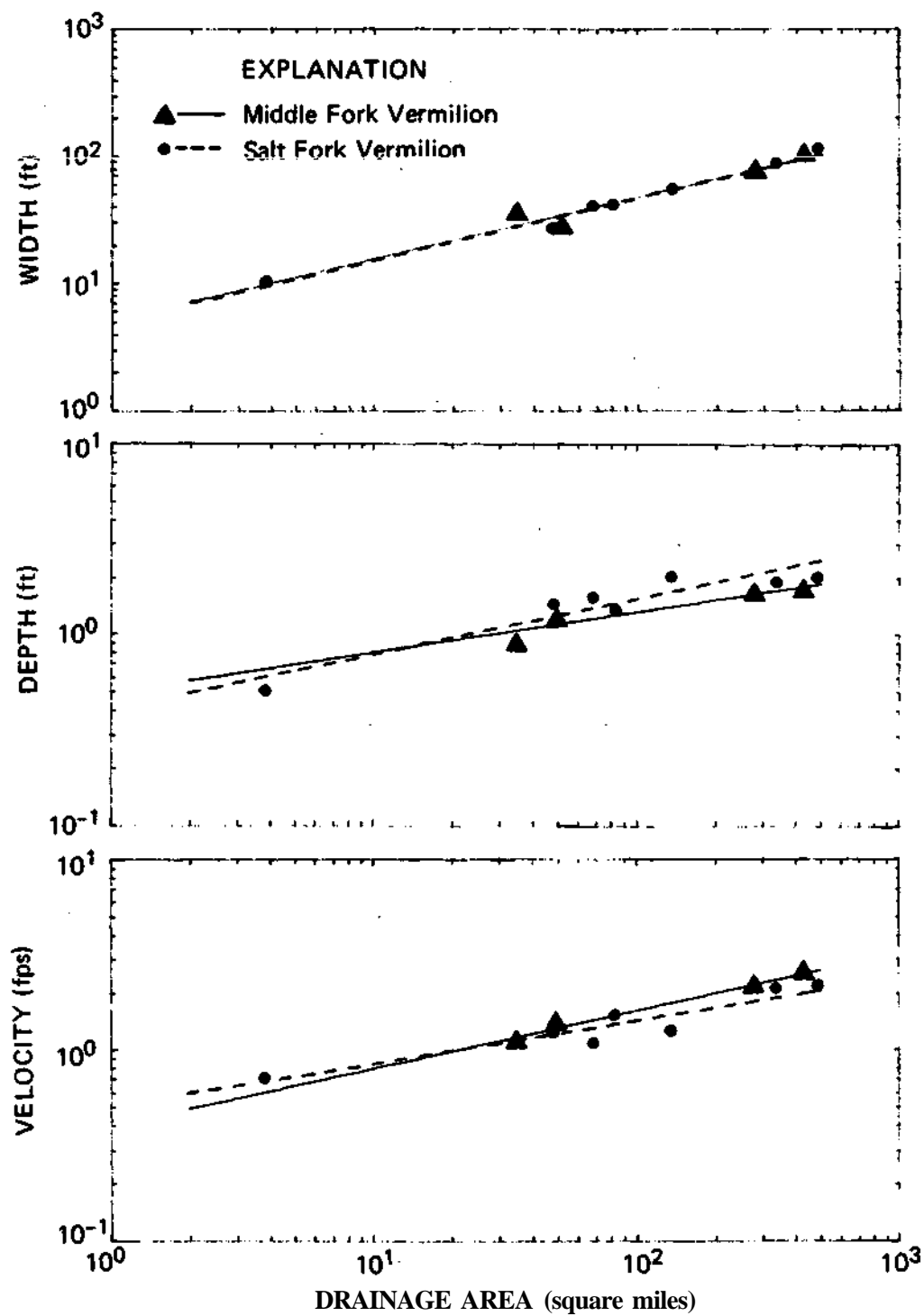


Figure 18. Width, Depth, and Velocity versus drainage area for F - 0.2

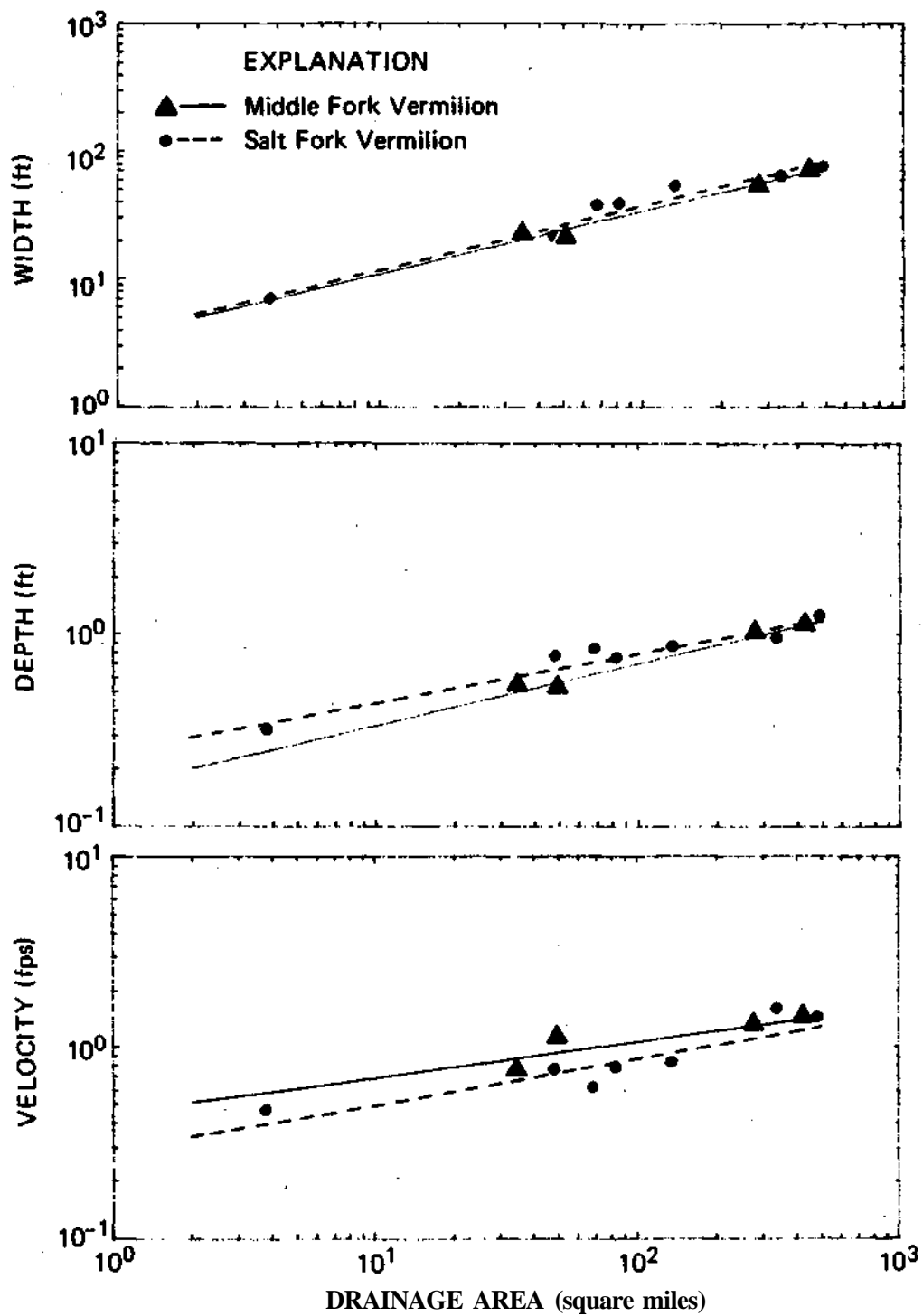


Figure 19. Width, Depth, and Velocity versus drainage area for  $F = 0.5$

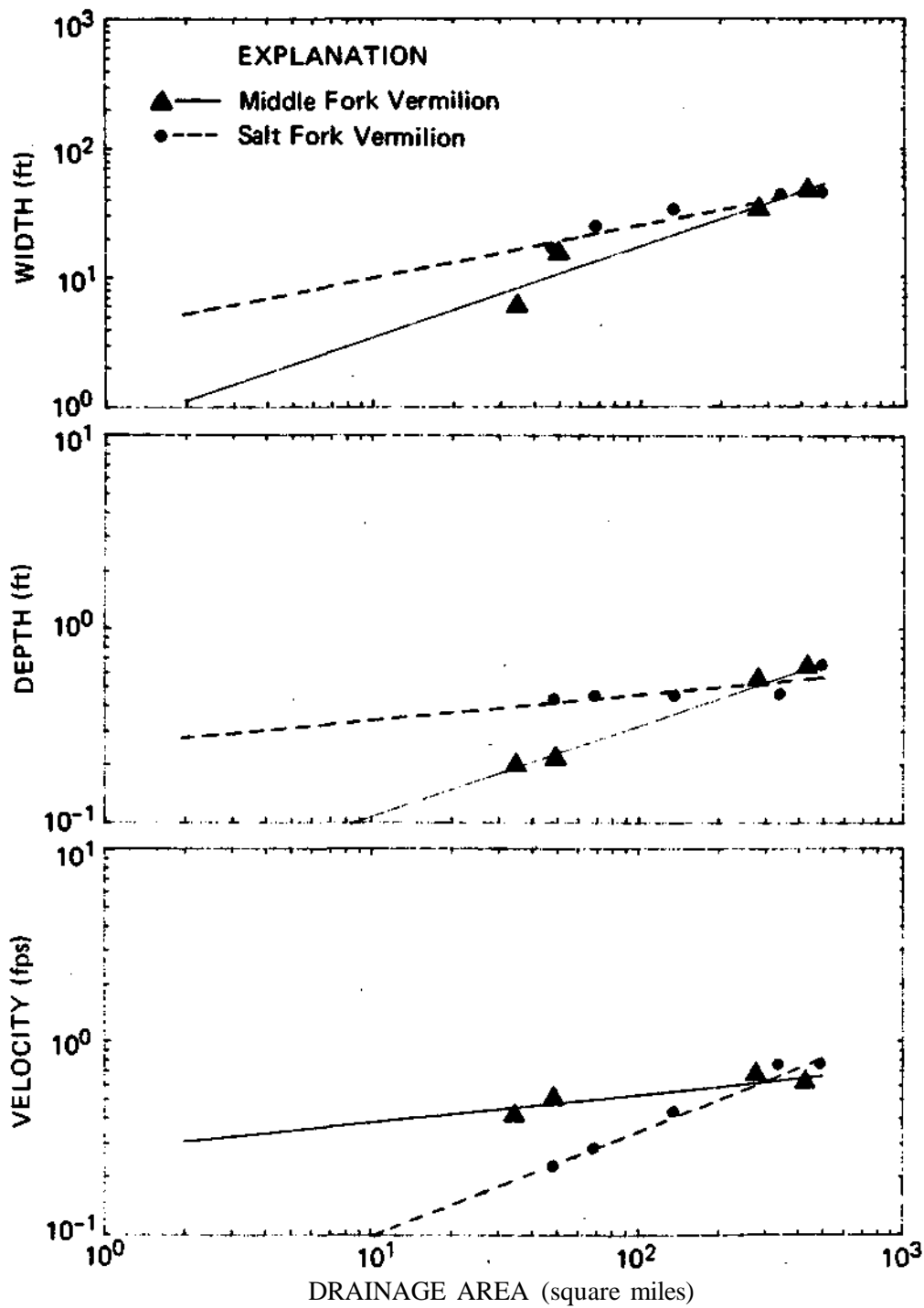


Figure 20. Width, Depth, and Velocity versus drainage area for  $F = 0.8$

frequency. Parameter values computed from the station equations are plotted at the corresponding station drainage areas. Data from the Middle Fork stations are plotted with triangles and data from the Salt Fork stations are plotted with circles.

The basin equations plotted converge to cross at a drainage area value in the range of 300 to 500 sq mi. Four gaging stations (two in the Middle Fork River and two in the Salt Fork River) represent streams with drainage areas in this range. All four are located in streams with natural channels. At a flow duration equal to 20% the two basin equations plotted for each parameter (W, D, and V) are nearly the same. As flow duration increases, i.e., as discharge decreases, differences between the hydraulic conditions in the two basins become more evident. The equations diverge with decreasing drainage area as illustrated in the plots for flow durations 50 and 80%.

Streams in the Salt Fork Basin with drainage areas less than about 200 sq mi have greater flow width and depth and lesser velocity than comparable streams in the Middle Fork Basin. The greater width of streams in the Salt Fork Basin is clearly indicative of the channel modifications in that basin.

## **FIELD STUDY**

Ten stream reaches were selected for a detailed study of depths and velocities in pools and riffles. Five of these study reaches are located in the Middle Fork Basin and five are located in the Salt Fork Basin. The study reaches were selected to represent a range of drainage areas. Each study reach was surveyed to locate three consecutive riffles with two intermediate pools. Measurements were made along 13 transects for three or more discharges in each reach. Thus more than 30 sets of field data were collected. This information was used to investigate the distribution of the local values of depth and velocity throughout a stream reach.

### Study Reaches

Study reaches were selected to provide a representative sample of stream conditions throughout each basin. The upstream drainage areas at

the study sites range from 33.9 to 426.0 sq mi in the Middle Fork Basin and from 20.4 to 488.3 sq mi in the Salt Fork Basin. The reaches are designated as MF1 through MF5 for the Middle Fork Basin, with MF1 having the smallest drainage area, MF2 the next-largest, and so on. The Salt Fork Basin study reaches are similarly designated as SF1 through SF5. The locations of the study reaches in terms of township, range, and section, as well as the name of the USGS 7.5-minute quadrangle containing the stream reach, are given in Table 9. The stream name, drainage area at the study reach, and length of the study reach are also listed. The study reaches in each basin are numbered 1-5 on the maps in Figures 1 and 4.

The two reaches representing the smallest drainage areas in the Middle Fork Basin (MF1 and MF2) lie in streams which have been channelized, and MF3 is located in a section of the stream which was channelized at one time. The upper reaches of the Middle Fork River where MF1 and MF2 are located have clearly been channelized. The stream channel is straight for considerable distances, the channel side slopes are regular, and the width is fairly constant. The reaches are fairly well cleared of brush, but numerous center sand bars are evident at low flows, as well as small islands which support vegetation. The sediment deposits indicate that the channels have not been dredged for a long time. Field inspection of MF3 confirmed that some channel modifications had been made; however, they do not seem to be as extensive as found in the upper reaches. The width of the channel corresponds to that expected in a natural stream with that drainage area, the pool-riffle definition is good, and the bank and side slopes are irregular. It apparently has been some time since any channel work was performed and the reach may be in a transition period, with conditions gradually returning to the natural state.

In the Salt Fork Basin, SF2 and SF3 represent the channelized portions of the Saline Branch and the Upper Salt Fork River, respectively. There is no evidence of recent clearance or other maintenance work in the channels where reaches SF2 and SF3 are located. Numerous bars have formed in the channel in reach SF3. Sediment deposition problems in this stream have been apparent since it was originally channelized (Hay and Stall, 1974). SF2 is downstream of the effluent outfall from the Urbana-Champaign treatment plant. Reach SF3, downstream of the confluence of the Upper Salt Fork River and the Saline Branch, carries effluents from Urbana-Champaign,

Table 9. Study Reaches

<u>Reach no.</u>	<u>Quadrangle name</u>	<u>Township Range Section</u>	<u>Stream name</u>	<u>Drainage area (sq mi)</u>	<u>Reach length (ft)</u>
<b>Middle Fork Basin</b>					
1	Melvin W	T24N R08E S15	Big Four Ditch	33.9	190
2	Perdueville	T23N R09E S08	Big Four Ditch	81.1	730
3	Paxton	T23N R10E S30	Big Four Ditch	161.9	770
4	Penfield	T22N R14W S17	Middle Fork	232.6	775
5	Danville NW	T20N R12W S21	Middle Fork	426.0	1303
<b>Salt Fork Basin</b>					
1	Oakwood	T19N R13W S33	Jordan Creek	20.4	240
2	Flatville	T19N R10E S06	Saline Branch	81.4	442
3	St. Joseph	T19N R10E S22	Salt Fork	240.0	1465
4	Homer	T19N R13W S31	Salt Fork	380.2	800
5	Oakwood	T19N R13W S26	Salt Fork	488.3	1090

Chanute Air Force Base, and Rantoul. The reach representing the stream with the smallest drainage area, SF1, is located in a section of Jordan Creek which apparently has not been channelized, although the channel upstream has been dredged. The two reaches of streams with the largest drainage areas, SF4 and SF5, represent the natural channel of the lower Salt Fork River.

