EFFECTS OF SUSTAINED ELEVATED DISCHARGES FROM INTRABASIN FLOW DIVERSION ON THE FLUVIAL GEOMORPHOLOGY OF EAST BRANCH PERKIOMEN CREEK, BEDMINSTER, PENNSYLVANIA

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ABSTRACT OF THE THESIS

Effects of Sustained Elevated Discharges from Intrabasin Flow Diversion on the Fluvial Geomorphology of the East Branch Perkiomen Creek, Bedminster, Pennsylvania

by ROLF V. ACKERMANN

Thesis Director:
Professor Gail M. Ashley

The intrabasin transfer of water required for seasonal cooling of the Limerick nuclear power plant in southeastern Pennsylvania via the East Branch Perkiomen Creek provides and opportunity to observe and record the response of a natural (fluvial) system to sustained elevated discharge. The stream flows over and is partially cut into jointed mudstones which outcrop in ~20% of the banks and inhibit meander migration. The channel bed is armored with a thin veneer of imbricated coarse gravel; bank and floodplain materials consist of dense, coherent clayey mud. Structural control on channel orientation is evident at the regional and local level.

As a direct result of flow diversion, the mean annual discharge of the East Branch Perkiomen Creek has increased by 450% from 6.8 cfs (0.19 m^3/s) to 37.7 cfs (1.07 m^3/s). The annual hydrograph has been altered from its natural flashy character (low baseflow with episodic storm runoff peaks) to one of alternating elevated summer plateaus (diversion period) and lower winter plateaus. There is a regular seasonal switch in flow regimes, reversing the relative magnitude of summer and winter flows. Storm peaks have become much less pronounced. The channel is exposed to extended periods of elevated flow

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DEDICATION

This thesis is dedicated to:

Rolf and Virginia Ackermann

My parents, whose undying support does not go unappreciated

Maria Krause-Ackermann

Meine liebe Oma

Dr. Henry Hanson

A mentor; a friend

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INTRODUCTION

Stream and river channels are used by society for a number of purposes, including potable water sources, recipients of treated effluent, flow diversion, and recreation. Fluvial systems are widely acknowledged to be in dynamic equilibrium with a number of independent and dependent variables. A major perturbation of the system often results in a catastrophic response on the human scale. Such an example is the severe flooding of the Mississippi and Missouri Rivers in the summer of 1993 as a result of higher than normal precipitation. Such perturbations are of a short duration, even on a human time scale, and can be difficult to evaluate. The long-term effects of changing precipitation trends are much harder to evaluate since they take place over a period of time greater than the average human lifespan.

As populations the world over increase, so does demand for electricity and groundwater. In order to produce electricity and operate safely, nuclear power plants require large amounts of water for cooling purposes. It is sometimes necessary to bring water in from other basins to provide the volumes of water needed for consumptive use. As stress on aquifers and reservoirs increases due to urbanization, it will become increasingly necessary to implement intrabasin and interbasin transfer projects to provide water for power generation, manufacturing, irrigation, and human consumption. These flow diversions take on many forms, often using existing river channels as inexpensive flow conduits.

During high electricity demand periods (summer months), Limerick Nuclear Generating Station outside Philadelphia, Pennsylvania, requires cooling water for consumptive use in excess of what is available from the Schuylkill river. Philadelphia Electric Company (PECo; a complete listing of abbreviations is provided in Table 1) thus opted to implement a flow diversion to make up the difference. This flow diversion uses a natural stream channel, the East Branch Perkiomen Creek, as a conduit for the majority of

Table 1: List of abbreviations and symbols used in the text

Abbreviations

PECo	Philadelphia Electric Company
PPPS	Point Pleasant Pumping Station
TAMS	Tippets-Abbot-McCarthy and Stratton
DER	Pennsylvania Department of Environmental Resources
DRBC	Delaware River Basin Commission
ESMP	Erosion and Sedimentation Monitoring Program
NPDES	National Pollution Discharge Elimination System
USGS	United States Geological Survey
RA	Prefix for cross sections established for this study
RU	Prefix for the cross section used with the Rutgers University stream gage
TS	Prefix for ESMP transects
BM	Bench mark
cfs	cubic feet per second
ft	feet
g	gram
kg	kilogram
l	liter
lbs.	pounds
m	meters or rank in flood frequency calculation
mgd	millions of gallons per day
N	Newtons or number of years of record in flood frequency calculation
s	second

Symbols

A	channel cross sectional area
a	width (w) coefficient in hydraulic geometry calculations
b	width (w) exponent in hydraulic geometry calculations, or integer coefficient in power-law relations
c	depth (h) coefficient in hydraulic geometry calculations
D_A	drainage area
d	depth at a point in the cross section
d_{50}	grain size (b-axis) that 50% of the sampled population (by frequency) is smaller than

d_{16}	grain size (b-axis) that 16% of the sampled population (by frequency) is smaller than (one standard deviation below d_{50})
d_{84}	grain size (b-axis) that 84% of the sampled population (by frequency) is smaller than (one standard deviation above d_{50})
f	depth (h) exponent in hydraulic geometry calculations
Fr	Froude number
g	acceleration due to gravity
h	mean flow depth at a cross section
in	inches
k	velocity (U) coefficient in hydraulic geometry calculations
L	broad (large) meander wavelength
L_t	thalweg distance
L_v	valley distance
m	velocity (U) exponent in hydraulic geometry calculations, or slope exponent in power-law relations
"n"	Manning's "n"
P	wetted perimeter
Q	discharge
Q_{bkf}	bank-full discharge
Q_{ma}	mean annual discharge
R	hydraulic radius
Re	Reynold's number
$R.I.$	Recurrence interval
S	water surface slope
$S.I.$	sinuosity index
U	mean flow velocity
w	top-width of stream cross section
w_b	bank-full channel width
λ	small hydraulic meander wavelength
μ	molecular viscosity of water
θ_c	dimensionless critical shear stress (Shield's Parameter)
ρ_w	density of water, varies with temperature
ρ_s	density of the sediment
τ	measured shear stress

τ_{bkf}	shear stress at bank-full discharge
τ_c	critical tractive force (critical shear stress)
τ_d	shear stresses measured during diversion flows
τ_f	shear stress required to flush fines from the surface of the armored channel
τ_r	shear stress required to move (re-arrange) 30% or the armoring material, and flush deep fines.
ω	stream power (3 different types denoted by suffix of 1, 2, or 3, e.g. ω2)

the distance of the flow diversion from the Delaware River. The flow diversion has been in operation for five years. The amount of water diverted via the East Branch Perkiomen is substantially more than the natural flow of the creek. For the life of the diversion thus far, an erosion and sedimentation monitoring program has been in effect, producing a useful record of channel change since prior to the diversion project.

This creek and the flow diversion provide a unique opportunity to study a system that has had one of its independent variables (discharge) changed by a known magnitude for a known, extended period of time. In essence, it has had its equilibrium state substantially altered. The existing channel monitoring data set provides a record of channel form for the period of the altered state, further enhancing the opportunity for study. By studying such an altered system, more can be learned about fluvial responses to significant, extended, external perturbations.

This study has four objectives: 1) first and foremost to assess the effect that the intrabasin transfer project has had on the hydrology, hydraulics, sedimentology and fluvial geomorphology of the East Branch Perkiomen Creek; 2) to seek an explanation for any channel changes by utilizing existing records from a United States Geological Survey gage located on the creek, records on volumes pumped to the East Branch Perkiomen Creek, the data set provided by the monitoring program records, as well as geologic, geomorphic, hydraulic, and surveying data collected specifically for this study; 3) to predict magnitudes of channel change during the flow diversion into the future; and 4) to compare the flow diversion to the East Branch Perkiomen and its effects to other flow diversions, as well as to natural channels without flow diversion, and with similar characteristics. The results of this study should help us to learn more about how natural dynamic-equilibrium systems react to sustained anthropogenic changes of one of their independent variables. The results should also have broad practical applicability to the future planning and design of transfer projects which use second- and third-order bedrock channels as conduits for diverted flow.

BACKGROUND

HISTORICAL - EAST BRANCH PERKIOMEN

Early Studies

In the early 1970's, Philadelphia Electric Company (PECo) began construction of a nuclear generating station. Limerick Nuclear Generating Station (Limerick) was completed in the middle and late 1980's, and is located near Limerick, Pennsylvania (a suburb of Philadelphia) along the banks of the Schuylkill River (Figure 1). Limerick is a 2100 megawatt facility with two reactors. Unit 1 came on line in 1986, and Unit 2 came on line in 1989.

Periods of high electricity demand in the summer coincide with low river stage. As a result, projected consumptive use of cooling water for two reactors operating at or near capacity exceeded acceptable withdrawal limits from the Schuylkill. During periods of low stage on the Schuylkill, natural flow is supplemented from local reservoirs in order to preserve water quality. Projected withdrawals would have had an adverse impact on water quality. The need for additional water to be supplied to Limerick thus arose. Two options were assessed: 1) The construction of a reservoir specifically for the use of Limerick, and 2) An intrabasin transfer of water from the Delaware River. The second option would involve the use of a creek in the basin as a conduit for the diverted flow. The creek selected for this was the East Branch Perkiomen, in Bucks County, near Bedminster, Pennsylvania (Figure 1). The second option also included flow diversion to a second creek, the North Branch Neshaminy near Buckingham, Pennsylvania (Figure 1), in order to ease the demand for groundwater predicted for Bucks and Montgomery Counties by the twenty-first century.

An environmental impact statement prepared by the Delaware River Basin Commission (1973) concluded that the diversion of water from the Delaware would have far fewer adverse impacts than the construction of a new reservoir. The potential adverse impacts on the East Branch Perkiomen were predicted to be temporary erosion and