The ten study reaches represent nearly every combination of channel form and drainage area in the two basins. There are virtually no natural channel streams in the Salt Fork Basin with drainage areas less than 20 sq mi or in the range of 50 to 300 sq mi. There are almost no small streams (drainage area up to about 30 sq mi) in the Middle Fork Basin with natural channels. In the basins, streams with drainage areas in excess of 300 sq mi have not been modified by channel reconstruction.

#### Channel Conditions

Descriptive information on the channel conditions, such as bank slope, channelization, and bank stability, is given in Table 10 for each study reach. The following discussion explains the criteria used in developing the classifications shown in Table 10.

Study reaches are denoted as either channelized or unchannelized. A reach is assumed channelized if it shows clear evidence of artificial improvements such as channel widening, deepening, and straightening, which alter channel geometry. If no such evidence is present, the reach is assumed unchannelized or natural. Half of the ten study reaches are in a channelized condition.

Pool-riffle sequences were found to be in various stages of development. The overall definition is largely dependent on the history of the study reach, but generally pool-riffle definition can be considered as either fair, good, or excellent. The specific criteria used for describing the pool-riffle definition are given below:

- a) Relative depth: Riffle should have a significantly shallower average depth than in a pool.
- b) Relative velocity: Riffle should have a significantly higher average flow velocity than in a pool.
- c) Relative substrate: The riffle bed material should be coarser (larger particle size) than in a pool.

Table 10. Physical Characteristics of the Study Reaches

		<u>Study reach no. 1 2 3 4 5.</u>				
		<u>Middle Fork Basin</u>				
Drainage area above reach, mi <sup>2</sup>	33.9	81.1	161.9	232.6	426.0	
Channelized	X	X	X			
Pool-riffle definition	excellent	fair	good	excellent	excellent	
Reach plan geometry	straight	straight	straight	meander	meander	
Bank slope	moderate	moderate-steep	steep-very steep	very steep-vertical	vertical	
Bank stability	stable	stable	unstable	unstable	unstable	
Maximum bank height	15'	20'	20'	10'	70'	
Average bottom width of channel	12'	25'	30'	50'	80'	
Local land cover (June-Sept)	planted field	planted field	planted field	pasture	forest	
		<u>Salt Fork Basin</u>				
Drainage area above reach, mi <sup>2</sup>	20.4	81.4	240.0	380.2	488.3	
Channelized		X	X			
Pool-riffle definition	excellent	excellent	fair	excellent	good	
Reach plan geometry	meander	straight	straight	meander	meander	
Bank slope	moderate-steep	steep-very steep	moderate-steep	very steep-vertical	very steep	
Bank stability	stable	unstable	stable	unstable	unstable	
Maximum bank height	10'	20'	25'	50'	50'	
Average bottom width of channel	15'	40'	70'	55'	85'	
Local land cover (June-Sept)	pasture	forest	planted field	forest	forest	



- d) Riffle to riffle spacing: Riffle spacing typically corresponds to 5-7 times the top water width at 20% duration flow.

Reach plan geometry is classified as straight or meandering. By reach plan geometry is meant the configuration of the study reach as it would appear from above. The sinuosity is defined as the ratio of stream length to valley length (Schumm, 1963). This ratio can vary from unity to a value of 4 or more. Study reaches having a sinuosity of 1.5 or higher are classified as meandering and those with ratios below 1.5 are classified as straight. Straight study reaches are channelized, and meandering study reaches are unchannelized.

The bank slopes vary widely between study reaches and are closely related to the naturalness of the reach (channelized or unchannelized) and the extent of local incision. In natural or unchannelized study reaches, bank slopes occasionally change within the study reach itself, but not very significantly. The study reach bank slopes were generalized into four categories:

Moderate	- less than or equal to 1:1 slope (vertical to horizontal)
Steep	- 1:1 to 3:1 slope
Very Steep	- 3:1 to 5:1 slope
Vertical	- greater than 5:1 slope

The slope is an average measure of the vertical to the horizontal displacement at the banks. In no case do bank slopes cover more than two of the above slope ranges for a given study reach.

Banks were classified as either stable or unstable. The extent of bank stability is mainly a function of bank material, bank slope, vegetation, and stream incision. Stable banks are relatively firm and steadfast. The movement and rearrangement of material, or mass wastage, at a stable bank is minimal. In contrast, banks classified as unstable are variable and changing. Slopes are relatively steep and mass wasting processes are clearly evident. Although many types of mass wastage were observed, typically the movement was in the category of soilfall, rockfall, or rotational slump. Bank stability fluctuates throughout the basin, but usually channelized reaches are more stable than unchannelized reaches.

### Streambed Substrate Characteristics

A program of substrate sampling was conducted to qualitatively determine the bed material particle sizes in the study reaches. Substrate samples were collected at distances of  $W/4$ ,  $W/2$ , and  $3W/4$  (where  $W$  is the top water width) along each of transects 1, 3, 5, 7, 9, 11, and 13. Thus 21 samples were collected in each study reach. For gravel-size material and smaller, a 6-inch-diameter vertical pipe was used for collecting the sample. For coarser material (greater than gravel size), a grab bucket was used. When using the grab bucket, particular care was taken not to disturb the sample when lifting it from the streambed to the water surface. Substrate samples were analyzed in the field and ranked by particle size according to the modified Wentworth scale:

<u>Rank</u>	<u>Substrate Size</u>
1	Organic cover
2	$\leq 1/16"$ - Sand
3	$1/16" - 1/4"$ - Gravel
4	$1/4" - 1"$ - Coarse gravel
5	$1" - 2 \frac{1}{2}"$ - Small cobble
6	$2 \frac{1}{2}" - 5"$ - Cobble
7	$5" - 10"$ - Large cobble
8	$> 10"$ - Boulder

An overall average rank ( $R$ ) for the reach was calculated as well as the average ranks for the riffle ( $R_r$ ) and pool ( $R_p$ ). Ranks are summarized in Table 11.

Figure 21 shows that the average rank of the substrate decreases with increasing drainage area in the channelized reaches. In the natural channels substrate size is considerably less variable with respect to drainage area, although the average rank of bed material in the natural reaches is significantly higher than in the channelized reaches. In a mature stream it is generally expected that substrate size decreases in the downstream direction (Leopold et al., 1964). The presence of large substrate material in the lower portion of the Vermilion River basin is an indication of the relative underdevelopment and immaturity of the stream system.

The change in substrate rank in moving from a riffle to a pool condition is about 0.9 for the natural conditions and varies from 0.1 to 0.5 for the channelized reaches. Sediment sorting is obliterated when a

Table 11. Substrate Ranks in Study Reaches

<u>Reach</u>	<u>R</u>	<u>R<sub>r</sub></u>	<u>R<sub>p</sub></u>	<u>ΔR</u>
SF1	4.22	4.86	3.73	1.13
SF2	3.23	3.70	2.88	0.82
SF3	2.23	2.25	2.21	0.04
SF4	5.28	5.53	5.09	0.44
SF5	4.52	4.90	4.23	0.67
MF1	3.70	3.88	3.57	0.31
MF2	2.42	2.53	2.34	0.19
MF3	2.75	2.91	2.63	0.28
MF4	3.75	4.10	3.49	0.61
MF5	3.76	4.80	3.07	1.73

Note: R - average rank; R<sub>r</sub> = average substrate rank at riffle; R<sub>p</sub> = average substrate rank at pool; and ΔR = R<sub>r</sub> - R

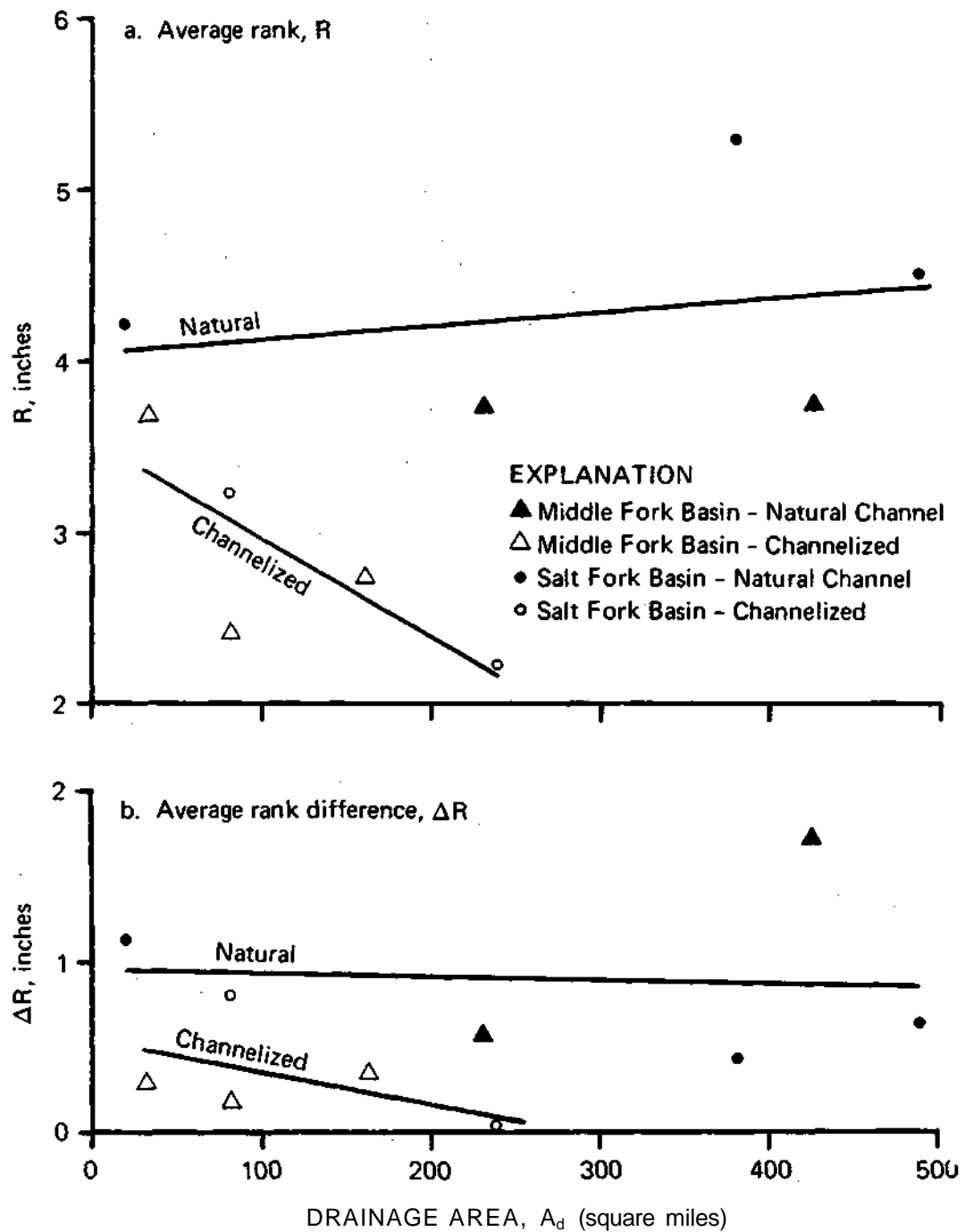


Figure 21. Substrate rank versus drainage area

channel is dredged, but with the passage of years, the natural system of riffles and pools tends to reassert itself.

### **Dissolved Oxygen Concentrations**

During daylight algae and plant-like organisms absorb carbon dioxide from the atmosphere and release oxygen in the course of photosynthesis. Areas with algae have higher dissolved oxygen (DO) levels during daylight hours and lower DO levels at night. The amount of dissolved oxygen in a stream is closely related to photosynthetic activity and reaeration (Eckenfelder, 1970). The extent of photosynthesis depends upon the available sunlight, effectiveness of sunlight penetration, available nutrients, algal mass, and temperature. Photosynthetic activity exhibits a diurnal variation. Dissolved oxygen levels do not vary appreciably from about 10:00 a.m. to 4:00 p.m. Stream oxygen levels are further influenced by the extent of natural reaeration. They are higher in the shallows (riffles) than in the deeps (pools).

Dissolved oxygen concentration was measured with a YSI Model 54 oxygen meter at two different discharges in each study reach. Measurements in each reach were taken at three equally spaced locations along each of transects 1, 3, 5, 7, 9, 11, and 13. Transects 1, 7, and 13 were at the riffles and the others were in the pools. Additional measurements were taken in pools immediately upstream and downstream of the study reach. For each reach Table 12 lists values of average DO in the reach, riffles, and pools; the difference in DO values at the riffles and pools; discharge when DO measurements were made, and associated flow duration; average water temperature during measurements; and average clock time during measurements. Measurements were taken during July and August 1986, and stream temperature averaged approximately 26°C. Most measurements were made during afternoons and some were made in late mornings. A wide range of discharges is represented, and flow durations ranged from 12% to 90%.

The DO in the Vermilion Basin increases appreciably with decreasing discharge (Figure 22). The concentrations range from about 7 ppm (mg/l) at high flow ( $F = 0.1$ ) to 10 ppm and higher at low flow ( $F = 0.8$ ). At low flow the stream is relatively shallow, allowing for more efficient penetration of sunlight to the streambed surface, where most oxygen-producing organic material is located. As more sunlight penetrates to the

Table 12. Dissolved Oxygen Measurements

<u>Site</u>	<u>Date</u> (1986)	<u>Q</u> (cfs)	<u>F</u> (%)	<u>DO</u> (ppm)	<u>DO<sub>r</sub></u> (ppm)	<u>DO<sub>p</sub></u> (ppm)	<u>DO</u> (ppm)	<u>T°C</u>	<u>Time</u>
MF1	8-21	0.26	87	6.73	7.20	6.56	0.64	27.87	5:00P
MF1	7-16	12.23	44	9.24	9.38	9.17	0.21	29.91	1:30P
MF2	8-8	1.78	90	9.38	9.76	9.23	0.53	30.37	2:00P
MF2	7-16	37.63	38	8.17	8.26	8.13	0.13	29.24	3:30P
MF3	8-8	6.73	82	8.83	8.88	8.78	0.10	27.91	12:00P
MF3	7-17	61.21	43	7.63	7.63	7.62	0.01	28.16	11:00A
MF4	8-7	11.47	79	10.31	10.44	10.26	0.18	26.00	5:00P
MF4	7-17	93.44	41	6.98	7.08	6.93	0.15	29.00	3:30P
MF5	8-21	12.51	86	9.60	10.01	9.45	0.56	26.09	2:30P
MF5	8-5	26.42	75	10.55	11.03	10.37	0.66	25.65	1:00P
S.F1	7-9	4.49	55	9.06	9.30	8.93	0.37	24.61	11:30A
SF1	7-11	13.39	29	7.13	7.26	7.07	0.19	22.98	3:00P
SF2	7-9	28.01	45	10.32	10.51	10.22	0.29	26.31	3:00P
SF2	7-11	133.27	12	6.75	6.80	6.73	0.07	23.07	5:30P
SF3	8-21	29.08	66	10.84	11.55	10.58	0.97	24.89	12:00P
SF3	7-18	124.24	35	6.27	6.37	6.22	0.15	26.79	10:30A
SF4	8-7	36.19	69	8.29	8.37	8.25	0.12	23.06	2:00P
SF4	7-18	251.26	29	7.23	7.27	7.22	0.05	27.76	2:00P
SF5	8-5	36.00	73	12.66	13.17	12.49	0.68	25.01	4:00P
SF5	9-22	101.62	56	8.97	9.22	8.88	0.34	19.30	2:30P

Note: DO = average DO in the reach; DO<sub>r</sub> = average DO in the riffles;  
DO<sub>p</sub> = average DO in the pools; DO = DO<sub>r</sub> - DO<sub>p</sub>; F denotes flow  
duration; and ppm = parts per million, or milligrams per liter