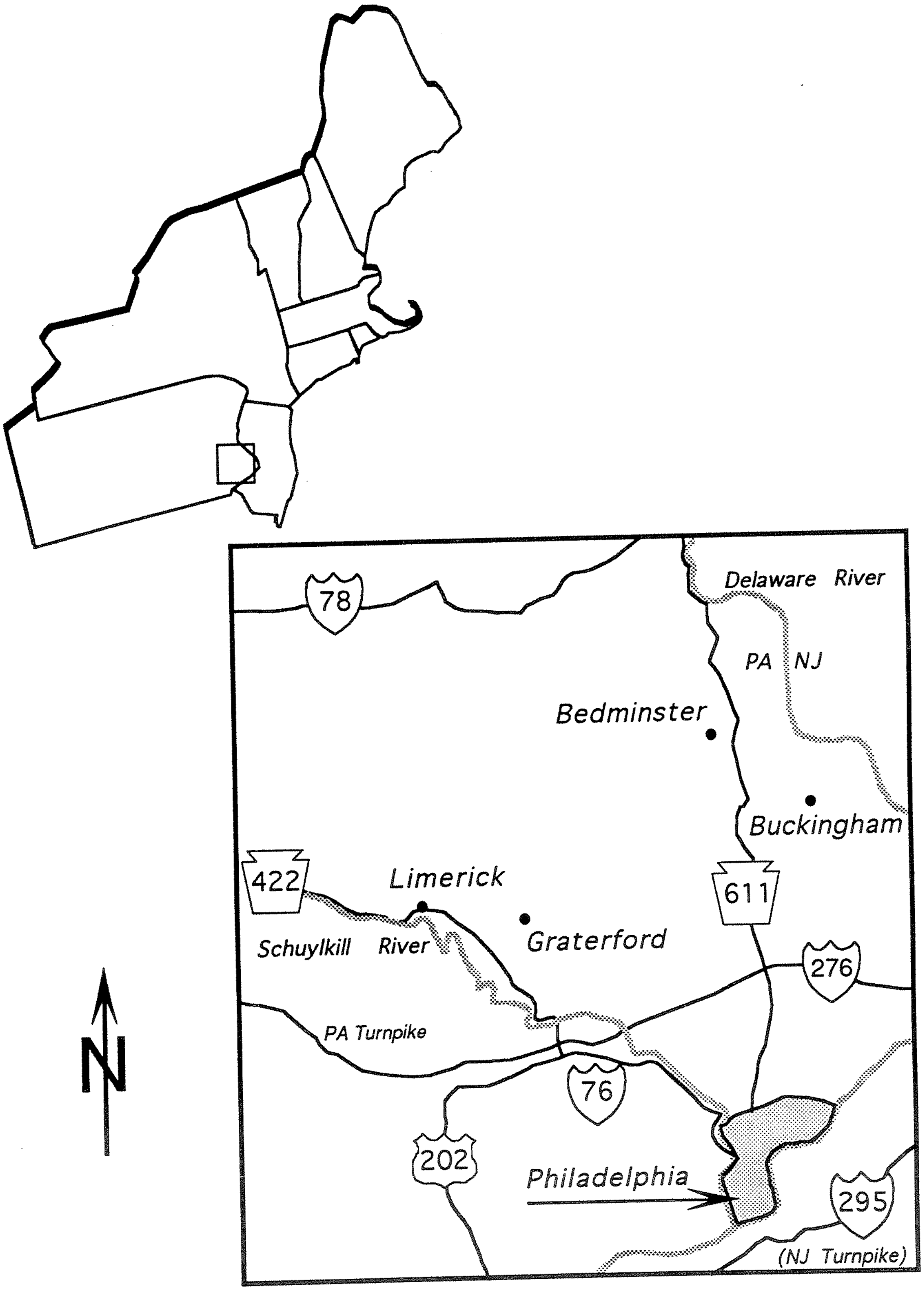


Figure 1: General location map.

sedimentation. A previous study (E.H. Bourquard Associates, Inc., 1970a,b) found that the projected flows into the channels were non-erosive in the materials that formed the channels. The increased water flow in the East Branch Perkiomen was predicted to have the beneficial effect of increasing the fish population and improving water quality during periods of low natural flows due to an increase in aeration (Delaware River Basin Commission, 1973). Potential adverse impacts on the Delaware River were limited to consumptive loss of the diverted flow, the effect of which was determined to be minimal.

In 1982, the Pennsylvania Department of Environmental Resources (DER) prepared an environmental assessment report which outlined the general engineering plan for the intrabasin transfer, as well as re-assessed potential impacts of the transfer project. DER found that the increased flows would be beneficial to aquatic life in the creeks, and that the project design flows of 65 cfs were considered non-erosive. DER confirmed the need for the water diversion in light of the need for cooling water at Limerick and to ease stress on groundwater supplies in Bucks and Montgomery Counties from increased demand.

In 1984 Tippetts-Abbett-McCarthey-Stratton (TAMS), an engineering firm contracted by PECo, completed an erosion study on the East Branch Perkiomen Creek. The erosion study concentrated on a ~2 km reach of the stream immediately downstream of the proposed location for the outfall (point at which diversion water would be discharged into the stream) and energy dispersion structure (a series of tumblers designed to reduce the velocity and force of incoming diversion flow). This study determined that the design flows of 65 cfs would be contained within the banks of the creek (bankfull discharge was determined to be 100-150 cfs). The study also determined that the river bed consisted of an armor of cobbles and gravel, as well as some sand. The banks were determined to be comprised of silty, clayey, gravelly sand to medium, plastic silty clay. The channel bottom was calculated to be stable at 87.5 cfs, with velocities at the banks being within the non-erosive range for cohesive soils. Frequency of bank failure due to rotational slump was predicted to decrease with sustained discharges (such as the project design discharges) because of a reduction in rapid drawdown of the water surface (such as after a large storm event). Rapid drawdown was cited as resulting in excessive pore pressure in bank materials, causing slumping. The study concluded that the channel bottom would not be subject to scour at the velocities to be expected for the design discharges, although some shale rock fragments might be transported during large foods. The only bottom materials expected to be entrained by the design flows were those that were smaller than 10 mm (pebbles), which is smaller than the materials armoring the channel bed.

In 1985, DER conducted a hydraulic and streambed stability investigation (PA DER, 1985) for the East Branch Perkiomen Creek (North Branch Neshaminy Creek was also evaluated in this study). The study concentrated on a relatively short reach of the stream immediately downstream of the proposed location for the outfall structure. Using HEC-2, a streamflow computer modeling program, several locations within the study reach were determined to be stable or unstable with respect to natural flows. A stable channel was defined as one where actual shear stress exerted by flowing water on the channel is less than the critical shear stress required to move materials in the channel. An unstable channel was defined as one where actual shear stress exceeds critical shear stress.

The channel bottom was found to be stable at both natural flows and the design discharges. This was attributed to the natural armor of the channel, which had been left behind after natural flows had removed finer-grained materials. The streambanks were found to be made of fine-grained soils and several were found to be unstable at design discharges. These banks were found to be unstable at natural flows as well. However, no stable streambanks were found to become unstable at design flows. The 1985 DER study concluded that the diverted flow would not lead to any additional instability within the study reach. However, those reaches that were unstable at natural flows were predicted to experience accelerated erosion at design discharges. The study did note that natural forces may cause stable reaches to become unstable at both natural and design flows. It was also found that the change from non-pumping to pumping conditions was not likely to induce additional sedimentation within the study reach.

The pipelines and energy dispersion structures were constructed in the mid to late 1980's. In 1989, PECo prepared an erosion and sedimentation monitoring plan (ESMP) (RMC, 1989) in accordance with requirements set forth in the stream encroachment permit (E09-077A) granted by DER. This plan outlined a phased start-up of pumping operations in conjunction with periodic surveys of a number of cross-sections along the East Branch Perkiomen. Phase I was divided into three stages of 10 cfs, 20 cfs, and 27.1 cfs. Pumping during Phase II would be divided into three stages of 40 cfs, 50 cfs, and 67 cfs. The phased start-up was implemented between August 1989 and August 1990.

The maximum pumping rate for normal operations was set at 65 cfs. This was selected as the maximum because it was 60% of the 1-year flood flow at the Elephant Road bridge (112 cfs), and 30% of the 1-year flood flow at the United States Geological Survey (USGS) gage at Bucks Road bridge (238 cfs). In addition, 65 cfs is well below what TAMS and PECo determined to be the threshold of change (100-150 cfs) for the creek. The pumps would be shut down when the discharge at the USGS gage equalled or exceeded 125 cfs, so as not to aggravate the stream when it was at or near flood stage. Minimum pumping rates during low electricity demand periods (winter months) were set at 10 cfs, so as to minimize dramatic on-off effects between summer and winter diversion flows.

The monitoring program initially consisted of a photochronology of the creek to aid in the assessment of changes to the stream channel during the phased start-up program. Eight cross-sections downstream of the outfall structure, and one upstream (as a control), were surveyed after each stage of the phased start-up, and quarterly thereafter. The cross-sections were also surveyed after major storm events where flows at the USGS gage had exceeded 238 cfs (the one year flood, as determined by TAMS). The monitoring program included provisions for stabilization of the stream channel if it was determined at any point that there had been significant erosion in one or more of the surveyed cross-sections.

Significant change was defined as an increase of 1.5 ft in stream width and/or an increase of 0.75 ft in channel depth, as measured at the transects. The stream encroachment permit required that all surveyed cross-sections be submitted to DER in the form of plotted cross-sections comparing pre-operational channel form and most recent surveyed channel form.

The monitoring program was implemented in July 1989, and is ongoing. Table 2 shows the chronology of survey dates of the ESMP. Surveys other than scheduled quarterlies are noted. These periodic surveys comprise a major portion of the data set used for this thesis. They provide a useful record of channel change over a four and a half year period. Due to pending litigation concerning the flow diversion, raw data were not available from either PECo or their contracted consulting firms. Instead the data were acquired for this study in the form of plotted cross-sections. These cross-sections were acquired from DER Harrisburg and Conshohocken (who had an incomplete chronology), and DRBC. PECo has petitioned DER to terminate the program on the grounds that there has not been appreciable change in the monitoring cross-sections over the period of the program. An analysis of the periodic surveys of the cross-sections is included later in this thesis.

In July 1991, R.U.I. Associates completed a report on soil erosion impacts from the use of the East Branch Perkiomen for water diversion (Hepner, 1991). This report found that as of March 1991, there had been loss of the upper soil horizons due to higher water levels, causing loss of vegetation. R.U.I. found that erosion along the stream banks had occurred as a result of the stream channel expanding due to the flow diversion. The less dense upper (Bt) horizons were cited as being more erodible, and had been stripped away by flows, leaving the dense, compact lower (Bx) horizon behind. Roots cannot penetrate this horizon, and consequently run out over it. With the loss of the Bt horizon, most of the vegetation was lost as well. This was cited as an apparently continuing process, and that further erosion would occur as the channel continued to adjust to the flow diversion.

Table 2: Chronology of surveys of ESMP transects.

Date	Comments
13-Jul-84	Surveyed by TAMS (1984) erosion study
19-Jul-89	Pre-operational survey
16-Aug-89	High Flow
12-Sep-89	End Stage I of Phase I (10 cfs)
27-Sep-89	High Flow
25-Oct-89	End Stage 2 of Phase I (20 cfs)
20-Nov-89	End Stage 3 of Phase I (27 cfs)
3-Jan-90	One day test of full diversion flow (67 cfs)
1-Feb-90	High Flow
26-Feb-90	Prior to Spring Restart of Phase II
19-Mar-90	End Stage I of Phase II (40 cfs)
11-May-90	High Flow
30-May-90	High Flow
25-Jun-90	High Flow
9-Aug-90	Mid point of full-flow test (Phase II, 50 cfs)
26-Sep-90	End of full-flow test (Phase II, 67 cfs)
10-Oct-90	High Flow
20-Dec-90	
20-Mar-91	
26-Jun-91	
27-Sep-91	
9-Dec-91	
2-Mar-92	
2-Jun-92	
31-Aug-92	
20-Nov-92	
18-Dec-92	High Flow
7-Apr-93	High Flow
25-Aug-93	
2-Dec-93	High Flow
7-Dec-93	High Flow

- High flows are those where discharge at the USGS gage at Bucks Road Bridge exceeded 238 cfs
- Those surveys without comments were scheduled quarterly surveys

In September 1991, a report on the long-term effects of elevated discharge on the East Branch Perkiomen Creek was completed (Ashley, 1991). This report found that based on empirically based process-response studies from the literature, the stream channel would respond to the sustained, elevated discharges in the same way as if the mean annual discharge had been increased from 2 cfs (pre-pumping) to 73 cfs. Ashley (1991) indicated that channel widening was more likely than channel deepening because of the bedrock and gravel armor in the channel bed. Ashley (1991) emphasized that established empirical relations between the mean annual discharge and meander wavelength (distance between inflection points of adjacent stream meanders) would be altered by an increase of the mean of the maximum month (mean discharge during the month of the year with greatest flow), resulting in an increase in meander wavelength (thus implying erosion). Ashley (1991) observed that hydrographs of USGS discharge data from the East Branch Perkiomen during the diversion period bore no resemblance to those from prior to the diversion. Maintained saturation of bank materials by high water levels was suggested in this study as potentially leading to increased erosion as well, since saturated materials are weaker than unsaturated materials.