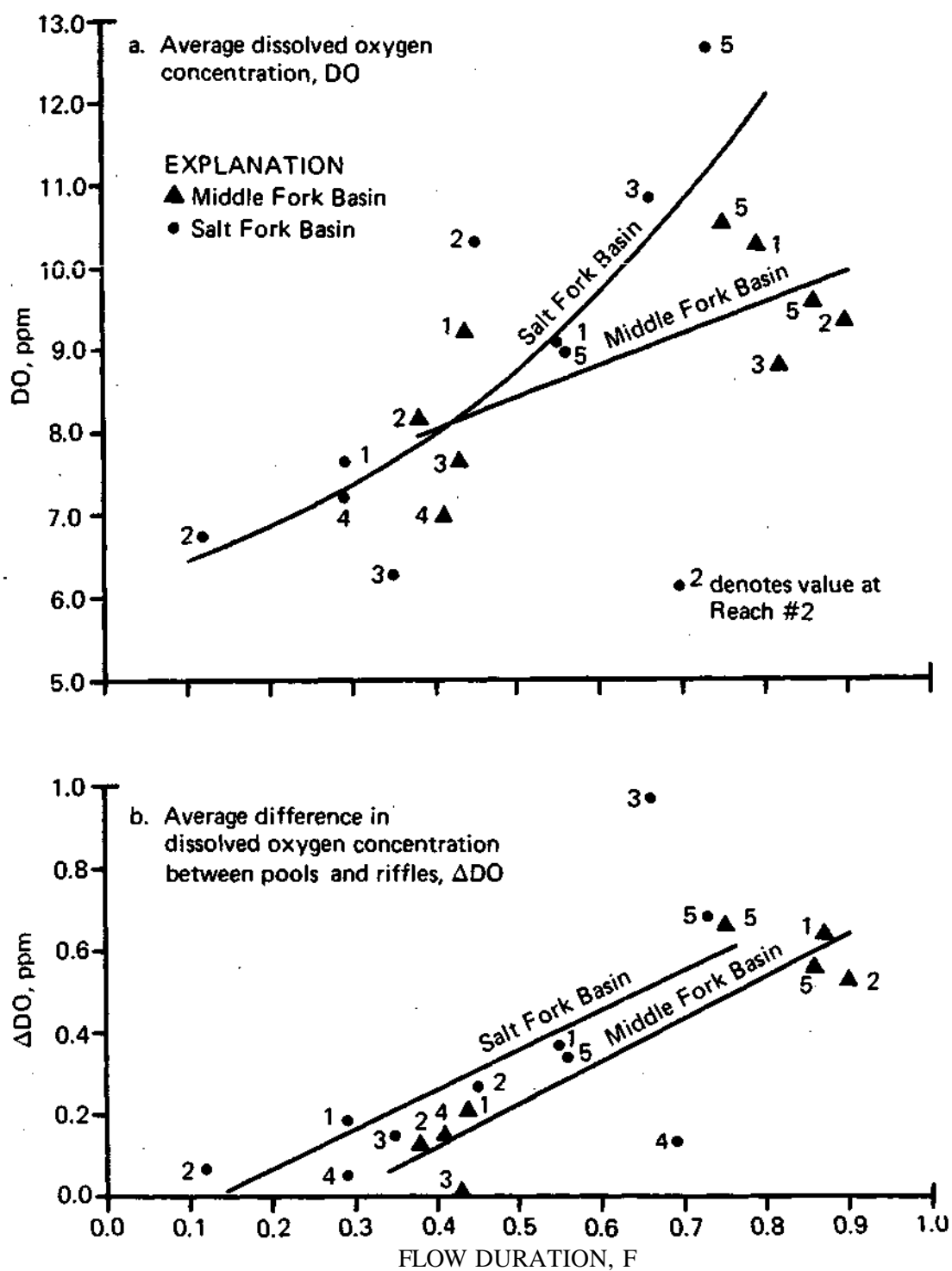


Figure 22. Dissolved oxygen concentration versus flow duration

bed surface, photosynthetic activity increases and DO tends to increase. However, at high flow, the increased depths inhibit the penetration of sunlight to the bed surface, causing a decline in photosynthetic activity and a consequent decrease in DO.

Figure 22 further indicates that DO tends to be slightly higher in the Salt Fork Basin than in the Middle Fork Basin in the medium to low-flow range ( $F = 0.5 - 0.9$ ). For example, DO is approximately 12 ppm in the Salt Fork Basin but only about 9.5 ppm in the Middle Fork Basin at the same flow duration of 80%. The release of nutrient-rich wastewater treatment plant effluents into the Salt Fork and Saline Branch by Champaign, Urbana, Rantoul, and Chanute Air Force Base is the probable cause of this. Abundant nutrient availability in the Salt Fork relative to the Middle Fork increases oxygen-producing organisms in the stream. In addition, an examination of U.S. Geological Survey water quality records indicates a significant difference in suspended sediment, or turbidity. Turbidity tends to be higher in the Middle Fork than in the Salt Fork. As a result, sunlight penetration to the bed surface is less in the Middle Fork, causing less photosynthetic activity than in the Salt Fork. At the medium flow condition ( $F = 0.4$ ), the DO of the Salt Fork and Middle Fork become approximately equal. This is probably due to the effects of the dilution of wastewater inflow from treatment plants because of the high discharges. The lower nutrient concentrations associated with the higher-flow condition diminishes the oxygen-producing effect that is observed at the lower flows in the Salt Fork.

Of particular interest in these measurements is the variability of dissolved oxygen from riffles to pools. It is seen from Table 12 that average dissolved oxygen concentration in daylight is always greater in the riffles than in the pools regardless of the flow condition and other variables. This can be attributed to the mixing action which takes place at the riffles because of typically higher velocities, coarser substrates, and shallower depths and hence more photosynthetic action than in pools. These characteristics enable the stream to have higher DOs at the riffle before returning to the dissolved oxygen concentrations in the pools. Figure 22 indicates that ADO tends to increase with decreasing discharge, and this increase occurs at an approximately similar rate in both the Salt



Fork and Middle Fork. The DO approaches zero at high flows ( $F = 0.2 - 0.4$ ) and increases to 0.6 ppm and above at low flows ( $F = 0.7 - 0.9$ ). The difference between pool and riffle depths and velocities increases with decrease in discharge, and substrate ranks are somewhat higher at the riffles than at the pools. During high-flow conditions these differences are less significant because depths and velocities in pools and riffles do not vary as greatly as during low flows.

#### Field Procedures

A systematic measurement procedure was developed for all streams, in which thirteen transects were measured in each reach defined by three consecutive riffles. One transect was located at each riffle and five transects were located in each pool (Figure 23). Transects were equally spaced between riffles. Six uniformly spaced depth and velocity readings were made across each transect. Thus there were a total of 78 data points for each discharge measured in a reach. The grid spacing established for the transects and sampling points is in proportion to the stream dimensions: width and riffle-pool spacing. The schematic sketches in Figure 23 show the location of transects and the position of measurements across the stream. Additional velocity and depth measurements were made at one or more transects for accurate computation of discharge.

Velocities and depths were measured for three different discharges in each reach. As only the relative variations in depth and velocity were needed, level surveying to determine water surface slope was not necessary. The procedure that was established requires significantly less field work and time than data collection requiring level surveying.

Fieldwork was conducted in October and November 1985 and in April, May, and June 1986. Fieldwork was done during relatively dry periods, timed to avoid unsteady flow conditions after rainfall events. The flow durations of the discharges have the greatest differences that could be achieved. Numerous attempts were made to measure low flows (flow durations in the range of 70 to 90%) in SF2 and SF3. Because of the large volume of effluents discharged upstream, flows rarely if ever declined to these lower natural flow levels. Overall, flow durations of measured discharges ranged from 13 to 90%. The flow durations corresponding to the flows observed in

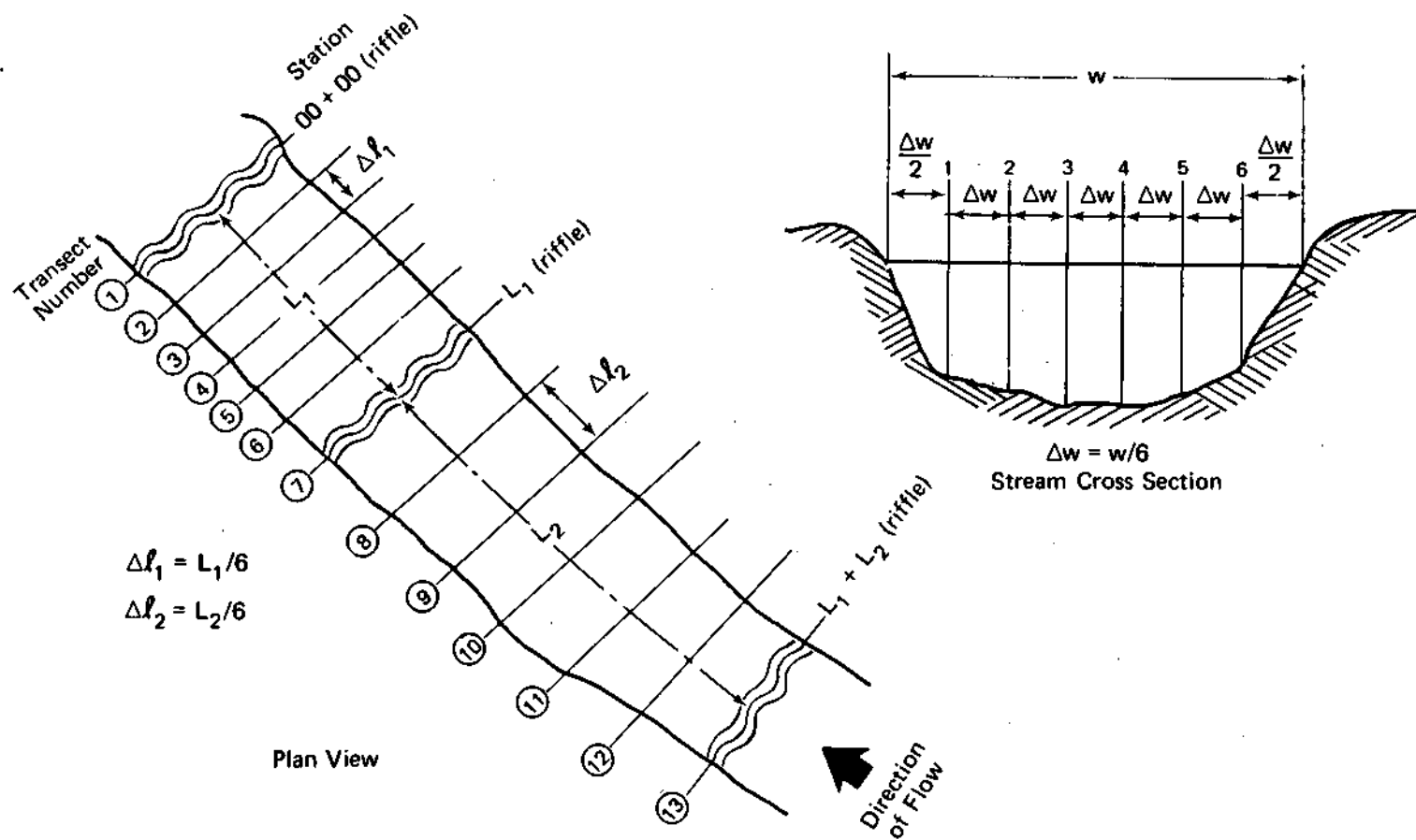


Figure 23. Schematic sketch of transect locations and division of channel cross section

the field were computed by interpolating between the computed flows at various flow durations with the regression equations previously presented in Table 2.

### **Analysis of Field Data**

Discharge, flow duration, beginning date of fieldwork, and reach average parameter values are listed in Table 13. The three discharges measured at each reach are designated a, b, and c. For reaches MF1 and SF4, four discharges were measured and these are given as a, b, c, and d. Field data were analyzed by using computer programs developed specifically for the study, augmented by statistical analysis procedures available in the SPSS (Statistical Package for the Social Services) computer software package.

Each depth and velocity sampled is assumed to represent flow conditions in a portion of the reach designated by a quadrilateral flow surface area,  $a_k$ . The bounds of the quadrilateral area are defined by the mid-point distance between measurements. A weighting factor,  $W_k$ , proportional to the ratio between this quadrilateral stream surface area and the total surface area of the riffle-pool sequence was computed for each data point. A riffle-pool sequence was defined as the section of the reach from riffle center to riffle center, e.g., the reach section between transect 1 and transect 7 and between transect 7 and transect 13. The flow surface area,  $A_{RP}$ , of the riffle-pool sequence was computed. The percent of the riffle-pool sequence represented by a quadrilateral component was then calculated by dividing  $a_k$  by the  $A_{RP}$  of the sequence. The weighting factor,  $W_k$ , was determined by dividing this quotient by 2 or the number of riffle-pool sequences in the reach.  $W_k$  is the proportion of the total reach area represented by  $a_k$ , as follows:

$$W_k = (a_k/A_{RP})/2.0 \quad (9)$$

where  $\sum_{k=1}^N W_k = 1.0$  ( $N$  = number of data points, 78).

Thus the data collected in each riffle-pool sequence are equally weighted even if the areal extents of the riffle-pool sequence in the reach differ. The weights are equal if stream width is constant and the

Table 13. Discharge and Average Values of W, D, and V  
Measured in Study Reaches

Study reach	Meas.*	Start date	Q (cfs)	Flow duration(%)	Arithmetic average values		
					W (ft)	D (ft)	V (fps)
Middle Fork Vermilion System							
1	a	10/22/86	53.8	13	16.6	1.90	1.76
	b	05/09/86	16.9	36	14.4	1.09	1.13
	c	04/28/86	5.0	62	14.2	0.65	0.64
	d	10/15/85	2.2	68	13.7	0.52	0.44
2	a	10/23/85	114.7	15	31.3	2.64	1.51
	b	05/13/86	30.0	44	27.8	1.33	0.85
	c	10/09/85	2.3	86	27.5	0.49	0.20
3	a	10/25/85	170.3	20	51.6	2.17	1.62
	b	05/23/86	76.8	37	49.4	1.39	1.28
	c	10/11/85	3.4	90	33.5	0.69	0.31
4	a	05/28/86	110.1	38	62.2	1.64	1.19
	b	10/16/85	35.2	62	57.2	1.20	0.67
	c	10/14/85	12.8	77	52.0	1.03	0.31
5	a	06/19/86	267.8	30	108.1	2.24	1.26
	b	08/04/86	31.3	73	87.4	1.37	0.34
	c	08/19/86	15.1	84	83.8	1.25	0.25
Salt Fork Vermilion System							
1	a	11/11/85	29.1	15	18.4	1.43	1.38
	b	05/02/86	10.9	35	17.9	1.00	0.99
	c	10/17/85	5.3	52	17.1	0.85	0.64
2	a	11/08/85	68.2	25	44.1	1.17	1.51
	b	06/23/86	46.3	33	43.9	0.92	1.35
	c	06/26/86	29.8	44	43.8	0.82	0.97
3	a	06/27/86	80.1	46	80.0	1.02	0.99
	b	07/07/86	66.7	50	77.0	0.94	0.93
	c	07/28/86	44.0	59	72.9	0.79	0.77
4	a	11/06/85	230.9	31	71.6	1.87	1.72
	b	05/27/86	149.6	42	70.4	1.62	1.37
	c	10/30/85	69.4	59	60.6	1.19	1.03
	d	08/06/86	35.5	70	57.1	1.09	0.70
5	a	06/20/86	293.0	32	95.8	1.86	1.88
	b	08/01/86	48.4	69	92.0	0.95	0.73
	c	08/18/86	31.0	75	87.4	0.79	0.64

\*a, b, c, and d denote different measurements in each reach

transects are equally spaced. The weights were used in all statistical calculations. The average and standard deviations of all measured depths and velocities were computed for each observed discharge at each of the ten reaches. For purposes of discussion, these values will be referred to as averages and standard deviations for each reach.

### **Riffles and Pools**

Depth and velocity variations through riffles and pools create the diversity of habitat conditions needed by various riverine life forms. The length, spacing, and differences in bed elevation of riffles and pools govern the availability of different types of habitats. The consistency in the pattern of riffle-pool formation found in the study reaches was investigated. Bed form patterns were examined in terms of riffle-to-riffle spacing as well as field observations of riffle and pool lengths. The difference in depth of flow in pool areas and riffle areas was computed. Conditions found in the natural channel reaches were compared to those in the channelized reaches.

The average riffle-to-riffle spacing,  $RS$ , is expected to be between five and seven times the stream width (Leopold and Maddock, 1953; Harvey, 1975). Channel width increases as drainage area increases. Thus the distance between riffles increases as drainage area increases. Harvey (1975) demonstrated that spacing between riffles correlates closely with average flow widths for a 20% flow duration discharge,  $W_{20}$ , where the width is computed from hydraulic geometry relations.

Riffle-to-riffle spacing was computed as the distance between transects 1 and 7 and 7 and 13 for each study reach. The computed values are shown in Table 14. The width at a 20% flow duration was computed for each study reach by using the basin equations for the basin in which the reach is located. As can be seen from Figure 18, the two basin equations for width at a 20% flow duration yield nearly the same values for the full range of drainage areas. Thus additional comparisons of channelized versus natural widths is not necessary. The ratio of riffle spacing to  $W_{20}$  was computed and is given in Table 14.

Riffle-to-riffle spacing generally increases with increasing drainage area for the natural channel reaches. In the natural channel reaches riffle spacing is around 10 times  $W_{20}$ . This is greater spacing than

Table 14. Riffle Spacing in Study Reaches

Study reach	Drainage area (sq mi)	RS (ft)	$W_{20}$ (ft)	$RS/W_{20}$
MF1	33.9	190	29.08	6.53
MF2	81.1	700	44.37	15.78
MF3	161.9	720	62.04	11.61
MF4	232.6	775	73.96	10.48
MF5	426.0	1303	99.16	13.14
SF1	20.4	240	22.00	10.91
SF2	81.4	442	43.16	10.24
SF3	240.0	1465	73.09	20.04
SF4	380.2	800	91.47	8.75
SF5	488.3	1090	103.34	10.56

Note: RS - riffle spacing in ft;  $W_{20}$  = width at F = 20%,  
computed from basin equations

usually found but the pattern is consistent. The riffle spacing in the natural channel reaches in both basins is comparable. Reaches MF2 and SF3, located in channelized streams, have very great riffle-to-riffle spacing and larger ratios than the natural channel streams.

When channels are constructed, the cross section is typically uniform for the entire length of the project. Riffle and pool forms are eliminated. The existence of riffles in the channelized reaches shows that riffle-pool sequences tends to reassert themselves in time. The distance between riffles will probably decrease in the channelized sections with time if they are left undisturbed.

The distinction between riffles and pools was less in some reaches than others (see Table 10), particularly in reach SF3. The stream channel of the Salt Fork from its confluence with the Saline Branch downstream to about Sidney has been extensively modified. Considerable dredging has been done, and numerous small impoundments have been constructed by local landowners. Virtually no streamwise variation was observed in bottom sediments. Sandbars are randomly spaced along the central portion of the channel. The riffle sites were chosen on the basis of slight differences in average depth.

The streamwise lengths of riffles and of pools were estimated in the field from observed variations in bed sediments and flow depths. Transect average depths were computed and plotted versus distance in the streamwise direction for each discharge measured in each reach. The variations in transect average depth along the stream length were in good agreement with the field estimates of riffle lengths. In nearly every case the transects adjacent to a riffle transect (e.g., transects 2, 6, 8, 12) had a notably greater average depth than found at the riffle for each discharge measured at the site. The field-observed riffle and pool lengths are noted in Table 15 for each reach. The average riffle length listed in the table is the arithmetic average of the three consecutive riffles identified. The average pool length noted in the table was similarly computed. The last column of Table 15 shows the ratio of pool length to riffle length. The average pool length generally increased with increasing drainage area of the stream in the Middle Fork and Salt Fork Basins. There was no regular increasing or decreasing pattern in riffle lengths.

Table 15. Riffle and Pool Lengths in Feet

Study reach	Riffle 1	Pool 1	Riffle 2	Pool 2	Riffle 3	Riffle avg.	Pool avg.	Ratio pool/riffle
Middle Fork Basin								
1, C	12	66	15	98	12	13.0	82.0	6.3
2, C	65	290	70	270	55	63.3	280.0	4.4
3, N/C	45	325	65	290	55	55.0	307.5	5.6
4, N	30	385	45	305	50	41.7	345.0	8.3
5, N	25	710	40	395	75	46.7	552.5	11.8
Salt Fork Basin								
1, N	10	90	10	125	15	11.7	107.5	9.2
2, C	50	235	35	132	40	41.7	183.5	4.4
3*,C	40	1040	20	415	50	36.7	727.5	19.8
4, N	45	225	80	435	50	58.3	330.0	5.7
5, N	25	428	20	592	60	35.0	510.0	14.6

Note: N and C denote natural and channelized reaches, respectively

\*No clear distinction between riffles and pools



The average depth of flow through riffle areas was compared to the average depth of flow in the pool areas. The average flow depth at a riffle was computed as the arithmetic average of the six depth measurements at transects 1, 7, and 13. The average pool depth was computed as the arithmetic average of the depths measured at the remaining 10 transects. The difference, AD, was computed by subtracting the average pool depth from the average riffle depth. This procedure was repeated for each discharge measured at each study site.

The differences in average depths, AD, computed for each discharge are plotted versus drainage area in Figures 24a and 25a for the Middle Fork and Salt Fork, respectively. SF1 is located in a natural channel and has considerably higher D values than found at MF1, which is located in a channelized reach. SF2 and MF2 are both located in channelized streams. The AD's computed for flows in these reaches are close in value. SF3 has a very low value of D as would be expected. The two Middle Fork study reaches located furthest downstream have larger D values than the comparable two Salt Fork reaches. All four of these reaches are in natural-channel streams. The magnitude of D correlates with the degree of riffle-pool definition found at the site (see Table 10).

#### Depth Distribution

The distribution of depths in a reach was investigated by plotting the 78 depths measured at a single discharge on normal probability paper. The depths measured were ranked from low to high. The cumulative nonexceedance probability,  $p$ , was computed by using the weighting scheme described earlier and the plotting position formula ( $N$  = total number of points):

$$p_i = m_i / (N+1) \quad (10)$$

where  $m_i = \sum_{k=1}^i w_k$ , and  $w_k = W_k \times N$ , so that  $\sum_{k=1}^N w_k = N$ .

For each discharge plotted, points fall on an approximately straight line between the 10% and 90% non-exceedance probability levels. The slope

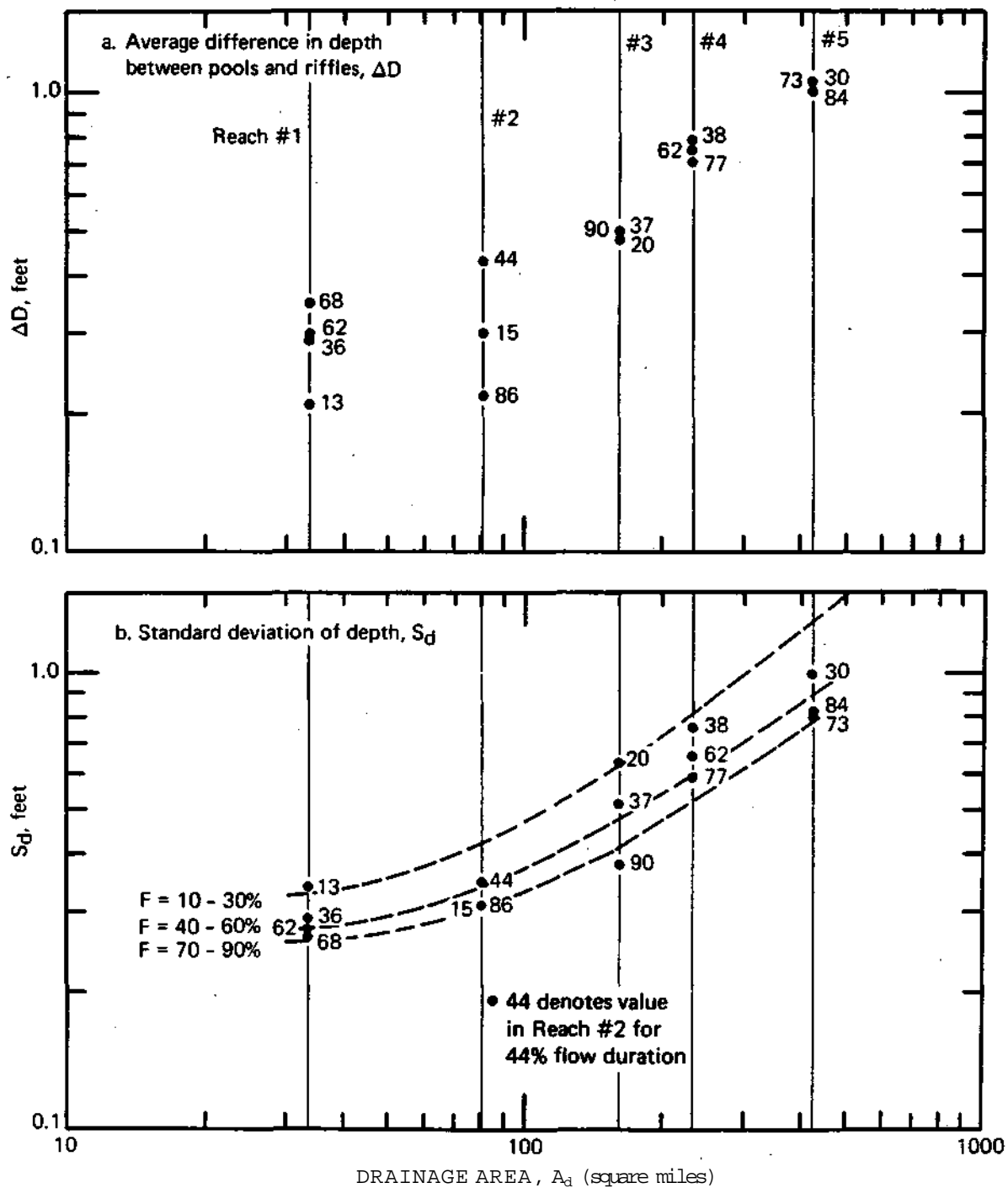


Figure 24. Average difference in depth between pools and riffles,  $D$ , and standard deviation of depth,  $S_d$ , versus drainage area,  $A_d$ : Middle Fork Vermilion River

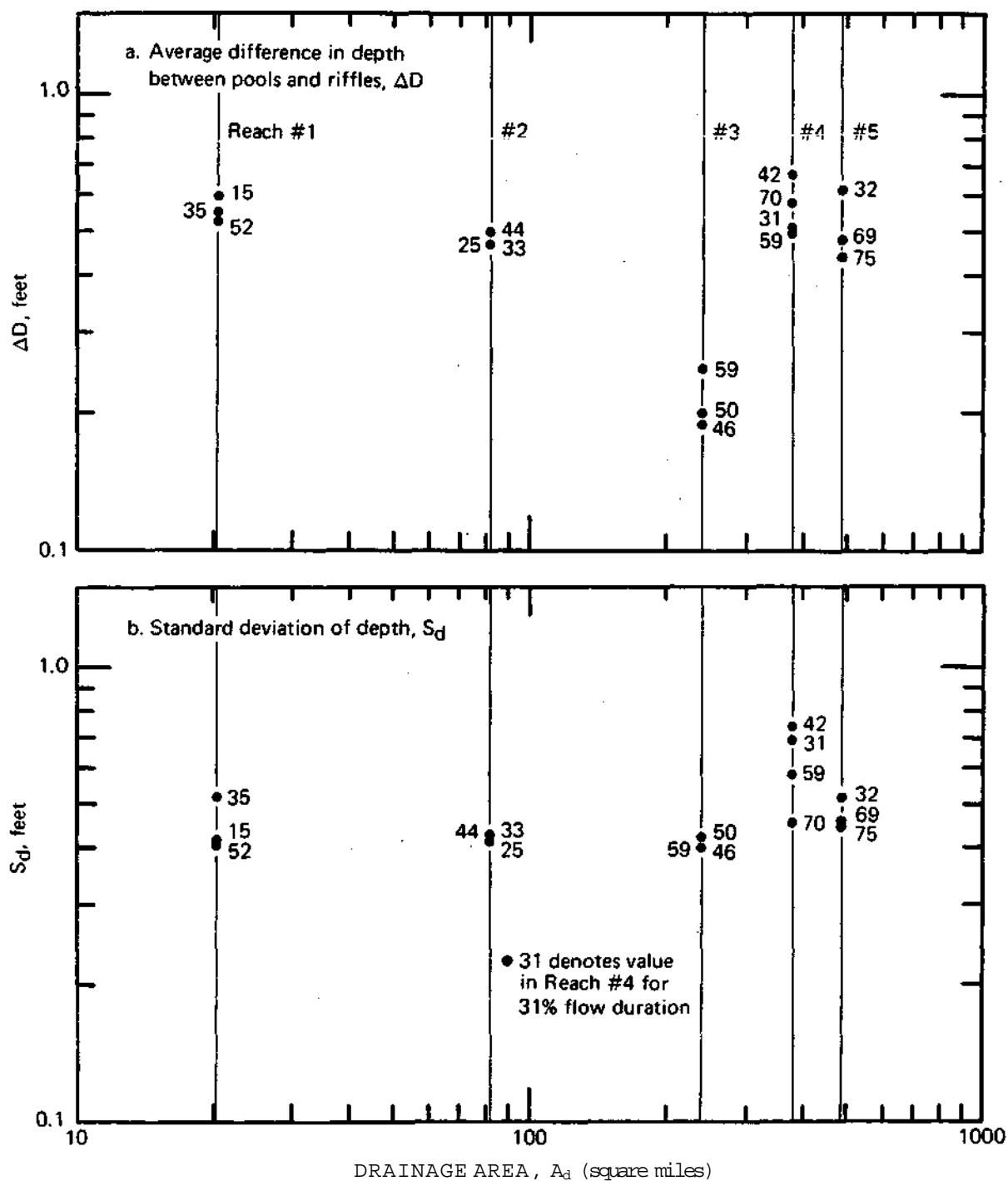


Figure 25. Average difference in depth between pools and riffles  $D$ , and standard deviation of depth,  $S_d$ , versus drainage area,  $A_d$ : Salt Fork Vermilion River

of the lines varies with discharge and drainage area. The reach average depth plots at approximately the 50% non-exceedance probability for each case.

The standard deviation of a variable with normal distribution is a measure of the spread of values about the mean. The variation of depth in a channel is predominantly influenced by pool and riffle formation; thus the standard deviation is a measure of the difference between pool and riffle depths. The correlation between the difference in riffle and pool depth  $D$  and the standard deviation of depth  $S_d$  can be observed in the plots of  $D$  and  $S_d$  versus drainage area,  $A_d$ . Figures 24a and 24b show  $D$  and  $S_d$  versus  $A_d$  for the Middle Fork study reaches. Similar plots for the Salt Fork study reaches are shown in Figures 25a and 25b. The difference between pool and riffle depths increases with an increase in drainage area. Consistent with this observation, the standard deviation of field-measured depths,  $S_d$ , is typically greater for a larger drainage-area reach than for a smaller drainage-area reach.

The parameter  $S_d$  was used as it has units of feet and is an actual measure of depth variations. Thus it retains a physical meaning when plotted versus  $A_d$ . Depths increase significantly with drainage area (when compared at the same flow duration). Computation of a dimensionless parameter such as the coefficient of variation may obscure real differences between the relative bed elevations of riffles and pools.

On the plot of  $S_d$  versus drainage area for the Middle Fork (Figure 24b) lines (shown dashed) were fit by eye to the data. Each line represents a range of flow duration. The corresponding flow duration for each measurement is noted above each data point. A comparison of  $S_d$  for the three discharges measured in each reach shows that in most cases  $S_d$  is larger at the smaller flow duration. Most of the Upper Middle Fork Basin has channelized streams, while the larger streams have natural channels. Therefore the study reaches represent the typical progression of conditions existing in the basin. The relationships plotted for  $S_d$  are a good representation of the progressive changes in depth variations in the basin.

No relationship is plotted for the Salt Fork Basin. Because the stream cross-sectional geometries are a product of separate engineering projects, there is no basis for assuming a continuous progression of change in the basin. Few if any natural-channel streams with drainage areas

between those found at SF1 and SF4 exist. A reliable relationship can not be interpolated between the data for SF1 and SF4. Alternatively, a tabular documentation was prepared from the field data to show the approximate values of  $S_d$  and the type of stream channel configurations to which they apply. The information is presented in Table 16 and provides an estimate of  $S_d$  for most stream conditions in the basin.

The variety of local depths expected within a reach for a given flow duration can be determined from the combined results of hydraulic geometry relations and relations developed from field data defining the distribution of depth. The average or mean depth,  $D$ , is calculated from the basin hydraulic geometry equation for depth. The distribution of normalized depths,  $Z$ , in a reach can be obtained from the normal cumulative probability distribution:

$$P(Z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^Z \exp(-Z^2/2) dZ \quad (11)$$

where  $P$  is the non-exceedance probability,  $Z = (d - D)/S_d$ , and  $d$  is the actual depth for which  $P$  is calculated.