The study concluded that the sustained elevated discharges imposed on the creek by the flow diversion would result in an increase in channel cross-sectional area due to lateral soil erosion and an increase in channel sinuosity. Ashley (1991) suggested that a more conservative threshold of change of 2-20 cfs than PECo's 100-150 cfs was warranted.

Flow Diversion

Figure 2 illustrates the complete diversion system as it was outlined in the 1982 DER report, and is in place now. Water is pumped from the Delaware River at the Point Pleasant Pumping Station (PPPS), located in Point Pleasant, Pennsylvania. Diversions from the Delaware are prohibited when such withdrawals would reduce flow at the Trenton USGS gage to less than 3000 cfs (PECo, 1989). If flows at the Trenton gage fall below

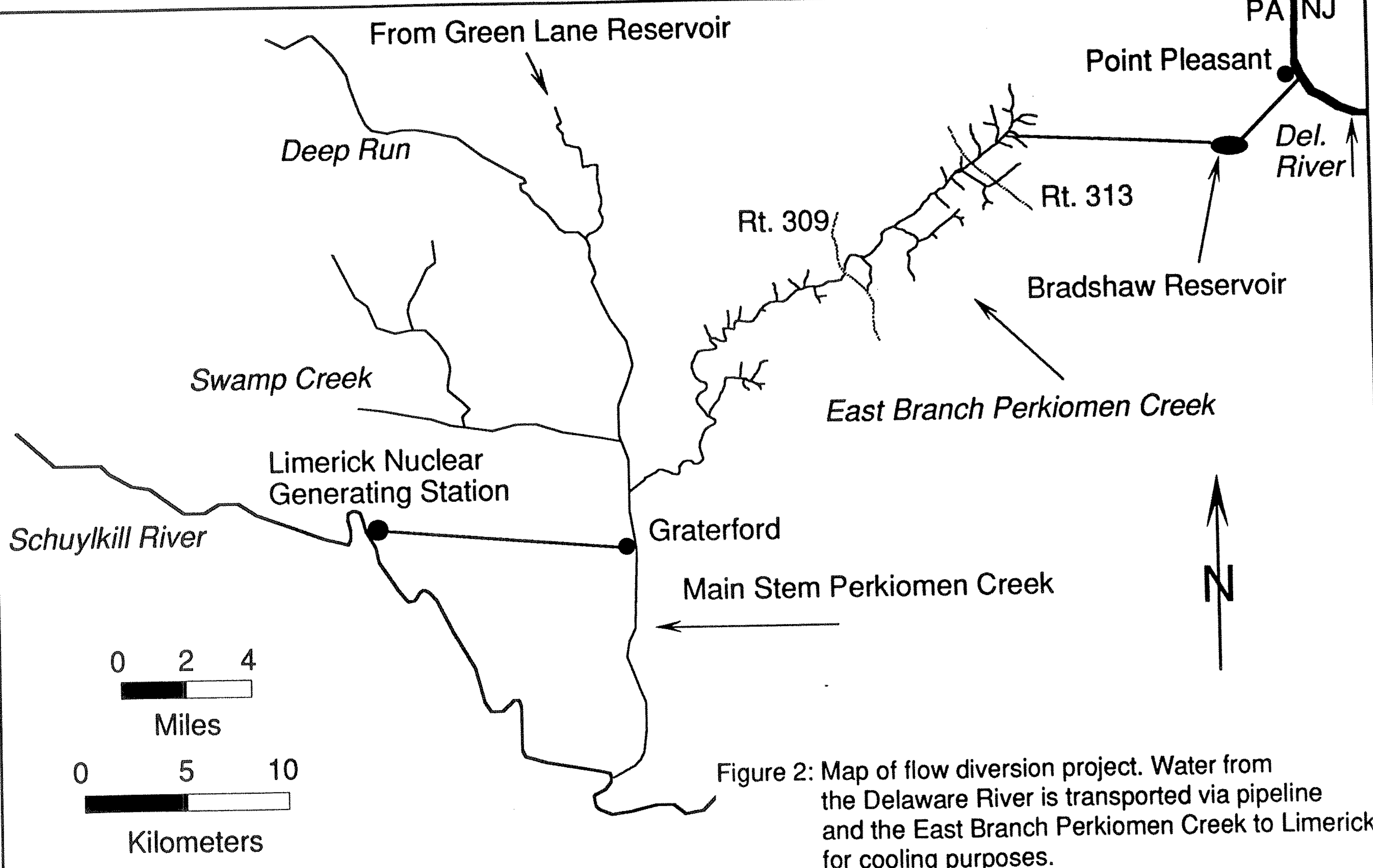


Figure 2: Map of flow diversion project. Water from the Delaware River is transported via pipeline and the East Branch Perkiomen Creek to Limerick for cooling purposes.

3000 cfs, pumping at Point Pleasant must be reduced, or the natural flow of the Delaware must be augmented by releases from Merrill Creek Reservoir near Phillipsburg, New Jersey. This reservoir has a capacity of 15 billion gallons, and 44% of the water is owned by PECo.

From PPPS, diverted flow travels ~2.8 miles via a 66 in. high-pressure line to Bradshaw Reservoir (Bradshaw), located in Bucks County. Pumping rates at PPPS are governed by water levels at Bradshaw. Bradshaw has an operating capacity of 23 million gallons (PECo, 1989). Bradshaw was built specifically for this intrabasin transfer project, and serves as a splitting point for the flows that go to the East Branch Perkiomen Creek and the North Branch Neshaminy Creek, as well as a storage facility for flows to Limerick. The volume of water pumped from the Delaware to Bradshaw for use by Bucks and Montgomery Counties is only a minor portion of the total pumpage. A minimum of 14 million gallons of water are stored at Bradshaw for PECo's use in the event that flow from Point Pleasant is not available.

Water is pumped from Bradshaw to the North Branch Neshaminy 0.9 miles via a 42 in. pipe, where it empties into the creek (Figure 3). The diverted water then flows downstream 3.5 miles to Lake Galena. Water pumped from Bradshaw to the East Branch Perkiomen travels 6.2 miles through a 42 in. high-pressure transmission main along a pre-existing natural gas pipeline (Texas Eastern) right-of-way to an energy dispersion structure located in the headwaters region of the creek (Figure 3). The dispersion structure is offset from the main channel, and the area immediately upstream and downstream of the outfall pipe is lined with rip-rap in order to minimize erosion by the sudden inrush of water. Water released by Bradshaw is continuously monitored for temperature, pH, and dissolved oxygen. Parameters monitored bi-weekly include aluminum, cadmium, iron, mercury, nickel, phenolics, zinc, and fecal coliform (which is monitored weekly).

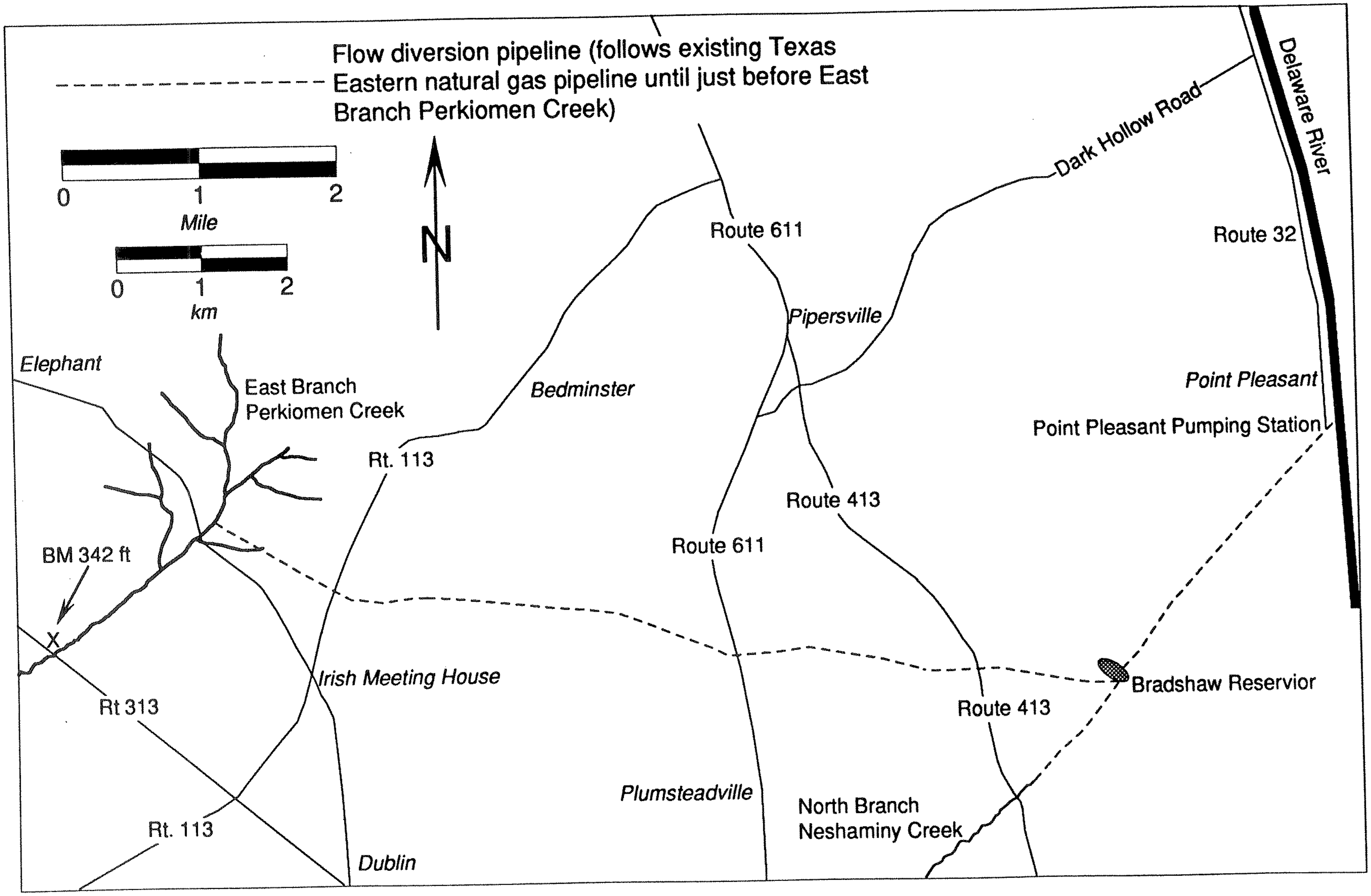


Figure 3: Map of the Delaware River - East Branch Perkiomen section of the Limerick flow diversion project.

A Water Processing Facility was built by PECo along the transmission main between Bradshaw and the creek. This facility cools and disinfects water prior to discharge to the East Branch Perkiomen. The temperature of the water needs to be lowered several days out of the year in order to minimize the impact on aquatic life in the creek, and is required by PECo's National Pollution Discharge Elimination System (NPDES) permit. The chiller operates six weeks per year, between mid June and late July (PECo, 1989). The disinfection (for fecal coliform) is performed by ozone injection, and operates from May through September (PECo, 1989).

Diversion flows travel in the East Branch Perkiomen and Perkiomen Creek channels 22.2 stream miles to a pumping station at Graterford, Pennsylvania, where they are pumped via high-pressure transmission main to the Limerick Nuclear Generating Station (Figure 2). Travel time from the outfall point to Graterford is approximately 18 hours. Hence, the volume pumped from Bradshaw to the creek on any given day is pumped from the creek at Graterford the next day. Pumping patterns are illustrated in Figure 4. In general, flows are in the range of 55-60 cfs during the period of May-November. Pumping rates at Bradshaw are regulated by PECo according to their need for cooling water at Limerick through the use of variable speed pumps at Bradshaw. To compensate for losses at the Water Processing Facility and during open-channel transport, an additional 0.5 cfs plus 3% of Limerick's need, respectively, are pumped from Bradshaw. The Bucks Road gage is monitored every 15 minutes, and a set of flood level switches are in place at the Bucks Road gage in order to alert PECo of flood conditions so that the pumps at Bradshaw can be shut down. The cut-off at the Bucks Road gage is 125 cfs.

According to the Limerick Generating Station Makeup Water System Operation Plan (PECo, 1989), diversion flows from the Delaware via the East Branch Perkiomen are utilized when (1) flows at the Pottstown gage on the Schuylkill are lower than 530 cfs, or (2) the temperature of the Schuylkill below Limerick exceeds 59° F and the Pottstown gage

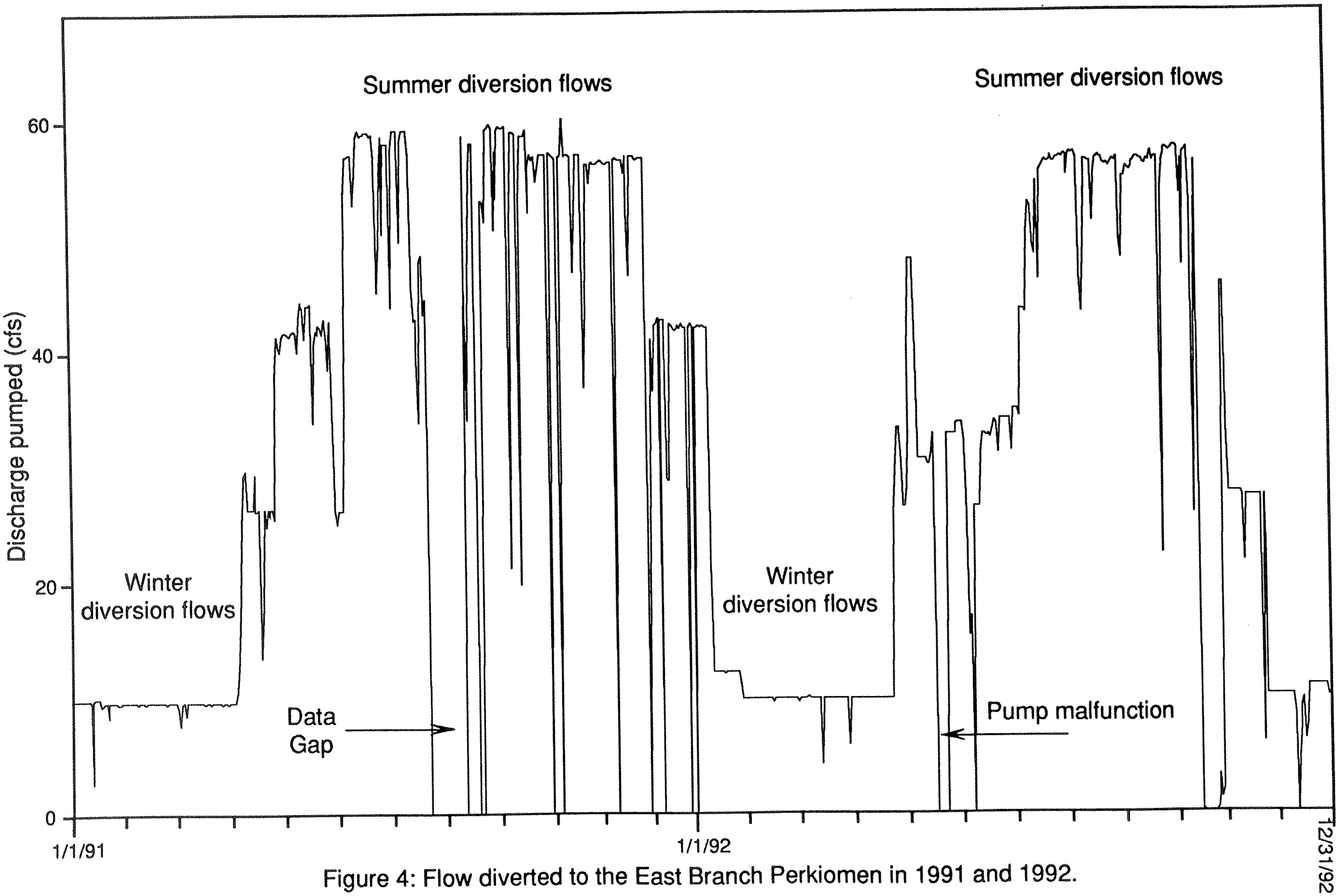


Figure 4: Flow diverted to the East Branch Perkiomen in 1991 and 1992.

reads less than 1791 cfs. The USGS gage on the main stem Perkiomen Creek at Graterford must register a minimum of 210 cfs during diversion periods. A minimum of 27 cfs must be maintained at the USGS gage at Bucks Road during diversion periods. A minimum of 10 cfs is maintained at the Bucks Road gage during the balance of the year.

Comparison with Other Flow Diversion Projects

The intrabasin transfer of water has been frequently used to increase the discharge of the receiving river in order to generate hydroelectricity, increase navigability, or support economic development (agricultural or industrial) (Hirsch *et al.*, 1990). Most of the intrabasin and interbasin transfers in the United States are for irrigation and municipal use, whereas in Canada (where transfers are significantly larger) transfers are used mostly for hydroelectric projects (Hirsch *et al.*, 1990). The average annual flow diversion to the East Branch Perkiomen Creek is approximately 20,000 acre feet. Out of the 256 known transfer projects within the conterminous United States, 37 divert greater quantities of water, with the largest being 4.4 million acre-feet per year (Petsch, 1985; Mooty and Jeffcoat, 1986). Ten diversions transfer approximately the same amount of water as the East Branch Perkiomen Creek project. The remaining 210 divert less than 20,000 acre-feet per year (Petsch, 1985; Mooty and Jeffcoat, 1986). The destinations of the transfers are only listed by state and county, not by waterway or municipal distribution authority. Thus, it is not possible to compare the East Branch Perkiomen Creek project with others beyond the amounts of water that are diverted.

GEOLOGIC AND HYDROLOGIC SETTING

GEOLOGY

The study area is located in the Newark basin of southeastern Pennsylvania (Figure 5). The basin is a manifestation of the rifting between Africa and North America during the break-up of Pangea (230-195 Ma) (Schlische, 1992). The lithologies that make up the

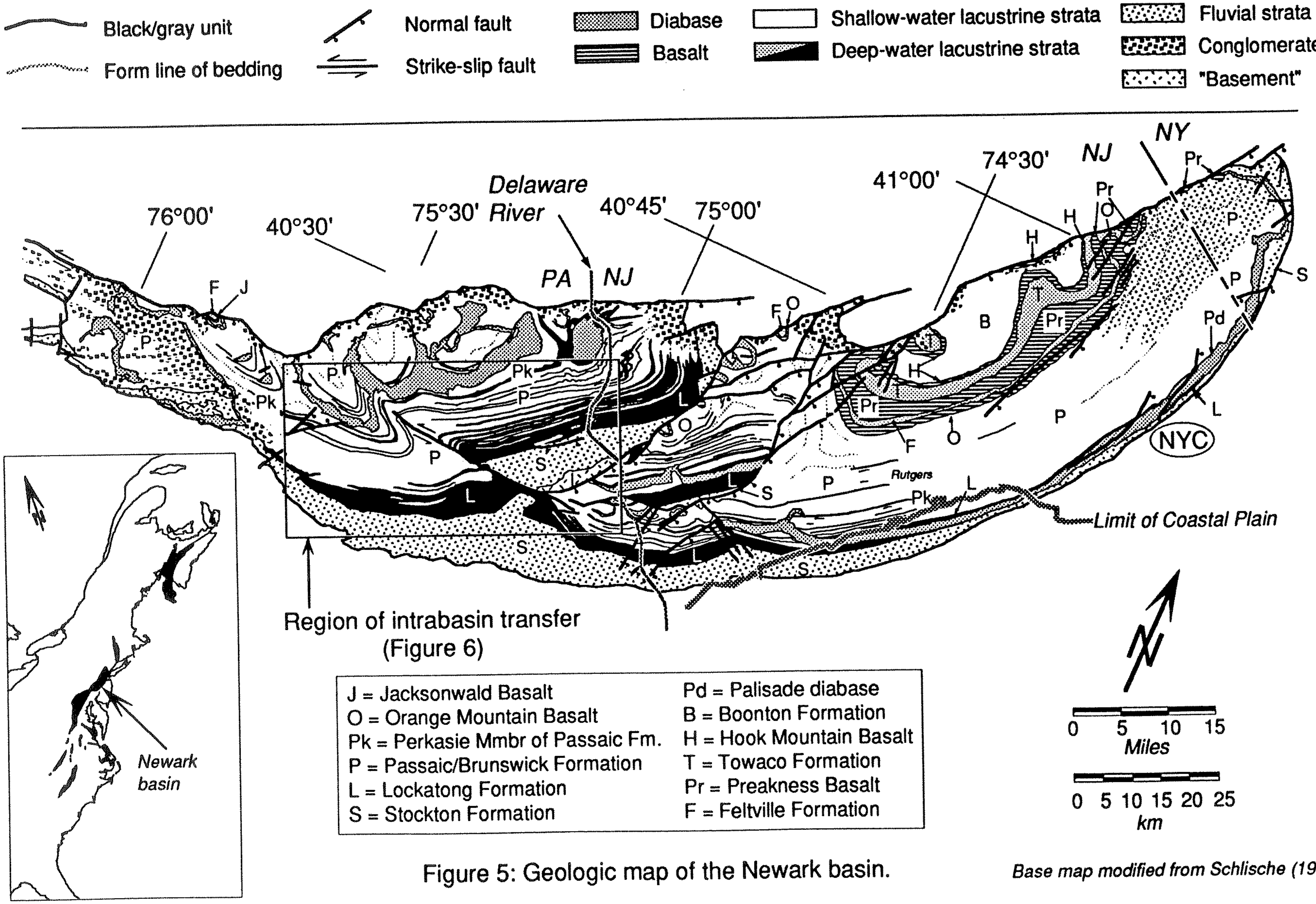


Figure 5: Geologic map of the Newark basin.