The value of  $Z$  is computed for a level of non-exceedance probability by using a numerical solution of the inverse standard normal probability distribution function. The standard deviation of depth is a function of the drainage area of the reach; its value is obtained from the relationship shown in Figure 24b or Table 16. Substituting the appropriate values of  $D$ ,  $S_d$ , and  $Z$ , the depth  $d$  for a given non-exceedance probability level,  $i$ , can be evaluated by solving for  $d_i$ , as

$$d_i = Z_i(S_d) + D \quad (12)$$

For example, 30% of the depths measured in a reach will be less than or equal to the depth,  $d_{30}$ , calculated from the value of  $Z$  at  $P(Z) = 0.30$ . The frequency of occurrence for each calculated depth is equal to the difference between successive non-exceedance probabilities; e.g., 10% of the depths in a reach will range between  $d_{20}$  and  $d_{30}$ , and the average depth in that range will be about  $d_{25}$ .

By following this methodology, the hydraulic geometry and depth distribution relationships developed for the basin can be used to compute

Table 16. Values of  $S_d$  for the Salt Fork Basin

Drainage area (sq mi)	Channel description	$S_d$ (ft)		
		F - 10-30%	F = 40-60%	F = 70-90%
15-50	Natural channel (excellent pool-riffle definition)	.42	.40	.38
50-300	Channelized	.42	.42	.42
300-390	Natural channel (excellent pool-riffle definition)	.90	.70	.45
390-500	Natural channel (poor pool-riffle definition)	.54	.48	.43

the expected values of local depths in a reach for any drainage area, over a full range of flow durations.

### Velocity Distribution

The magnitude of the variation of velocity within a reach was investigated by computing the standard deviation of velocity,  $S_v$ . The computed values of  $S_v$  showed little or no correlation with drainage area but a high correlation with mean (average) velocity,  $V$ . This lack of dependence on drainage area and high correlation with mean velocity were also found for the Sangamon Basin (Singh and Broeren, 1985). At comparable mean velocities,  $S_v$  values were greater for the natural-channel reaches than the channelized reaches.

The range of expected average velocities is fairly similar for all streams regardless of drainage area. This is illustrated in the hydraulic geometry relations for velocity shown in Figures 18 through 20. From these figures it can be seen that for streams with drainage areas of 20 sq mi average velocity varies from about 0.2 to 1.0 fps, and for the largest streams in the study (500-sq-mi drainage area) velocity ranges between 0.8 and 2.6 fps for flow durations from 80 to 20%.

The coefficient of variation,  $CV_v = S_v/V$ , was computed for each reach measurement. The coefficient of variation for the velocities,  $CV_v$ , was plotted with respect to  $V$ , as shown in Figure 26. Data from natural channels are plotted with solid symbols and data from channelized streams are plotted with open symbols. From the plot it can be seen that  $CV_v$  decreases with increasing  $V$ . There is a rapid increase in  $CV_v$  as  $V$  decreases below 0.5 fps. The standard deviation becomes a larger percent of the velocity as the average velocity decreases.

Regression analysis was performed to evaluate a functional relationship between  $CV_v$  and  $V$  for both the natural and channelized streams. The functions are plotted in Figure 26. These functions are mathematically expressed as:

$$\begin{array}{ll} \text{Natural Channel} & CV_v = 0.304 + 0.351/V \\ \text{Channelized} & CV_v = 0.240 + 0.179/V \end{array} \quad (13)$$

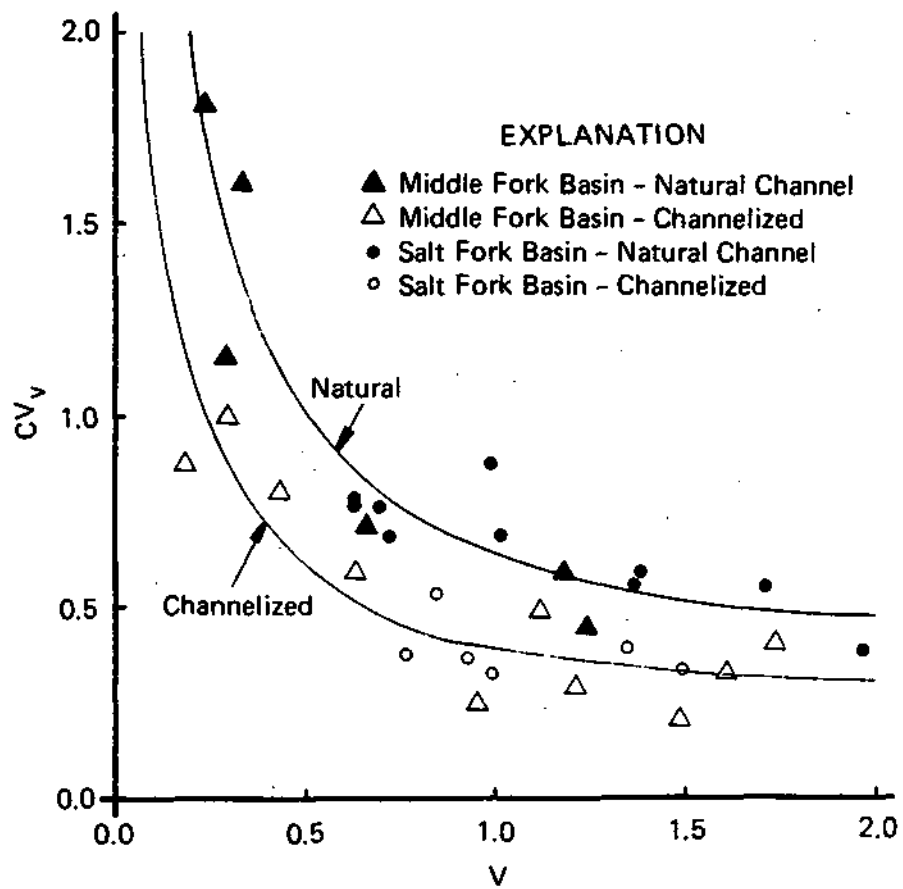


Figure 26. Coefficient of variation for velocity,  $CV_v$ , versus average velocity,  $V$



## Joint Distribution of Depth and Velocity

The methodology developed by Singh and Broeren (1985) and Singh et al. (1986) was used to investigate the joint distribution of depths and velocities by grouping velocities according to the cumulative probability of the simultaneously measured depth. Ten divisions of cumulative probability of depth between 0 and 1.0 were delineated, each corresponding to a probability interval of 0.1. The velocities measured concurrently with depths having a non-exceedance probability between 0 and 0.1 form a group, velocities associated with depths having a non-exceedance probability between 0.1 and 0.2 form a group, and so on. For each flow measured in a reach there are between 7 and 9 velocity and depth measurements within each incremental range of depth cumulative probability. Point velocities were normalized by dividing by the reach average velocity,  $V$ . Plots of normalized velocity versus coincident depth non-exceedance probability were developed for each discharge. The variation of normalized measured velocities within each depth probability group was then considered.

In each reach for each discharge there is considerably greater variation in the velocities measured at the lesser depths than at the greater depths. The higher velocities occur at depths with cumulative non-exceedance probabilities less than 50% (i.e., the depths which are less than the reach average depth). The greatest ratios of point velocity to average velocity occur at the lower average velocities. For  $V$  less than 0.5 fps many point velocities measured are three or four times as great. For  $V$  greater than 1.0 fps measured point velocities seldom exceed two times that magnitude.

The data sets of field-measured velocities from the natural channel reaches were segregated into three groups on the basis of the magnitude of mean velocity,  $V \leq 0.5$  fps,  $0.5 < V < 1.0$  fps, and  $V \geq 1.0$  fps. The same grouping was performed on field data sets from the channelized reaches. The distribution of local velocities characteristic of each of these six groups of data was investigated.

Figure 27 shows the frequency of occurrence of various normalized velocities. Five plots of frequency versus selected ranges of normalized velocity are shown on the left side of the figure. These plots were derived from the field data set from natural channels when the average

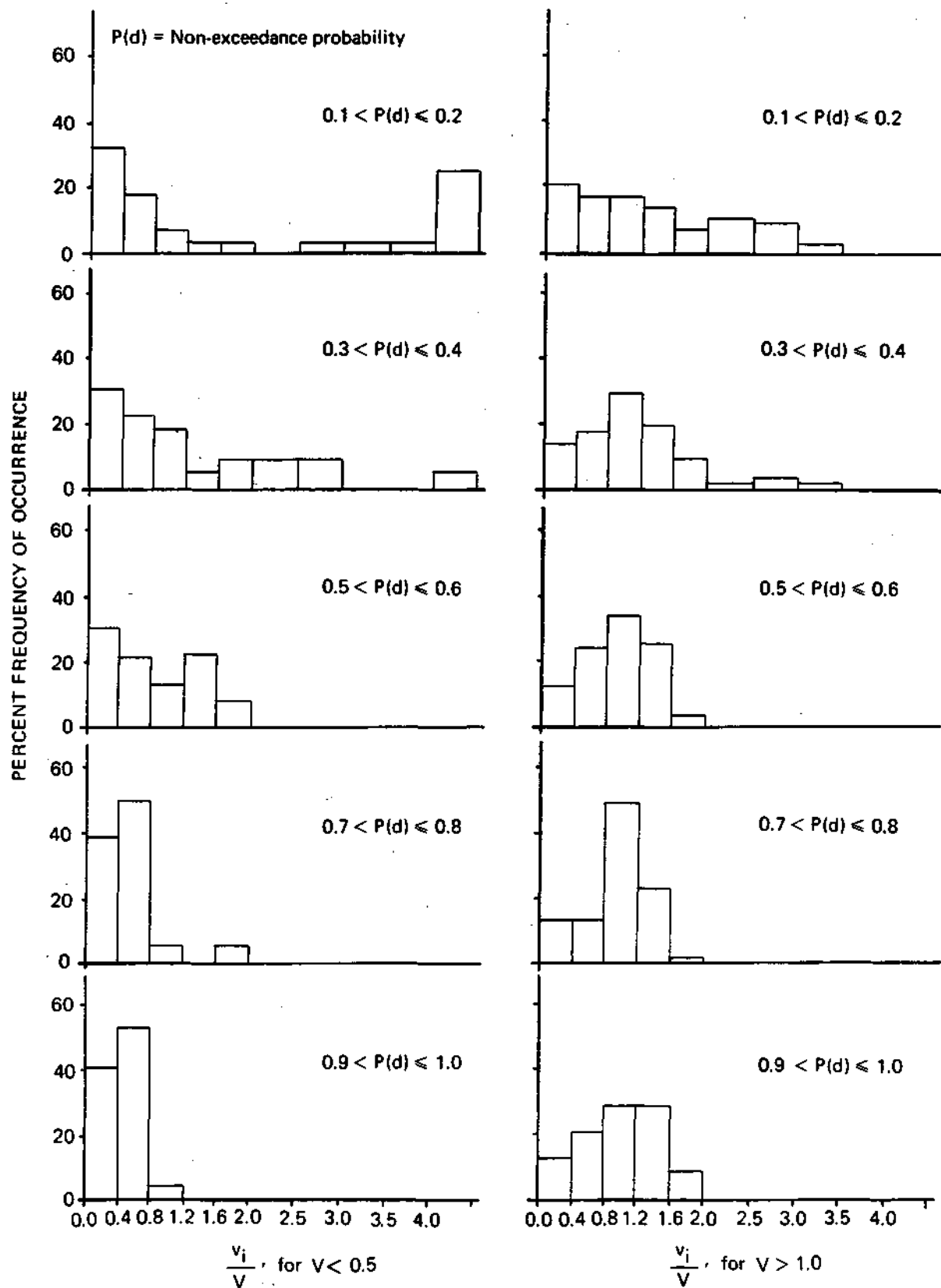


Figure 27. Frequency of occurrence of normalized velocities,  $v_i/V$ , for 10 depth probability intervals

velocity was less than 0.5 fps. Each plot represents the velocities measured concurrently with depths within a specified range of non-exceedance probability,  $P(d)$ . The first is for the lowest depths,  $P(d) = 0.2$ , and the last is for  $P(d) = 0.9$ . The five plots on the right-hand side were similarly developed from the data set of field measurements for  $V$  greater than 1.0 fps (natural channel reaches). The reduced scatter in the distribution of velocities with increasing  $V$  can be seen by comparing the plots for similar depth probability range. The greater range of velocity values at less depths (low  $P$ ) than at greater depths (high  $P$ ) can also be seen.

Similar distribution plots were developed for each of the six groups of field data. On the basis of these distributions, 100 normalized velocity values were selected to approximate the local joint distribution of depth and velocity for each group. Thus three distributions were developed for natural channel streams and three for channelized streams, representing the three velocity ranges noted earlier. Three ranges of  $V$  were selected,  $0.25 < V < 0.5$ ,  $0.5 < V < 1.0$ , and  $1.0 < V < 2.0$ . The average value of  $CV_V$  was computed for each range for natural and channelized streams. The normalized velocities were selected such that their arithmetic average is 1.0 and  $CV_V$  equals the appropriate value for the channel type and average velocity range.

#### ADJUSTMENT FACTORS FOR RESULTS OF BASIN EQUATIONS

The reach average values of  $W$ ,  $D$ , and  $V$  were computed from field data for each discharge measured. These average values were compared to values of  $W$ ,  $D$ , and  $V$  computed by substituting the stream drainage areas and the flow duration of the discharges measured in the basin equations. Considerable differences exist between calculated values and those from field measurements. At least three factors contribute to these differences: 1) basin equations are developed under constraints not applied to the field data computations; 2) the data collection procedures used by the USGS differ from those used in this study; and 3) hydraulic parameter relations differ for natural and channelized streams.

### Comparison of Field Data and Results of Basin Equations

The average width, depth, and velocity calculated from the field measurements in each reach for each discharge measured are given in Table 13. These values are the weighted arithmetic averages of the field-measured quantities. The data points were weighted on the basis of the water surface area represented as discussed previously. These values represent the average for a stream reach, not a particular cross section. The product of  $W \cdot D \cdot V$  does not usually, nor must it, equal  $Q$ .

Width, depth, and velocity were computed from the basin equations by using the respective reach drainage areas at the flow duration approximately corresponding to the measured discharge. The value of  $F$  used in the basin equations is adjusted so that the product of the predicted  $W$ ,  $D$ , and  $V$  is very nearly equal to the measured  $Q$ , following the procedure described previously in this report. The established procedure for developing hydraulic geometry relations (Leopold and Maddock, 1953; Stall and Fok, 1968) requires that continuity ( $W \cdot D \cdot V = Q$ ) be satisfied at each point by both the station equations and the basin equations. Basin equations predict typical transect average values, not reach average values of  $W$ ,  $D$ , and  $V$ . Thus, the reach average parameter values calculated from the field data and the predicted transect average values from hydraulic geometry do not represent exactly the same variables. Further, the station equations and the basin equations are evaluated by using the logs of the data for  $W$ ,  $D$ ,  $V$ , and  $Q$ . Regression analysis performed on the log-transformed data yields equations which predict the best estimate of the log of the parameters. When there is scatter in the data, this estimate represents the expected average value of the log of the dependent variable (e.g.,  $\log W$ ,  $\log D$ , or  $\log V$ ) for a given value of the log of the independent variable (e.g.,  $\log Q$ ). This procedure does not necessarily yield the best estimate of the average value of the non-transformed variable if there is a large degree of data scatter (Singh et al., 1987a).

The standard error of estimate for the station log-log relations is small, and differences between values predicted from this formulation versus a non-linear analysis would be small. However, the non-linear approach was examined for the station equations. With the methodology proposed by Singh et al. (1987a), non-linear regression analysis was

performed to develop station equations of the form  $\text{Var} = aQ^b$  ( $\text{Var} = W, D,$  or  $V$ ). The station equations so derived often do not satisfy continuity. This procedure represents a significant departure from established practice for developing hydraulic geometry relations. Further investigation of this alternative is recommended.

The difference between the field values of  $W, D,$  and  $V$  and the predicted values becomes greater with decreasing discharge. Low-flow hydraulics are significantly influenced by bed forms (Miller and Wenzel, 1984). Depths and velocities found at riffles differ considerably from those found in pools. As discharge increases, these differences become less significant and flow becomes more uniform throughout a reach. For low flows ( $F$  greater than 50%), hydraulic geometry equations consistently underestimate depth and overestimate velocity when compared to the field data. This same relationship between measured and predicted values was found in a similar comparison of information derived for the Sangamon River Basin (Singh et al., 1986). The implication is that the USGS flow measurement data used to develop the station equations and ultimately the basin equations were obtained near riffles and relatively shallow portions of pools.