Base map modified from Schlische (1992)

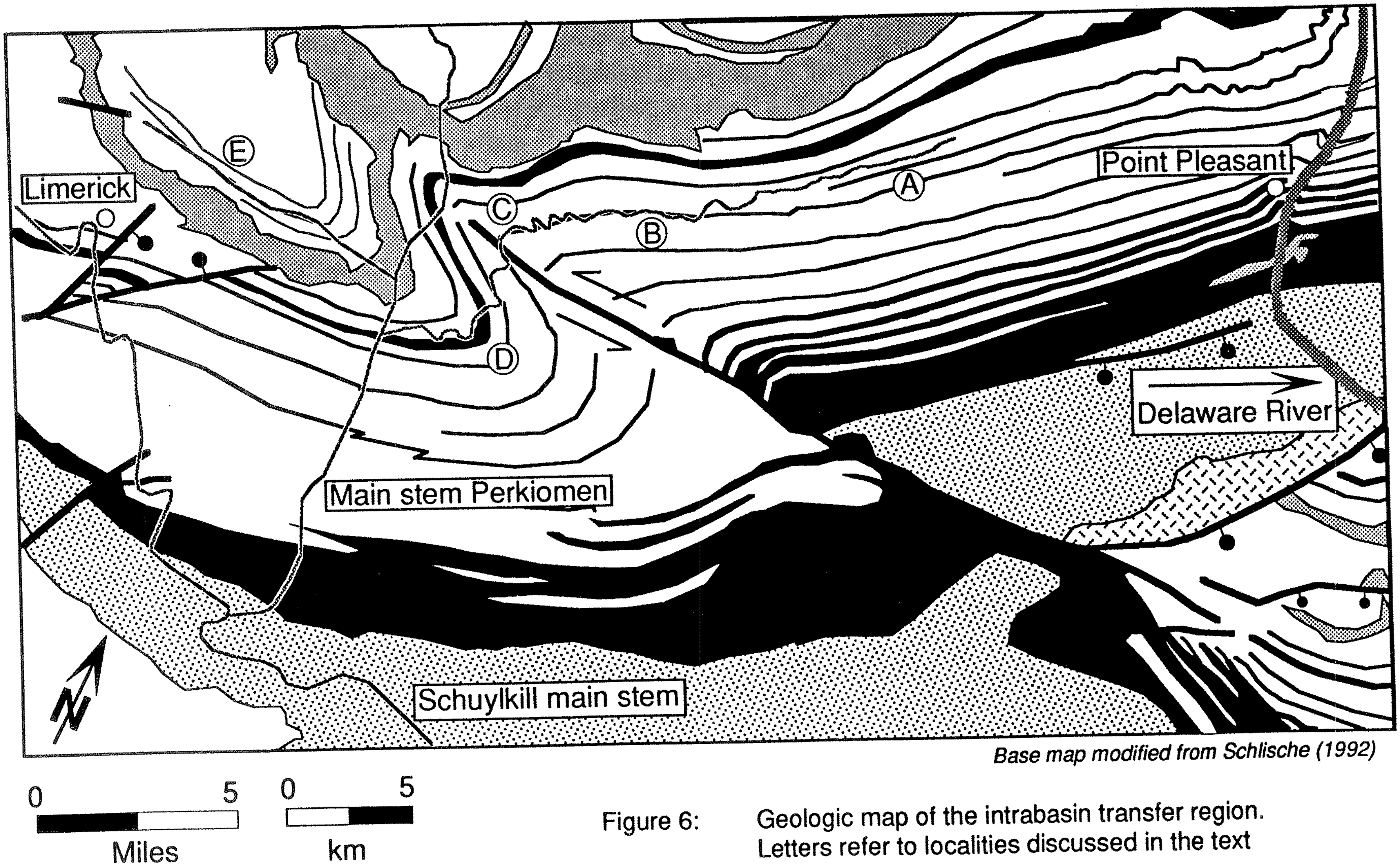
Newark basin are a series of cyclic fluvial/shallow lacustrine/deep lacustrine strata deposited in the half graben formed during rifting (Olsen, 1980). The rocks of the Newark basin generally dip to the NW, towards the border fault system, a result of subsidence of the hanging-wall block and reverse drag along the normal faults (Schlische, 1992). Joints trend generally northeast, and are sub-normal to bedding (Schlische, 1992; Jones, 1994). The rocks are locally warped into a series of transverse anticlines and synclines, whose fold axes strike NW-SE, a consequence of variable displacement along the segmented border fault system (Schlische, 1992).

The study area (Figure 6) is underlain by mudstones of the Brunswick Formation (Willard *et al.*, 1955) (known as the Passaic Formation in New Jersey). Bedding dips gently to the NW (Willard *et al.*, 1955), and is indistinct. Jointing is prevalent. Soils in the study area are thin (3-7 ft), and of the Abbotstown-Doylestown-Reaville/Bowmansville association (USDA SCS, 1975). These soils (with the exception of Bowmansville) are characterized as silt loams in the upper horizons, silty clay loams in the middle horizons, and shaley silt loams near the bedrock-overburden contact. Bowmansville soils are alluvial materials, and are classified simply as silty loams.

The parent materials of these soils are Triassic shales and siltstones (mudstones) of the Brunswick/Passaic formation (USDA SCS, 1975). Permeability is moderate in the upper 7-12 in., and low to very low below 12 in. (USDA SCS, 1975). Bedrock chips are abundant in the farm fields within the study area.

HYDROLOGY

The East Branch Perkiomen Creek lies within the Schuylkill River Basin, which in turn lies within the Delaware River Basin (Figure 7). The study area is located in the headwaters region of the East Branch Perkiomen Creek, just east of Rt. 113 near Bedminster, Pennsylvania (Figure 8). This area generally corresponds with the portion of the stream monitored in the Erosion and Sedimentation Monitoring Program. Where the



Base map modified from Schlische (1992)

Figure 6: Geologic map of the intrabasin transfer region. Letters refer to localities discussed in the text

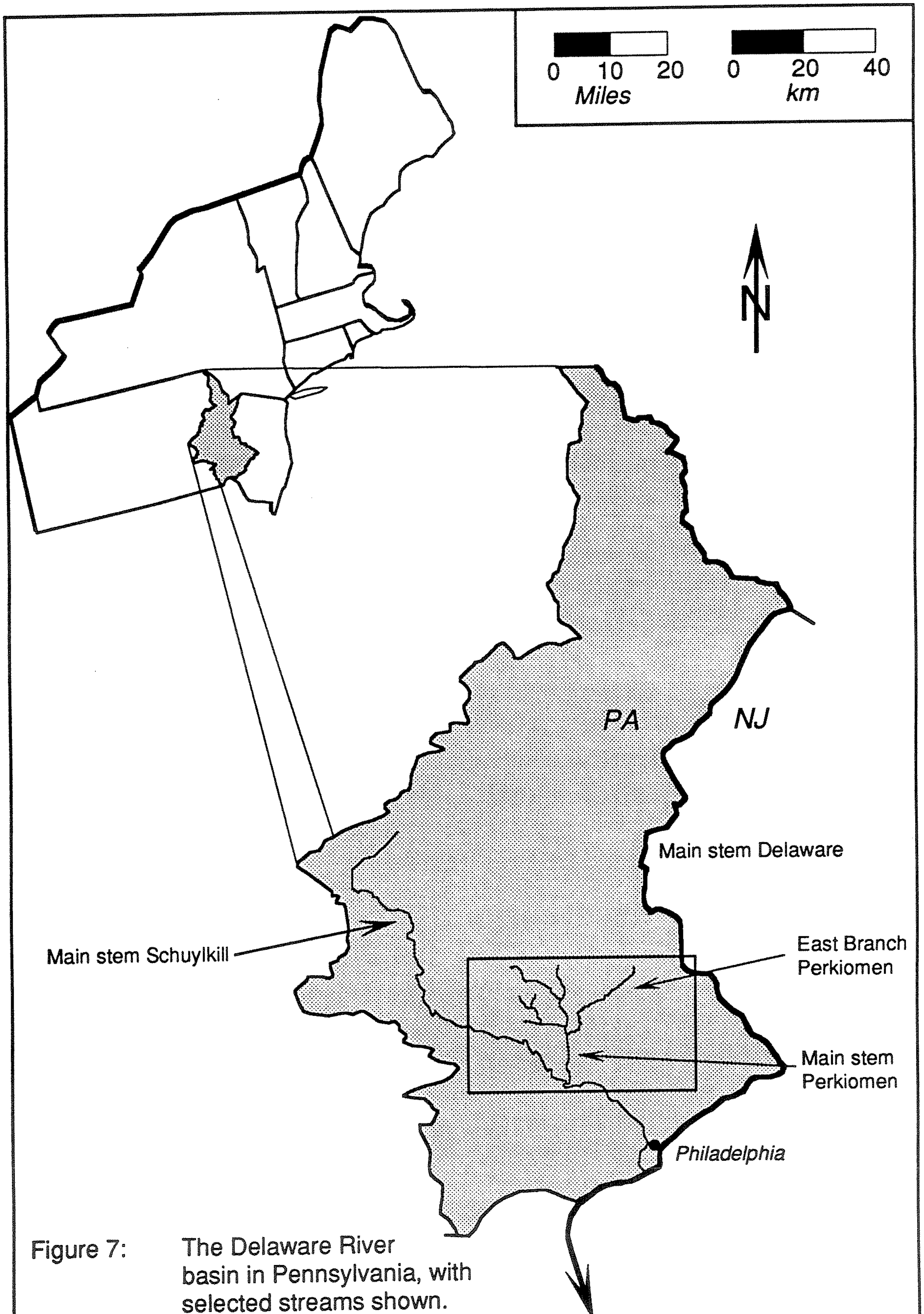


Figure 7: The Delaware River basin in Pennsylvania, with selected streams shown.

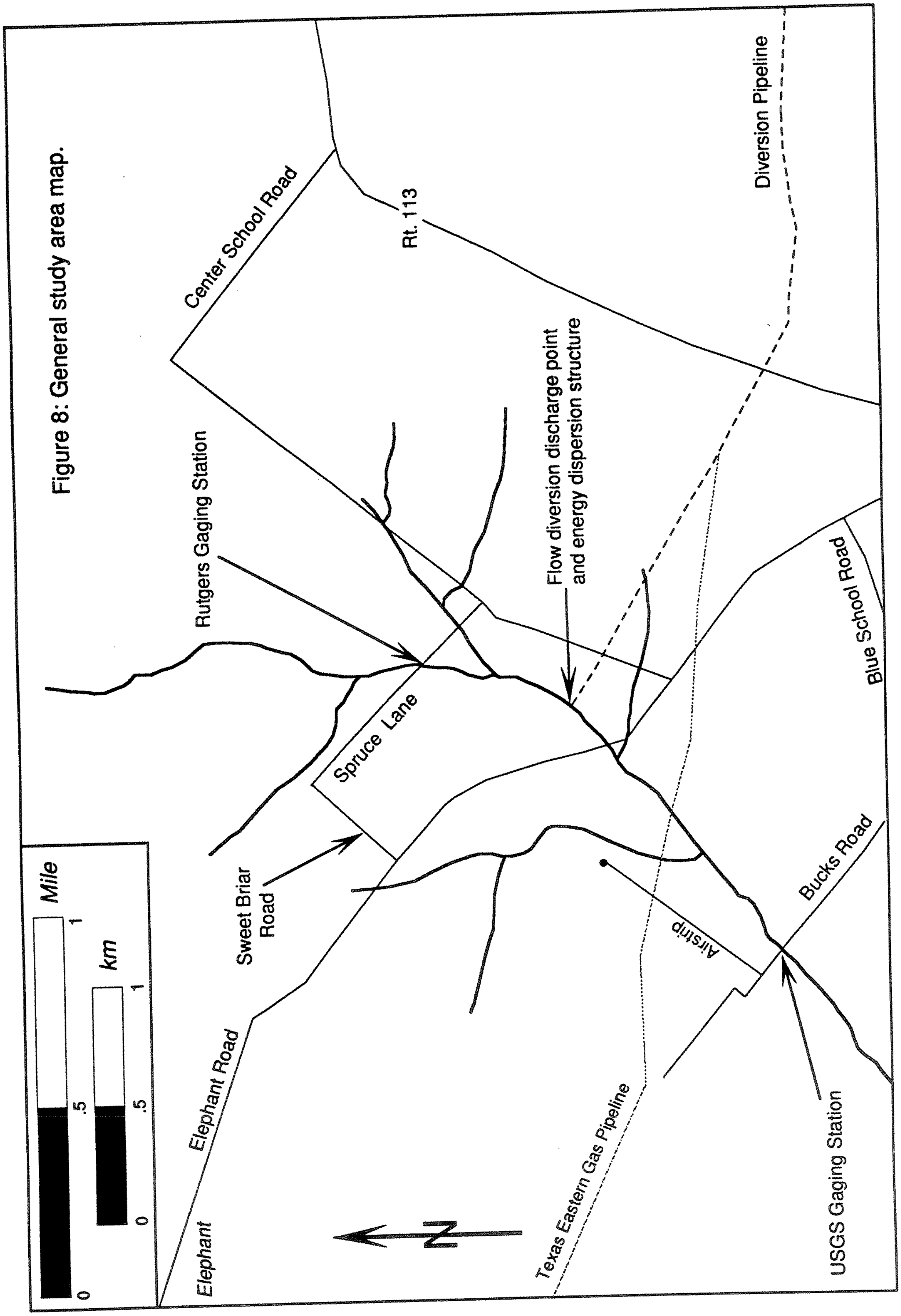


Figure 8: General study area map.

diverted flow is transferred at Graterford, Perkiomen Creek drains 279 mi^2 (722.6 km^2). At the lower limit of the study area (the USGS gage at Bucks Road), the East Branch Perkiomen Creek drains 4.05 mi^2 (11.29 km^2). At the upper limit of the study area (Figure 8) (the location of a Rutgers University water level recorder for this study), the creek drains 1.32 mi^2 (3.42 km^2). In the study area, the drainage pattern is a combination of dendritic and trellis, although more dendritic (Figure 9). The stream is third order throughout the study area. Based on a 1:24000 scale topographic map, the regional pattern of the East Branch Perkiomen is a hybrid between dendritic and trellis (Figure 2).

Runoff is flashy with dramatic overland flow during storm events, resulting in damage to vegetation along hillsides. This is a result of the thin, coherent overburden with low infiltration rates. The flashy nature of the basin is reflected in the prominent spikes in a yearly hydrograph (1986) for the creek, as measured at the USGS gage (Figure 10).

The entire record of discharge for the East Branch Perkiomen Creek as recorded by the USGS gage is shown in Figure 11. Prior to flow diversion (water years 1984-1988), flows at the USGS gage at Bucks Road exceeded 0.05 cfs 90% of the time, 1.0 cfs 50% of the time, and 11 cfs 10% of the time. Table 3 is a brief summary of the hydrology of the creek, comparing pre-pumping averages, diversion-period averages, and period of record averages. Complete USGS discharge data for the gage at Bucks Road, pumping records for the diversion to date, and discharge data from the Rutgers gage at Spruce Road are summarized in Appendix I.

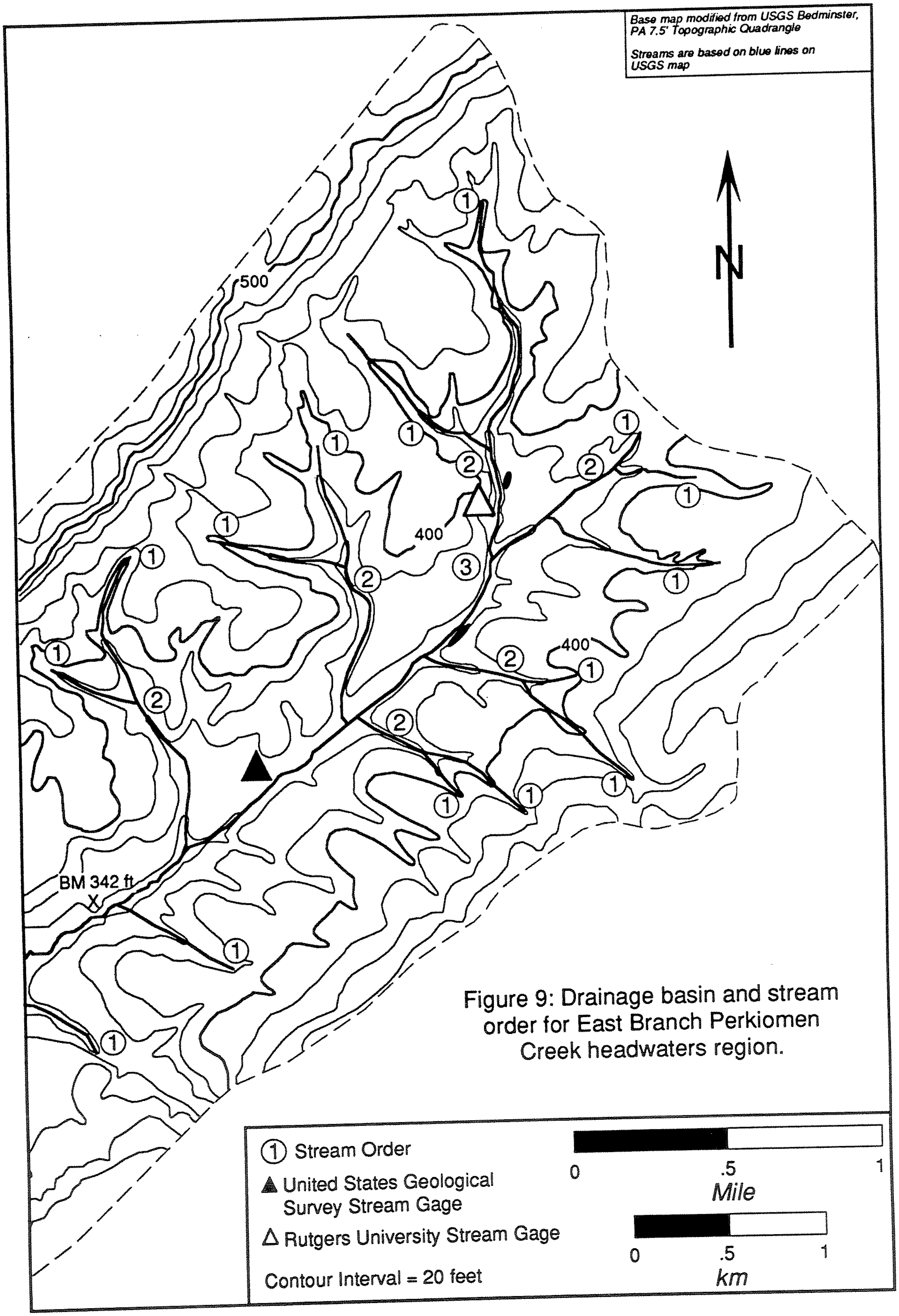


Figure 9: Drainage basin and stream order for East Branch Perkiomen Creek headwaters region.

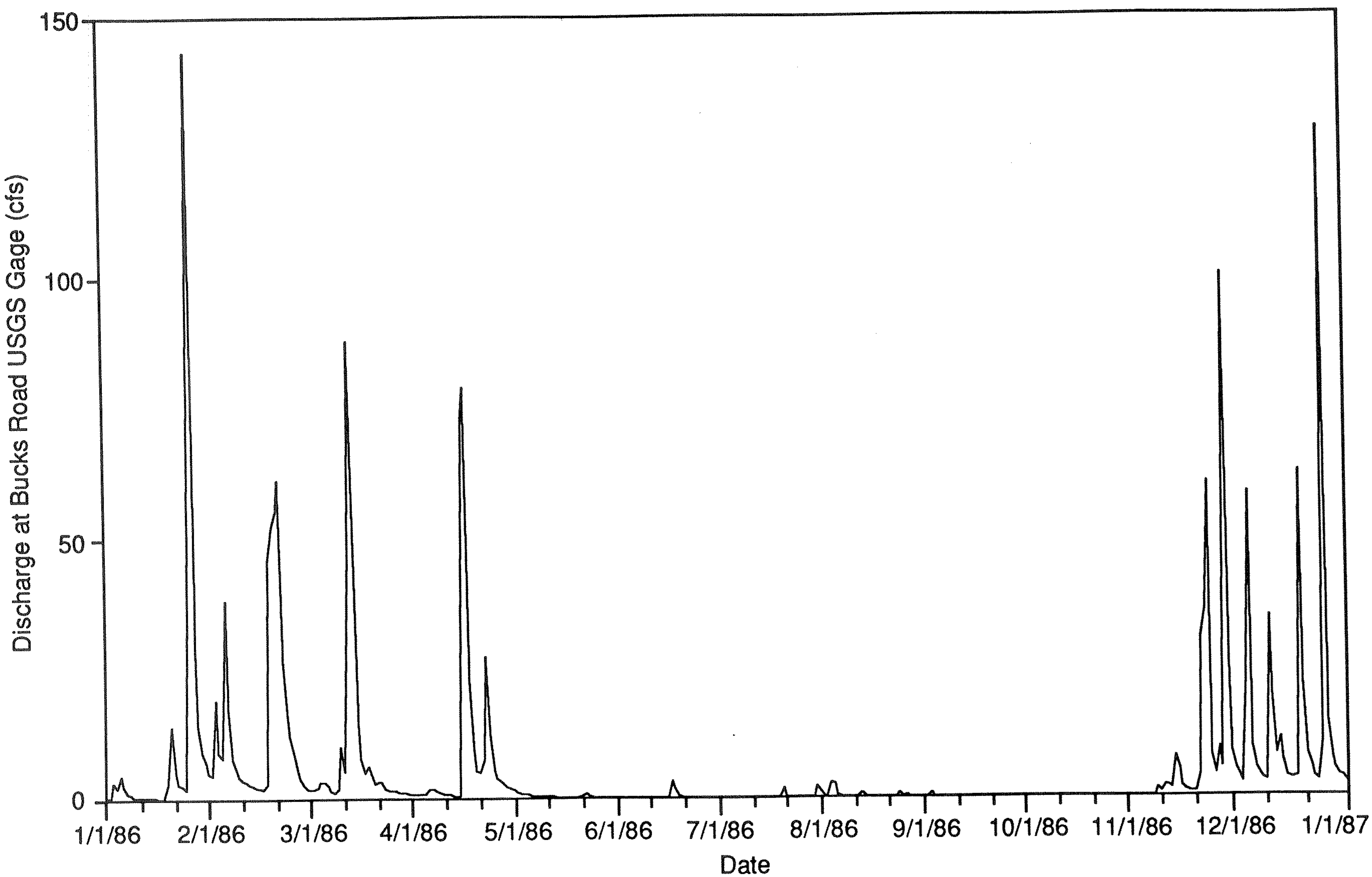


Figure 10: Pre-diversion (1986) annual hydrograph for USGS gage (Bucks Road) on the East Branch Perkiomen Creek.