The average depths and velocities computed from the field data represent a sampling from a range of flow conditions throughout riffles and pools. The object of the flow measurements made by the USGS personnel is to accurately determine the discharge. Wading measurements are made at sections where depths do not exceed 3 feet, flows are least turbulent, and velocities are sufficiently high to produce an adequate number of current-meter revolutions in a reasonable time. Although not an established practice, it would be expected that in the interest of expediency narrow flow sections would be preferred for routine measurements. In general, these criteria systematically exclude the deeper portions of pools with low velocities, as well as shallow riffles with more turbulent flow conditions. The data used to develop hydraulic geometry relations have a strong potential for bias. This is the primary factor causing differences between the hydraulic geometry results and the field values.

Channelized stream reaches tend to display different relations between hydraulic parameters than are found at natural channel streams. This is illustrated in the plots of the station data and basin equations

shown in Figures 5-15 and 18-20. Differences are greater at low flows than high flows for the stations used in this study. The Middle Fork Basin equations are developed from data collected in reaches which have not had significant channel alterations. The station data for the Salt Fork Basin were collected in streams which have undergone various degrees of modification. The relationship between the field data and the hydraulic geometry predictions will be influenced by the degree of similarity in channel configurations of the study reaches and the streams where the gages are located.

#### Development of Adjustment Factors

The purpose of a flow model is to predict the various hydraulic conditions expected throughout a reach for a range of discharges. The probabilistic distribution models for depth and velocity define the variations in these parameters about a reach average value. Estimates of the lateral dimensions of a reach are appropriately based on value of width representing a reach average. Through a determination of adjustment factors, parameter values calculated from the hydraulic geometry equations may be modified to better reflect reach average values measured in the field for all flow durations. The relationship between the results of hydraulic geometry equations (developed from USGS data) and reach average values computed from field data was investigated.

The ratios of average field data values for  $W$ ,  $D$ , or  $V$  to the values predicted from basin equations were computed. The magnitude of these ratios serves as a non-dimensional index of the differences between the field quantities and predicted quantities. For each parameter, the ratios from each reach and discharge were plotted versus  $F$ . Several trends were observed in this preliminary analysis. The magnitude of the ratios varies with  $F$  and to a lesser extent with drainage area. The plotted ratios representing natural channels in the Middle Fork show consistent trends. A different relationship with  $F$  was indicated by the ratios for the channelized reaches in the Middle Fork Basin. Separate trends in the data for the Salt Fork reaches show that this information can also be readily separated on the basis of natural versus channelized reaches. There was no

similarity in the ratios between basins. The variation of the ratios with  $F$  and  $A_d$  was individually investigated for both channel types in each basin.

## Methodology

The three discharge measurements performed in each reach provided sufficient data to evaluate an approximate relationship between  $W$ ,  $D$ , and  $V$ , and  $Q$  in each reach. Parameter values predicted from these field relations were then compared to values predicted from the basin equations.

A simple log-log linear relationship satisfactorily approximates the functional dependence of  $W$ ,  $D$ , and  $V$  on  $Q$  as measured in the field. Regression analysis was performed to evaluate the coefficients of the expression  $\log \text{Var} = a + b \log Q$  for each variable in each reach. Non-linear regression analysis was not needed as there was little scatter in the data.

The values of  $W$ ,  $D$ , and  $V$  were computed from the field equations for each reach at discharges corresponding to flow durations of 10-90%. Likewise the values of  $W$ ,  $D$ , and  $V$  were computed from the basin equations. The field equation values,  $W_{\text{field}}$ ,  $D_{\text{field}}$  and  $V_{\text{field}}$  were then divided by the hydraulic geometry results  $W_{\text{hg}}$ ,  $D_{\text{hg}}$ , and  $V_{\text{hg}}$ , respectively. This yielded a set of nine ratios corresponding to a range of discharges in each reach.

## Results

The magnitude of the ratios  $W_{\text{field}}/W_{\text{hg}}$ ,  $D_{\text{field}}/D_{\text{hg}}$ , and  $V_{\text{field}}/V_{\text{hg}}$  varies with flow duration,  $F$ , and drainage area,  $A_d$ . A mathematical expression was formulated to define the functional relationship between the  $W$ ,  $D$ , and  $V$  ratios and  $F$  and  $A_d$ . The form of the expression that best approximates this relationship overall for both channel types in each basin is:

$$C_{\text{Var}} = b_0 + b_1 F + b_2 F^2 + b_3 / A_d \quad (14)$$

where

$\text{Var} = W, D, \text{ or } V$

$b_i = \text{regression coefficient; } i = 0, 1, 2, \text{ or } 3$

$C_{\text{Var}} = \text{adjustment factor for the variable}$

The reach average values of  $W$ ,  $D$ , and  $V$  may be computed by multiplying the parameter computed from the basin equation by the adjustment factor, for a given  $F$  and  $A_d$  (for example,  $W = C_w \cdot W_{hg}$ ).

The coefficients ( $b_0$ ,  $b_1$ ,  $b_2$ ,  $b_3$ ) for the adjustment factor equations for each data set are listed in Table 17. The adjustment factor equations for selected drainage areas are plotted versus  $F$  in Figures 28 through 31. The ratios plotted in these figures are computed from the measured field data and basin equation results.

### Discussion

The field data do not provide an adequate sample to define reliable station equations. Data routinely collected by the USGS over a period of years provide a more reliable representation of streamflow conditions because they are available over a greater range of discharges, they are collected throughout the year, and the time period of the record assures that the data represent long-term conditions. The estimates of  $W$ ,  $D$ , and  $V$  at each reach determined from the field relations do provide a means of illustrating trends over a broader range of discharges than using only the measured data points.

The values of the adjustment factors vary from about 0.5 to about 1.5. The magnitude of the adjustment factors is influenced by the degree of similarity between the location where the USGS measurements were made and the study reaches selected to represent a wide range of stream conditions. Another factor accounted for by the adjustment factors is the difference in streamflow characteristics between small-drainage-area streams ( $A_d < 60$  sq mi) and large-drainage-area streams ( $A_d > 60$  sq mi).

The values of  $C_D$  for the Middle Fork Basin are for the most part greater than 1.0; thus the reach average depth is greater than predicted by the basin relations. Riffle and pool flow depths in the Middle Fork study reaches differ considerably as evidenced by the magnitude of  $D$  (Figure 24a). Assuming that the USGS measurements are typically made near riffles, multiplying the predicted value of depth by  $C_D$  adjusts for the greater depth of the pools. The adjustment factors for channelized streams in the Salt Fork Basin are very close to 1.0 (Figure 31). Riffle and pool sequences are destroyed by channelization, and the cross-section of the channel is fairly uniform. Thus flow characteristics do not vary greatly



Table 17. Adjustment Factor Equations

$$C_{VAR} = b_0 + b_1 (F) + b_2 (F^2) + b_3 (1/A_d)$$

Basin	VAR		$b_0$	$b_1$	$b_2$	$b_3$	Recommended range of $A_d$
<b>Middle Fork</b>							
Natural	W	1.365	-0.0476	1.000	-96.138		150-450
	D	1.241	0.463	0.607	-11.166		
	V	0.641	-0.508	0	68.374		
Channelized	W	0.863	-0.908	2.417	-9.164		25-100
	D	1.567	1.727	-1.708	-10.440		
	V	0.888	-0.901	0	17.766		
<b>Salt Fork</b>							
Natural	W	1.124	-1.484	2.463	-0.524		25-450
	D	0.571	1.811	-1.055	7.678		
	V	1.304	-0.745	0	3.186		
Channelized*	W	1.234	0.207	0.387	-16.017		50-250
	D	0.792	0.429	-0.357	-1.232		
	V	0.978	-0.621	0	32.035		

Note: F = decimal flow duration;  $A_d$  = drainage area in sq mi; W = flow width in ft; D = hydraulic depth in ft; and V = flow velocity in fps