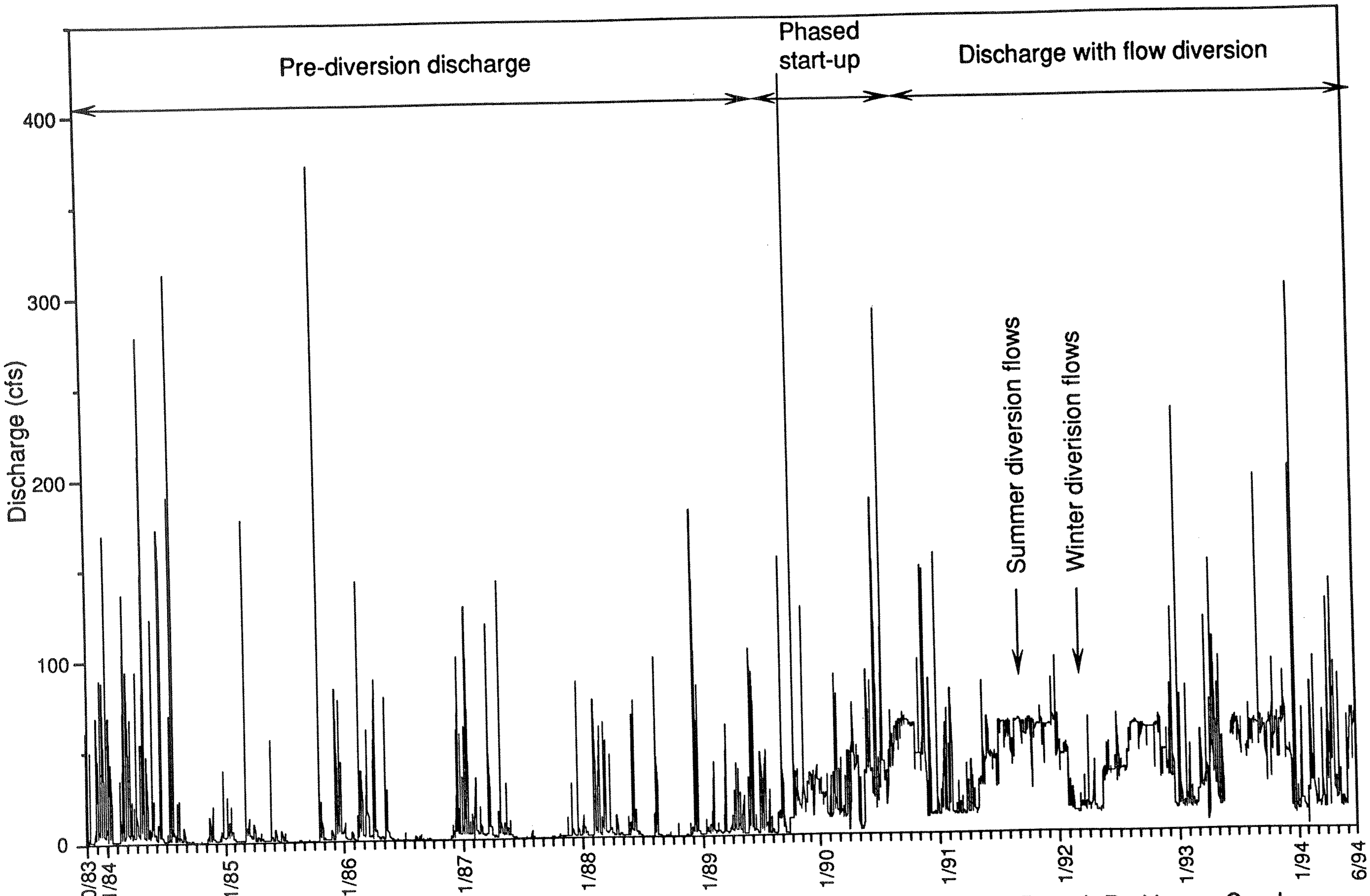


Figure 11: Period of record hydrograph for USGS (Bucks Road) gage on the East Branch Perkiomen Creek.

Table 3: Summary of hydrologic changes.

Water Year	Mean Ann. Q (cfs)	Mean of the Max. Month (cfs)		Minimum Q (month) (cfs)		Maximum Q (month) (cfs)	
1984	12.1	21.0	December	0.1	October	313.0	July
1985	4.0	11.8	February	0.0	September	372.0	September
1986	5.5	15.1	February	0.0	July	143.0	January
1987	5.1	12.6	April	0.0	June	142.0	April
1988	4.6	14.3	February	0.2	September	98.0	July
1989	9.4	25.7	September	0.0	October	418.0	September
1990	35.5	59.3	August	1.4	March	288.0	June
1991	35.9	58.3	September	9.8	February	146.0	October
1992	38.4	56.0	August	9.3	February	95.0	December
1993	41.0	56.0	June	5.0	March	231.0	December
	6.8	Prior to diversion					
	5.5	Prior to diverson, excluding 1984					
	37.7	With diversion					

Flow diversion years in boldface type

HYDRAULICS AND FLUVIAL GEOMORPHOLOGY THEORY

HYDRAULICS

Hydraulic analysis consists of the use and manipulation of several equations and principles. Bankfull channel cross-sectional area is defined as the product of width and mean depth. Cross-sectional flow area (A) is defined as:

$$A = wh. \qquad \text{(eq.1)}$$

where w = top width, and h = mean flow depth. Hydraulic radius (R), which is related to channel cross-sectional area (A) and wetted perimeter, (P) is defined as:

$$R = A/P \qquad \text{(eq.2)}$$

(Allen, 1985).

Reynold's number (a measure of hydraulic roughness, i.e. laminar vs. turbulent flow) is calculated using the equation:

$$Re = (\rho_w hU)/\mu \qquad \text{(eq.3)}$$

where ρ_w = density of water (which varies with temperature), U = mean flow velocity, and μ = molecular viscosity of water (.01) (Allen, 1985). Flow with a Reynold's number of less than 1000 is said to be laminar, whereas Reynold's numbers in excess of 2500 are associated with turbulent flow (Figure 12) (Allen, 1985).

Froude numbers characterize flow as subcritical, critical, or supercritical using the equation:

$$Fr = U/\sqrt{gh} \qquad \text{(eq.4)}$$

where g = acceleration due to gravity (9.8 m/s) (Allen, 1985). Flow with a Froude number of less than one is said to be subcritical, whereas flow with a Froude number of greater than one is said to be supercritical (Figure 12). If the Froude number is equal to one, standing waves (hydraulic jumps) will appear, and the flow is said to be critical (Allen, 1985).

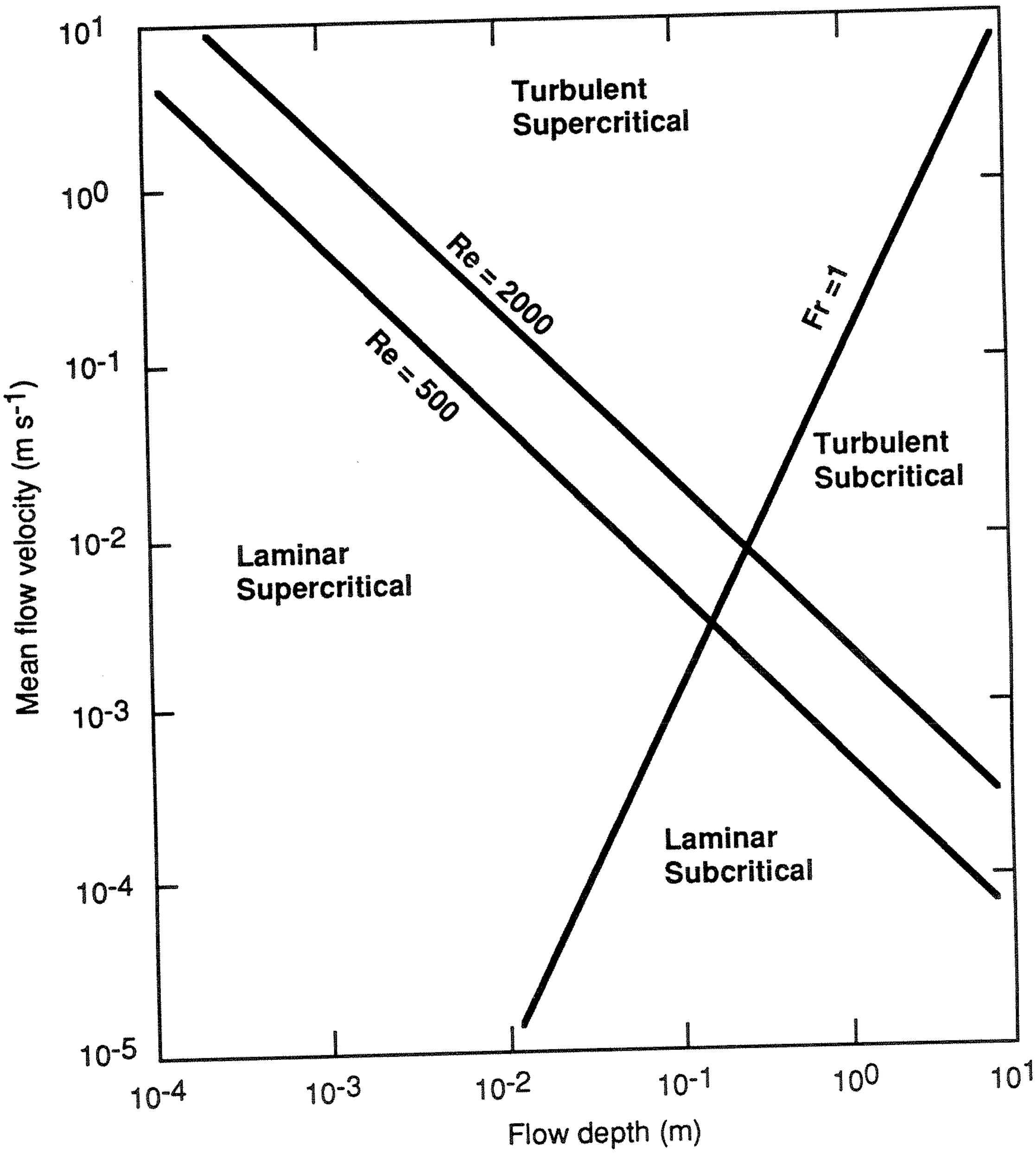


Figure 12: Regimes of free-surface flow, in terms of critical Reynold's (Re) and Froude (Fr) numbers. Modified from Allen (1985).

Measured shear stress (τ) is calculated as:

$$\tau = \rho_w g R S \qquad \text{(eq.5)}$$

where S = water surface slope (Allen, 1985; Gordon *et al.*, 1992). The distribution of shear stress (Figure 13) within a trapezoidal channel is not uniform (Chang, 1992). The maximum amount of shear stress applied to the banks can be calculated as being 1.08τ for the banks, and 1.37τ for the bed (Chang, 1992).

Critical tractive force (τ_c, shear stress required to move spherical grains with a median intermediate (b) axis denoted as d_{50}) can be calculated as:

$$\tau_c = \theta_c g d_{50}(\rho_s - \rho_w) \qquad \text{(eq.6)}$$

where ρ_s is the density of the sediment to be moved, and θ_c dimensionless critical shear stress (Gordon *et al.*, 1992). When determining τ_c for bed materials such as those in the East Branch Perkiomen, a minimum value of 0.1 should be used for θ_c, because of the highly imbricated nature of the armor lining the channel (Andrews, 1983; Church, 1978, cited in Gordon *et al.*, 1992). Millhouse (1986, cited in Gordon *et al.*, 1992) suggested using two different values of θ_c when dealing with imbricated, armored materials. For flushing surface fines from the channel bed, he suggested a value of $\theta_c = 0.021$. A value of $\theta_c = 0.035$ was suggested for moving (rearranging) 30% of the armor layer and 'deep' flushing of trapped fines. The d_{50} value to be used for calculating critical tractive force required for flushing of surface fines and rearrangement of armor material is that of the armoring materials, which happen to be all that are present in channel bed of the East Branch Perkiomen Creek.