\* For F = 0.1 - 0.7 only

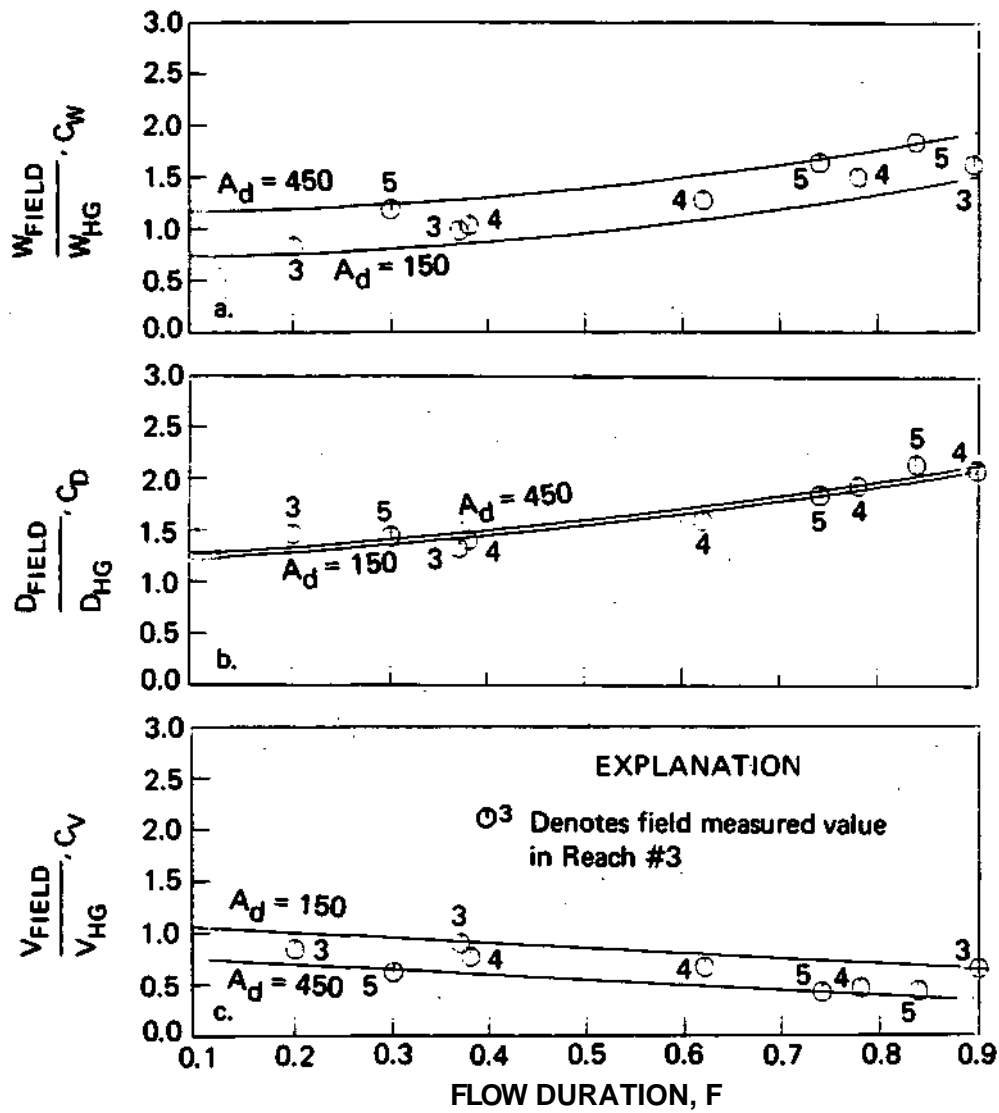


Figure 28. Adjustment factors for natural streams in the Middle Fork Basin

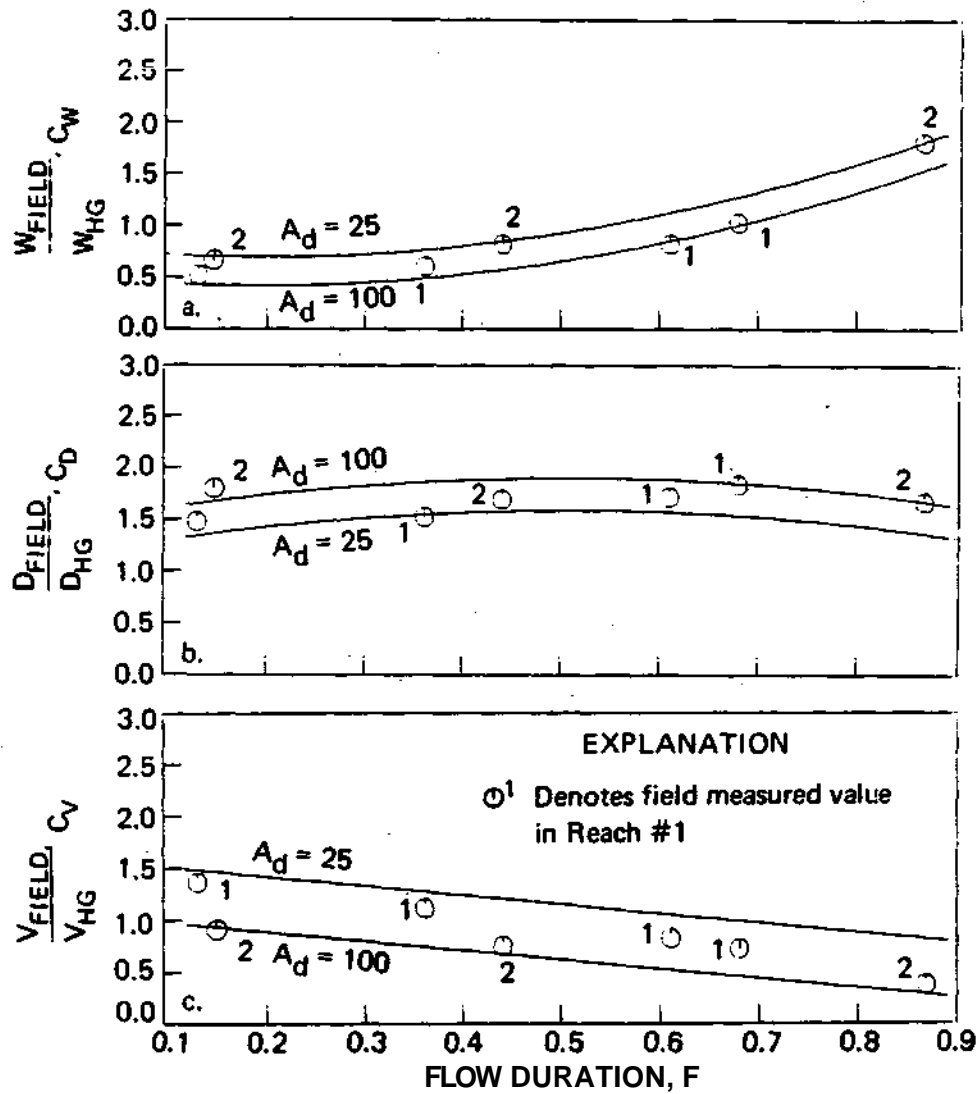


Figure 29. Adjustment factors for channelized streams in the Middle Fork Basin

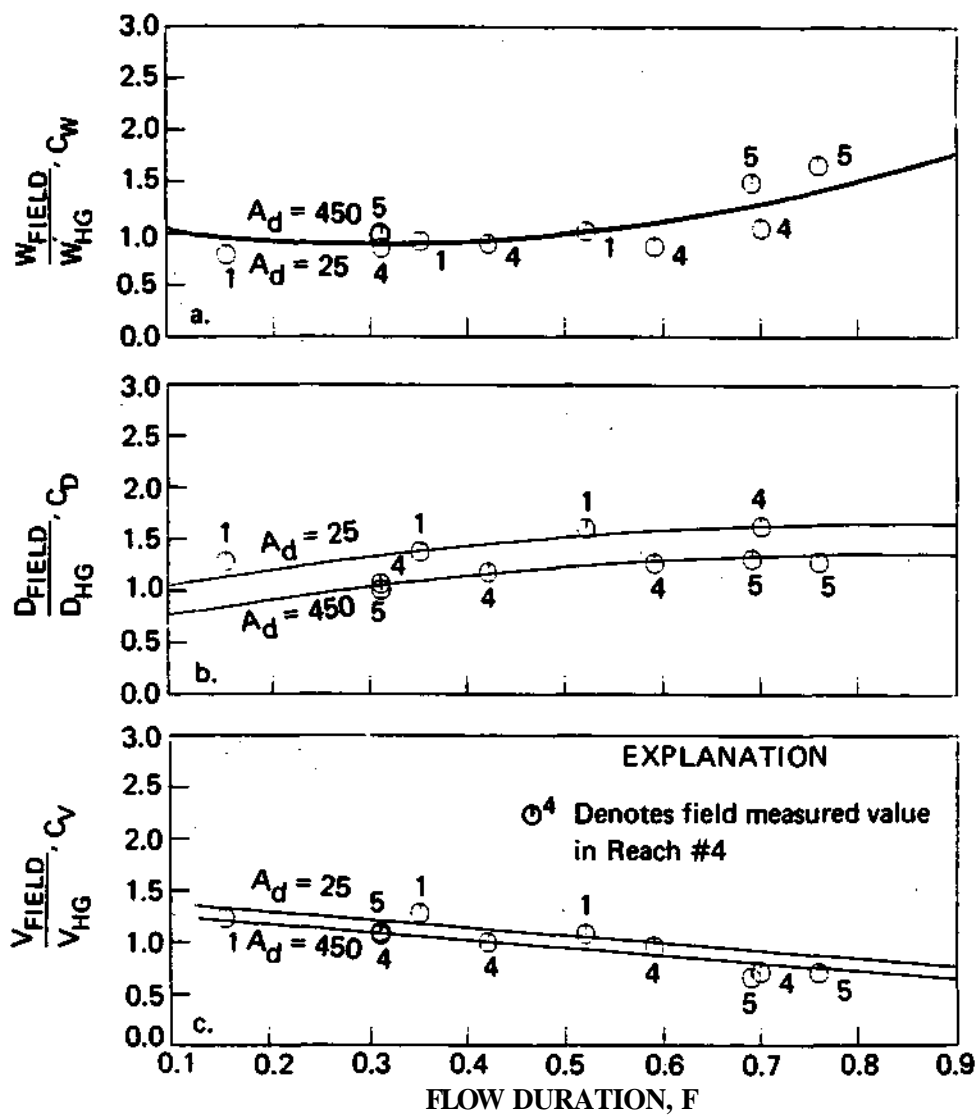


Figure 30. Adjustment factors for natural streams in the Salt Fork Basin

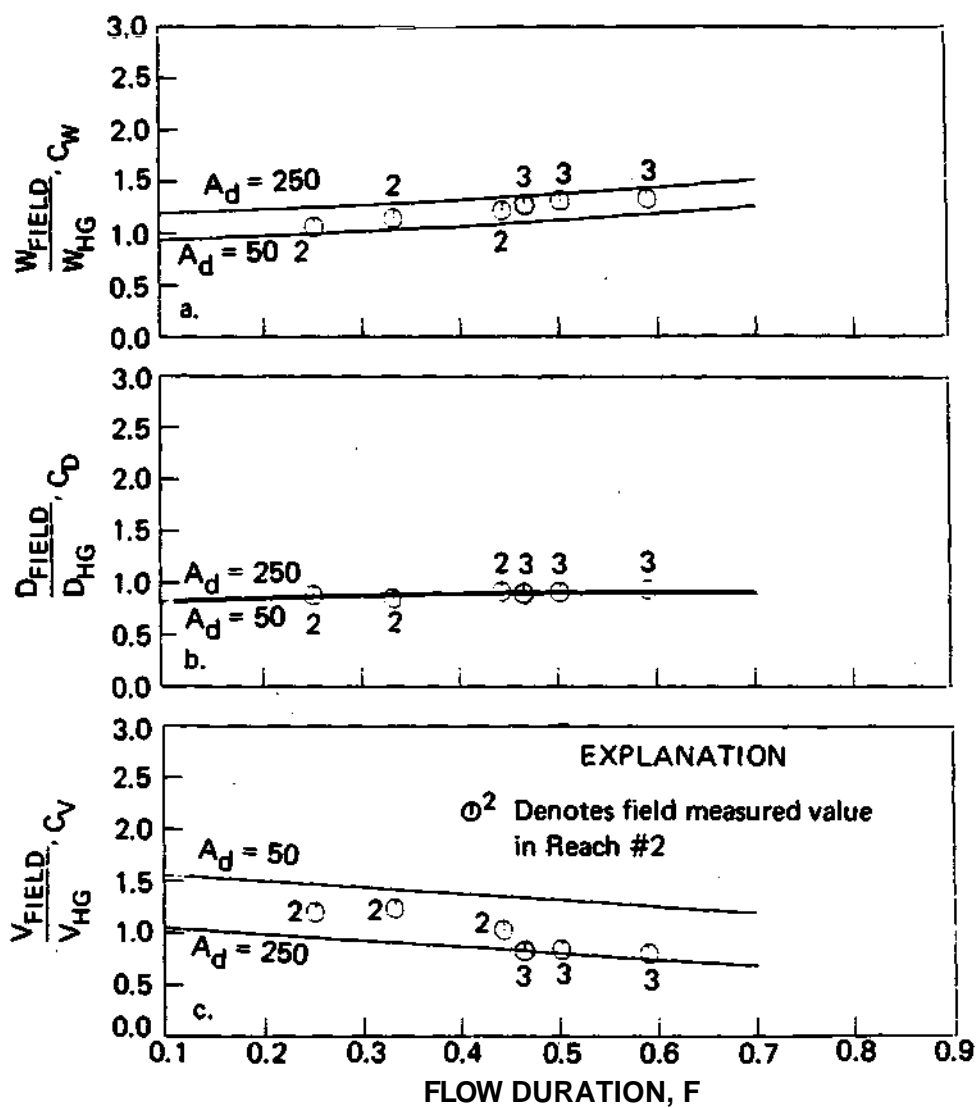


Figure 31. Adjustment factors for channelized streams in the Salt Fork Basin

along the stream length. Cross sections where the USGS performs their measurements have configurations similar to those of the study reaches. The basin relations plotted in Figures 18, 19, and 20 show greater depths in the Salt Fork Basin than in the Middle Fork Basin. However, the adjusted values of depth for the Middle Fork Basin may be greater than the Salt Fork values in some cases. Similar comparisons may be made for width and velocity.

#### FLOW AND AQUATIC HABITAT MODEL

The basinwide flow and aquatic habitat model developed for the Middle Fork and Salt Fork Basins simulates the hydraulic information needed to evaluate WUA (Weighted Usable Area) for streams throughout each basin for a broad range of discharges. The model predicts the local depths and coincident velocities throughout a stream reach as well as the proportion of the reach characterized by each depth and velocity pair for any desired discharge. Fish preference curves developed by the Cooperative Instream Flow Service Group (IFG) are then used to evaluate the suitability of the simulated local environments for target fish species.

In using the IFG flow models for calculating the WUA, a stream reach is conceptually segmented into cells having a measured surface area, and each cell is hydraulically represented by measured or interpolated depth and velocity. The probabilistic approach to flow modeling used in this study does not provide depth and velocity information for a specific cell in a known reach. Rather, through a statistical approach, depths and velocities are estimated for a given frequency of occurrence in the riffle-pool sequence.

The depth distribution defines the cumulative non-exceedence probability of a given depth. The velocity distribution provides information on the various velocities expected to occur for selected depths representing designated intervals of the cumulative depth probability function. Depths calculated at successive cumulative probabilities have a frequency of occurrence equal to the difference between the current and previous cumulative probability. Evaluating depth and velocity at uniformly incremented cumulative probability levels yields an equal frequency of occurrence for each depth-velocity pair.

The data collection and analysis conducted in this study were structured such that the probability of occurrence for the depth-velocity pair is related to a percentage of a riffle-pool-sequence surface area. For illustrative purposes, consider 10 depths evaluated at the 5%, 15%, 25%, and so on up to the 95% cumulative probability level for a given drainage area and flow duration. Each calculated depth has an equal frequency of occurrence from riffle center to riffle center (i.e., one riffle-pool sequence). Ten percent of the stream (as measured by flow surface area) will be represented by the 5% cumulative probability depth,  $d_{05}$ ; 10% by the 15% cumulative probability depth,  $d_{15}$ ; and so on. Ten velocities having an equal frequency of occurrence may be calculated for each depth from the applicable velocity distribution. Each depth-velocity pair,  $(d_i, v_{i,j})$ ,  $i = 1, 10$ ,  $j = 1, 10$ , therefore represents 1/100 of the stream flow surface area. The reach may be any length provided the drainage area remains approximately the same and the reach extends through at least one riffle-pool sequence, beginning and ending at the same location relative to the riffle-pool sequence.

The total flow surface of the reach ( $A_R$ ) is the product of the reach length and the average flow width per 1000 feet of stream length. Each cell represented by  $(d_i, v_{i,j})$  has a flow surface area,  $a_{i,j} = 1/100 \cdot A_R$ . It follows that:

$$A_R = \sum_{i=1}^{10} \sum_{j=1}^{10} a_{i,j} \quad (15)$$

The WUA is computed from a modified form of equation 1:

$$WUA = \sum_{i=1}^{10} \sum_{j=1}^{10} S(d_i) \cdot S(v_{i,j}) \cdot a_{i,j} \quad (16)$$

where  $S(d)$  and  $S(v)$  are the fish preference indexes. Figure 32 shows the fish preference functions  $S(d)$  and  $S(v)$  for the longear sunfish (spawning and adult life stages) and the largemouth bass (juvenile and adult life stages). In the computer algorithm a tabular index of fish preferences is used to determine the values of  $S(d)$  and  $S(v)$  for the desired fish species and life stage (Herricks et al., 1980). Taking  $a_{i,j}$  out of the summation, the resulting equation is

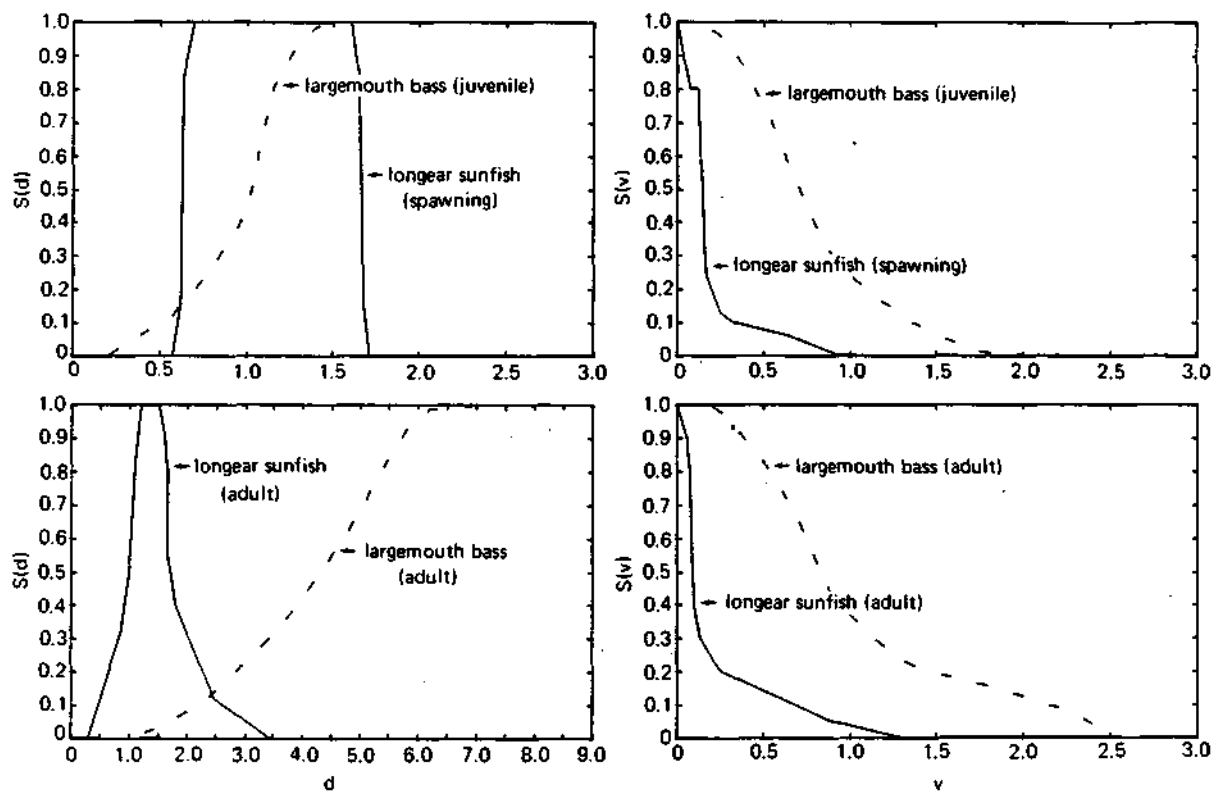


Figure 32. Preference curves for longear sunfish and largemouth bass



$$WUA = \frac{A_R}{100} \sum_{i=1}^{10} \sum_{j=1}^{10} S(d_i) \cdot S(v_{i,j}) \quad (17)$$

The model calculations proceed in a step-wise fashion:

1) For a stream with given drainage area, the flow-duration equations are used to evaluate discharges (Q) corresponding to selected annual flow durations (F) or to determine the flow duration corresponding to a specified discharge.

2) Values of W, D, and V are computed from the basin hydraulic geometry equations; through an iterative procedure the value of F used in the hydraulic geometry equations is adjusted so that  $W \cdot D \cdot V = Q$ .

3) The values of W, D, and V are multiplied by adjustment factors calculated from the adjustment-factor equations to yield the reach average values.

4) The standard deviation of depth,  $S_d$ , is determined from the relations shown in Figure 24b for the Middle Fork Basin or from the values listed in Table 16 for the Salt Fork Basin. A range of depths is computed from the normal probability distribution by using the reach average depth and  $S_d$ .

5) The appropriate velocity distribution for the given magnitude of reach average velocity is selected for the desired channel type (natural or channelized). Coincident velocities are calculated by multiplying the non-dimensional velocities defined by the velocity distribution by the reach average velocity.

6) The fish-preference values for each depth and velocity are determined and the WUA of the stream at each discharge is computed. Typically, a stream length of 1000 feet is used and WUA is calculated per 1000 feet of stream length.

A detailed sample calculation is presented by Singh et al. (1986).

The basin models calibrated for the Middle Fork and Salt Fork Basins are incorporated in computer programs which perform the calculations. The relations between WUA and flow duration may be graphically illustrated by using a plotting program compatible with the output from the simulation

programs. The relations between substrate and drainage area in both basins shown in Figure 21 may be used to further define the suitability of the habitat for a specific fish.

#### Adjustments for Effluent Discharges

The flow-duration equations presented in Table 2 define the relationship between natural flows and drainage area. Effluents discharged into streams increase the flow for a given flow duration. The accumulated effluent inflows must be added to the natural flow to determine the discharge downstream of outfalls from the wastewater treatment plants. For example, for the Saline Branch, which has a drainage area of 89.8 sq mi at its mouth, the natural 70% flow duration discharge ( $Q_{70}$ ) may be calculated from the flow duration equation:

$$Q_{70} = 0.09127 \cdot 89.8 = 8.2 \text{ cfs}$$

The average daily discharge from the Urbana-Champaign plant in 1985 was 22.4 cfs. Thus, for 1985 conditions,  $Q_{70}$  at the mouth of the Saline Branch is 30.6 cfs. This discharge is approximately equal to a natural flow having a flow duration of 46% at that location.

The combination of urban development and artificially increased streamflows typically results in alteration of the channel cross section from the natural state (Hammer, 1972). In the Salt Fork Basin, the streams receiving effluents have artificially constructed channel shapes which have been maintained by periodic clearing and dredging. The Salt Fork Basin relations already reflect the hydraulics of the channelized streams; therefore these relations may be readily used to predict W, D, and V of altered streamflows. The W, D, and V of a discharge formed by both natural flow and effluents may be calculated from the basin equations by using the flow duration of the equivalent natural flow, e.g., 46% in the above example (modified so that  $W \cdot D \cdot V = Q$ ).

Several discharge parameters for the three major wastewater treatment plants in the basin are listed in Table 18. The values are based on 1984-1985 flows from the treatment plants. The receiving streams and approximate drainage areas at the outfalls are also listed. The parameters in Table 18 are the average daily effluent discharge,  $q_{ave}$ ; the average maximum daily effluent discharge,  $q_{max}$ ; and the lowest 7-day average

Table 18. Effluent Discharges in the Salt Fork Basin

Treatment plant	Receiving stream	$A_d$ (sq mi)	1984-1985				$Q_{eff}$ (cfs)
			$Q_{ave}$ (cfs)	$Q_{max}$ (cfs)	$Q_{low}$ (cfs)		
Rantoul Sanitary District East Plant	Upper Salt Fork tributary		13.5	3.7	5.6	2.1	1.5
Chanute Air Force Base	Upper Salt Fork tributary		8.4	1.9	4.5	1.3	0.5
Urbana-Champaign Sanitary District Northeast Plant	Saline Branch		69.0	22.4	31.5	14.9	22.2

Note:  $A_d$  = drainage area;  $Q_{ave}$  = average daily effluent discharge;  
 $Q_{max}$  = average maximum daily effluent discharge;  $Q_{low}$  = lowest 7-day  
effluent discharge; and  $Q_{eff}$  = average effluent discharge

effluent discharge,  $q_{low}$ . The values of  $q_{ave}$  and  $q_{max}$  were determined from information obtained from the IEPA. The value of  $q_{eff}$  represents average effluent discharge minus streambed infiltration, or the average net addition to permanent flows in the downstream reach. Losses occur when effluents are discharged to a stream which under natural conditions would be dry and/or where the nature of the parent soils, ground-water level, and degree of stream incision result in flow losses along the stream length (Singh, 1971; Singh and Stall, 1973). The Rantoul and Chanute plants discharge into streams where flow losses occur. The  $q_{eff}$  values plus the natural flows computed from the annual flow-duration equations represent flow conditions for the 1985 condition of effluent flows. The quantity of effluent that is discharged varies from time to time, and thus the estimate of discharge for a given condition will also vary. Discharge estimates may be refined by using monthly flow durations to estimate the natural flow and values of effluents typical of each month.

#### **BASIN WEIGHTED USABLE AREA (WUA) RELATIONS**

Habitat response curves (WUA versus discharge or flow duration) may be readily developed for any stream in either basin by using the proposed model. Sample plots of WUA versus flow duration for selected streams in both basins are shown in Figures 33 and 34. Figure 33 shows the available WUA for the longear sunfish (spawning and adult) and the largemouth bass (juvenile and adult) in natural-channel streams with  $A_d = 450$  sq mi. Figure 34 shows the WUA for two life stages of the longear sunfish in streams with  $A_d = 250$  sq mi, as calculated for the Middle Fork Basin (natural channel) and for two different flow conditions in the Salt Fork Basin (channelized). (In some cases the average velocity was outside of the recommended range for the velocity distributions defined previously.)

The abscissa of the plots in Figures 33 and 34 is the flow duration corresponding to the natural flow (computed from the equations shown in Table 2) or the flow without any additions from effluent discharges. The two stream reaches in the Salt Fork (250 and 450 sq mi drainage areas) receive effluents from wastewater treatment plants. The 1985 effluent flows ( $q_{eff}$ ) were added to the natural flow computed to determine the 1985 condition discharge expected for a given flow duration in each reach. In

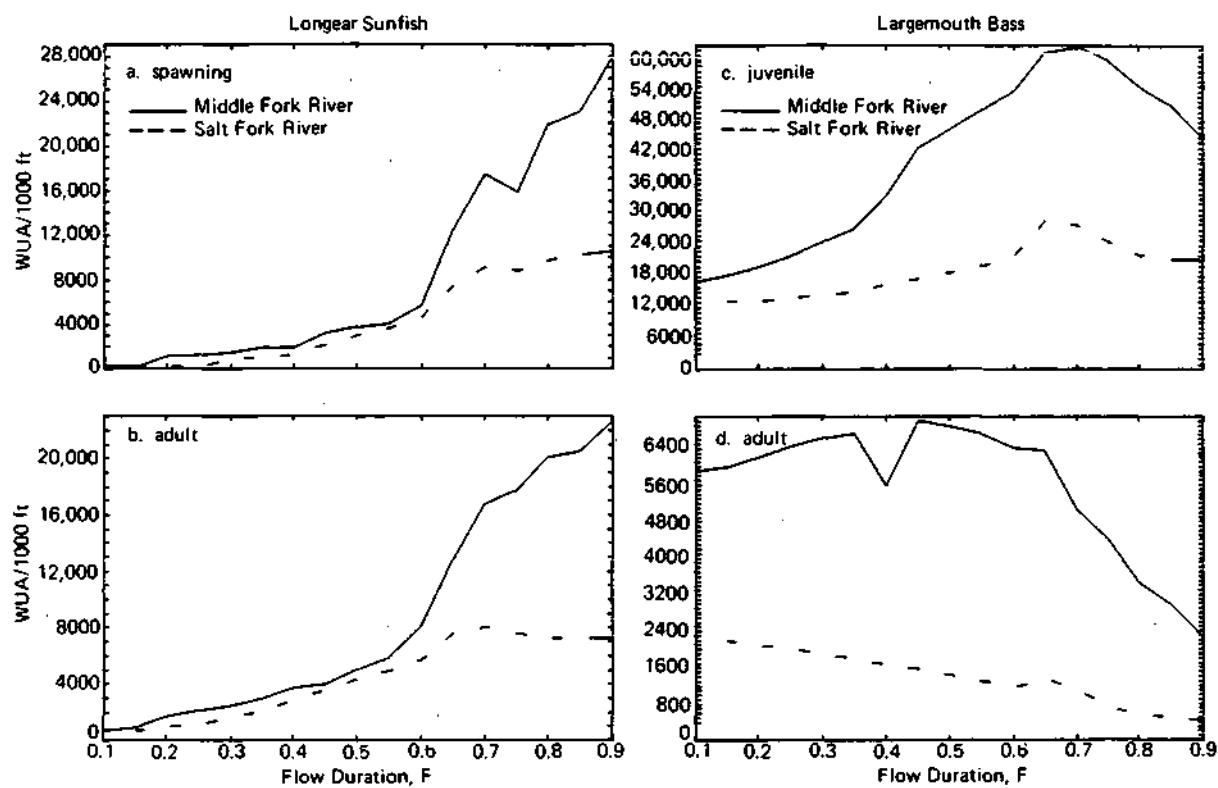
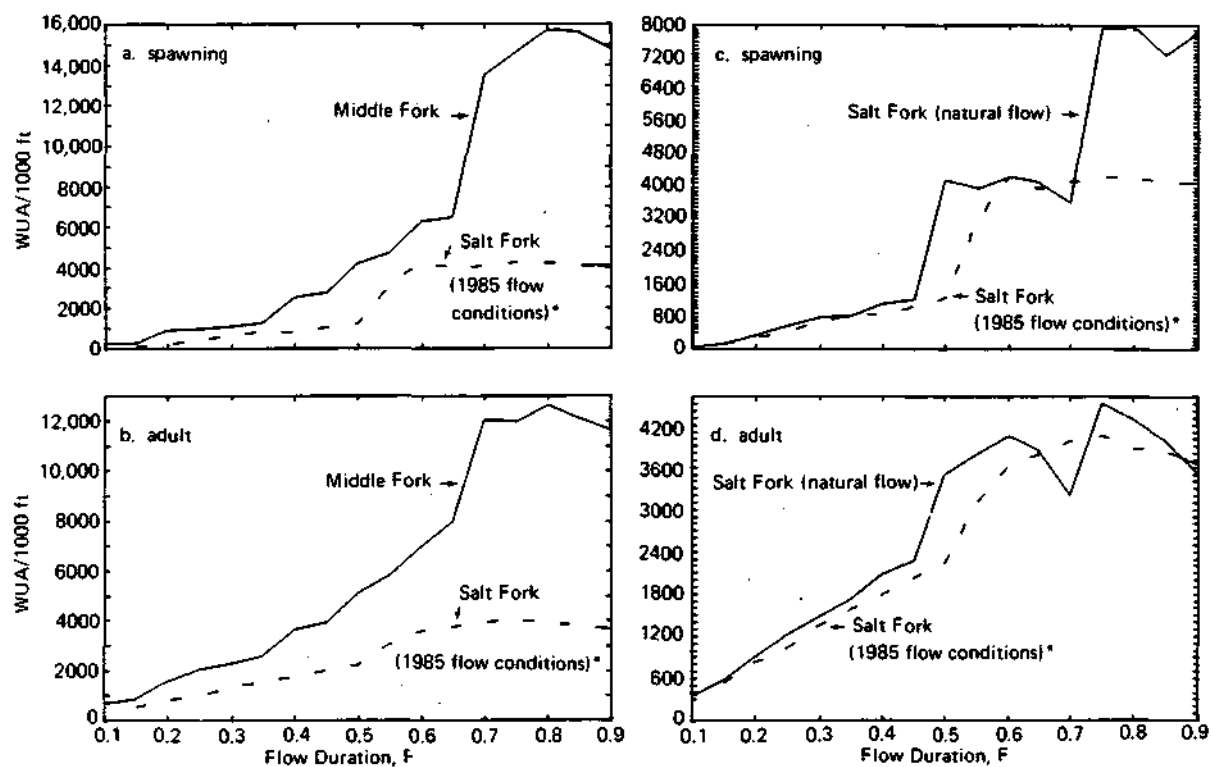


Figure 33. Weighted usable area, WUA, versus flow duration, F, for longear sunfish and largemouth bass for streams with drainage area = 450 sq mi



\*Natural flow plus 24.2 cfs effluent flow

Figure 34. Weighted usable area, WUA, versus flow duration, F, for longear sunfish in streams with drainage area - 250 sq mi

these cases where the streamflow is increased by effluent discharges the value of  $F$  used in the basin equations is determined through an iterative process so that the product  $W \cdot D \cdot V$  is equal to the computed 1985 condition discharge.

The longear sunfish and the largemouth bass are two sport fish species which may be found in the Middle Fork Basin. The longear sunfish also has been observed in the Salt Fork Basin (Greg Good, IEPA, personal communication, 1987). The habitat response curves shown in Figure 33 illustrate the relative differences in the quantity of usable stream habitat available in the two basins. Alteration of the physical habitat, e.g., flow rates and bottom types, resulting from channel and drainage modifications is one of the principal causes for decimation of fish species which inhabit clear flowing riffles or quiet pools (Smith, 1968). The higher values of WUA in the Middle Fork River than in the Salt Fork are consistent with the greater degree of stream modifications in the Salt Fork Basin and with observations of greater fish populations in the Middle Fork Basin.

Differences in the suitability of the habitat available in the Middle Fork River and the Salt Fork River are also illustrated in Figures 34a and 34b. The influence of increased flow caused by effluent additions to the Salt Fork tributaries is illustrated in Figures 34c and 34d. Differences in WUA for the two flow conditions (natural, and natural plus effluents) are greater at the higher flow durations (lower flows).

The habitat response curves provide valuable information on the relative abundance of useful aquatic habitat in a stream. They provide an analytical basis for comparing the quality and quantity of the habitat in different streams over a broad range of discharges. The impact of increasing or reducing discharge quantities may be evaluated on a quantitative basis by using the flow and aquatic habitat models.

#### SUMMARY

The Middle Fork and Salt Fork Vermilion River Basins lie within the same physiographic and hydrologic region. Small-drainage-area streams in the Middle Fork Basin have been channelized, whereas both small and medium-sized streams in the Salt Fork Basin have undergone extensive channel

modifications. Large urban areas have developed in the Salt Fork Basin. The large quantities of effluents discharged from wastewater treatment plants serving these communities increase flows in the receiving streams. Drainage modifications and urbanization within a basin alter the flow regime, water quality, and flow characteristics of streams in the network. The impact of such changes is usually detrimental to stream ecology.

The effects of channelization of streams can be observed in the streambed profiles, the distribution of riffle and pool lengths, and the difference in riffle and pool depths. The streambed profiles show that the streams in both basins are relatively immature and have not reached a state of equilibrium. The spacing between riffles and pools is greater in both basins than is typically found. The differences in depths between riffles and pools are less in channelized streams than in natural streams. The existence of riffles in the channelized streams (which were originally constructed with uniform cross sections) demonstrates that riffles and pools reassert themselves with time. There is less variation in substrate size, and finer bed materials, in the channelized streams than in the natural streams. These types of physical changes in the streams may lead to less availability of certain types of habitats, particularly riffle habitats, which are characterized by fast-moving shallow flows over coarse substrate.

Alteration of stream channels has a profound effect on flow hydraulics. The basin relations and adjustment factors developed for both basins quantitatively define the expected average conditions for streams throughout both basin networks. The basin equations developed from USGS data define  $W$ ,  $D$ , and  $V$  at a transect. The Middle Fork station hydraulic data appear to have been obtained at transects located at or near riffles. The Salt Fork Basin data satisfactorily define conditions typical of the fairly uniform channelized streams. The adjustment factors developed from the field data may be used to modify results from the basin equations to better reflect reach average conditions for various channel configurations.

Relations developed from the field data show the expected ranges of local depths and velocities. Differences in depth along a reach, as measured by  $D$  and  $S_d$ , increase with increases in drainage area in the Middle Fork Basin. The artificial construction of many of the channels in the Salt Fork Basin has obliterated this pattern. The variation and



distribution of local velocities are strongly correlated with the magnitude of the bulk flow rate (average velocity). Channelization results in less variation in local velocities about the average velocity. This is readily quantified by the coefficient of variation of velocity.

The high daytime levels of DO in the Salt Fork Basin arise from photosynthetic activity of large algae populations. These populations grow in response to high nutrient levels in the effluents discharged to the streams. The respiration of algae at night may lead to very low DO levels during this part of the diurnal cycle. Stream reaeration is enhanced by fast, shallow flows through riffles, as is shown by the difference in DO measured in riffles and pools.

The habitat response functions presented for the longear sunfish and the largemouth bass demonstrate the differences in habitat availability between the two basins for these sport fish. The results show that less suitable habitat exists in the Salt Fork; these results are in good agreement with observed differences in fish populations.

The basinwide probabilistic flow model interfaced with the IFG methodology may be used to evaluate the aquatic habitat of any stream in either basin for any discharge scenario. The model may be used to evaluate existing conditions, providing a numerical evaluation of current habitat quantity and quality. Proposed changes to streamflow or channel form may be incorporated in the model and studied in terms of their impact on the availability of suitable habitat. The capability of the model to provide an objective numerical assessment of the quality of the stream habitat makes it a valuable analytic tool. The habitat response curves generated from the model simulations provide the basis for establishing protected flow limits for target fish species. The model may be readily used as a management tool because of its basinwide applicability.

The purpose of this study was to investigate the physical character of each basin and to develop a flow and aquatic habitat model to quantitatively evaluate the availability of useful habitat in the area streams. The essential components of the developed flow and aquatic habitat model are: flow-duration and basin hydraulic geometry equations; distributions of local depths and velocities in a stream reach; adjustment factors for modifying the flow parameters computed from the basin equations to conform to those observed in detailed field investigations; and use of

the incremental methodology to simulate WUA from the information on local depths and velocities and fish preferences.

#### Recommendations for Future Research

The reliability of the relationships developed from field data may be improved by providing a broader data base. Field data collection should be expanded to include measurement of 5 or more discharges in each study reach. Study reaches should include 3 or more riffle-pool sequences. Measurement of flow parameters over a broader range of discharges will provide a better definition of the relationship between hydraulic geometry correction factors and flow duration. The extent of variation in average parameter values along a reach may be better examined by increasing the length or the number of the study reaches. Local velocities and depths occurring at flows when the average velocity is less than 0.25 fps should be measured to better define the velocity distribution in this range.

Relations developed from the collected substrate data show a correlation between substrate rank and drainage area. Additional data should be collected to validate the results and develop more refined distribution relationships. This information could then be incorporated directly in the flow and aquatic habitat model.

Correlations between reaeration rates and flow parameters need to be investigated so that DO availability may be incorporated in the model. Additional measurements of DO, particularly at night, would provide data necessary to fully define the diurnal cycle of DO levels and refine relationships between DO and flow.

The basinwide flow and aquatic habitat model should be applied to more river basins in Illinois. Values of coefficients evaluated for the various relationships used in the model could be compared in terms of their variability with basin physiography and morphology. Derivation of the model for basins throughout Illinois would provide a practical management tool for defining protected flows.

Several basins in Illinois have been studied by using the flow models supported by the IFG. A study of the reliability and repeatability of the flow dynamics simulated by those models, as well as of the proposed probabilistic model, should be conducted. Such a study will provide information needed to evaluate the merits of each model. Instream flow

studies vary in scope, and this investigation would provide information necessary to determine which flow model is appropriate for a particular type of study.

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