Manning's "n" (n),

$$U = (1/n)R^{.67}\sqrt{S} \qquad \text{(eq.7)}$$

is a composite factor accounting for various forms of flow resistance. Manning's "n" generally increases as turbulence and flow retardance effects increase. Manning's "n" usually varies with flow depth in natural channels (Gordon *et al.*, 1992). For example, at

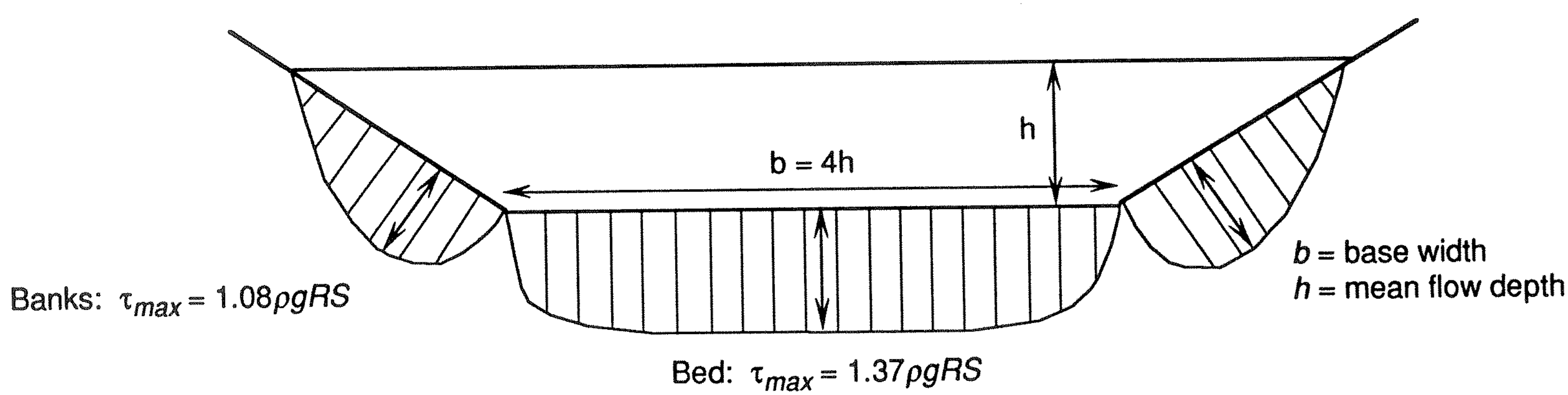


Figure 13: Distribution of boundary shear stress (τ) in trapezoidal channels. Longer chords indicate higher boundary shear stresses. Arrows indicate point of maximum boundary shear stresses. Modified from Chang (1992).

lower flows, Manning's "n" may actually increase as the relative prominence of obstructions (twigs, rocks, etc.) increases, increasing flow retardance.

FLUVIAL GEOMORPHOLOGY

A concept that pervades fluvial geomorphology theory and literature is that of dynamic equilibrium. A system in dynamic equilibrium is one that is continually adjusting to external factors, but those adjustments cluster around some mean, which itself is tending to some equilibrium state. Small adjustments take the form of cutbank erosion and point bar deposition, knickpoint migration, slope adjustment, and channel incision. An increase in the magnitude of flood flows due to a change in precipitation may result in channel enlargement in some areas, with deposition in others. Changes in urbanization may lead to increased runoff and sediment input, causing deposition in some areas, and scouring in others. Tectonism may increase the channel gradient, causing increases in velocity and stripping of some channel materials. The entire system tends towards an asymptote as it downcuts to baselevel.

Streams are generally believed to be adjusted to their bankfull flows (Leopold, 1994). The continuity equation,

$$Q_1 = Q_2$$

rewritten as,

$$(w_1 h_1 U_1 = w_2 h_2 U_2) \qquad \text{(eq. 8)}$$

(where Q = discharge in cubic feet per second (cfs), w = stream width (top width of cross-section), h = mean flow depth, and U = mean flow velocity (Allen, 1985)) is based on the fact that discharge in a natural channel will remain constant between two points along it, assuming there are no tributaries between them. If flow in the channel at one point has a different velocity than at the other point, then the channel must adjust to maintain the equation. The idea that a channel is adjusting to its flows gives rise to the fact that if the flows are changed, then the channel will adjust.

Rivers are ultimately the products of processes occurring on the landscape (Wolman *et al.*, 1990). The system studied here is part of a larger system, which is tending towards equilibrium, with its own sets of independent and dependent variables. This behavior is one of dynamic equilibrium, where the channel continually adjusts as it would under steady-state conditions (Figure 14A), but these changes are clustered around a mean that itself is tending towards some sort of equilibrium (Figure 14B).

The discharge of a stream is a measure of the volume of water that flows past a point per unit time. The velocity-area method is the most commonly used means by which to calculate discharge, and uses the equation:

$$Q = whU. \qquad \text{(Eq. 9)}$$

The sinuosity index (*S.I.*) of a channel is a measure of "wiggliness"; that is, how sinuous the channel is. The sinuosity index is calculated using the equation:

$$S.I. = L_t/L_v \qquad \text{(eq.10)}$$

where L_t = thalweg distance, and L_v = valley distance (Gordon *et al.*, 1992). A straight channel has an S.I. of 1, whereas meandering channels are arbitrarily set as those with an *S.I.* of 1.5 (Gordon *et al.*, 1992). Hydraulic meander wavelength, *L*, is simply the distance between the inflection points of one full meander. It may be related to bankfull channel width as

$$L = 12w_b \qquad \text{(eq.11)}$$

where w_b = bankfull channel width (Richards, 1982). Ashley *et al.* (1988) suggest the use of 10 as the coefficient in eq. 11 for the bedrock-influenced channel of the Raritan River in New Jersey. Hydraulic meander wavelength may also be related to discharge as

$$L = 24.5(Q_{bkf}^{.62}) \qquad \text{(eq.12)}$$

where Q_{bkf} = bankfull discharge (Allen, 1985).

Dunne and Leopold (1978) relate bankfull discharge (Q_{bkf}) to drainage area for a small basin in southeastern Pennsylvania (Brandywine Creek) as

$$Q_{bkf} = 61(D_A{}^{.82}) \qquad \text{(eq.13)}$$

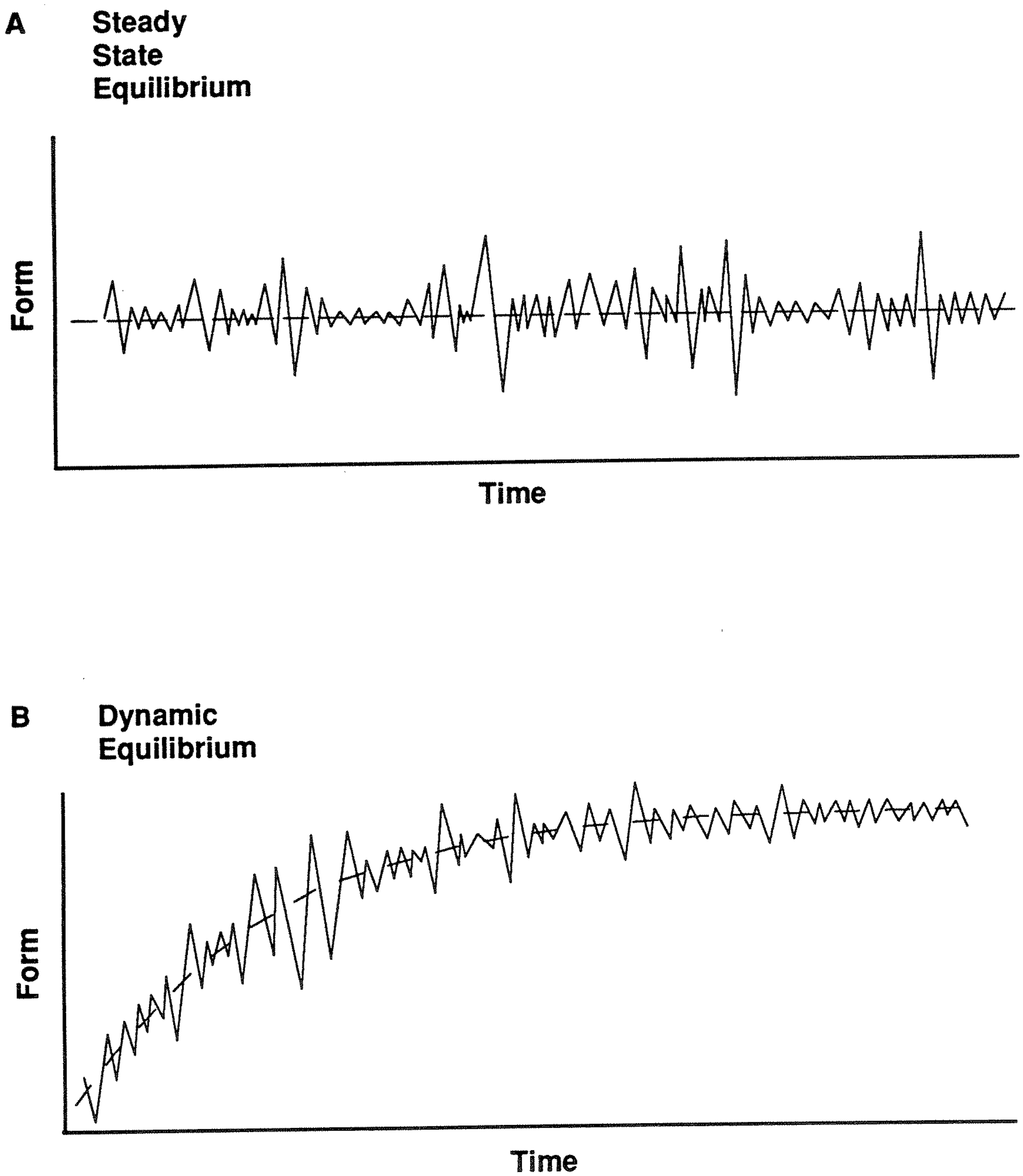


Figure 14: Equilibrium curves (modified from Chorley *et al.*, 1984).

where D_A = drainage area. They also related bankfull discharge to mean annual discharge (Q_{ma}) for a small unnamed basin in eastern Pennsylvania as

$$Q_{bkf} = 40Q_{ma}. \qquad \text{(eq.14)}$$

This basin had high discharges produced by heavy rains in the summer, with mean storm rainfall intensity being great over small areas (Dunne and Leopold, 1978). Bankfull discharge is generally considered to be the channel-forming flow, with a recurrence interval of about 1.5 years (Leopold, 1994).

Several methods are available to calculate stream power (ω), which may be used as a proxy for erosive power (Seidl and Dietrich, 1992). Hence,

$$\omega 1 = \tau U \qquad \text{in watts/m}^2 \text{ (Ns/m)} \qquad \text{(eq.15)}$$

$$\omega 2 = \rho g Q S \qquad \text{in watts/m (kgm/s}^3\text{)} \qquad \text{(eq.16)}$$

$$\omega 3 = (D_A)S \qquad \text{(eq.17)}$$

where D_A = drainage area (Gordon *et al.*, 1992). Eq. 15 is a measure of work per square unit area, and incorporates hydraulic radius through τ. This is the most commonly used means by which to calculate stream power. Eq. 16 expresses work in terms of linear distance, or reaches of a stream, and can be useful for comparing stream reaches. Eq. 16 incorporates discharge, which is the parameter being changed with addition of the diversion flows to the system. Both Eqs. 15 and 16 vary with changing flow conditions, but in different ways. Eq. 17 is not useful for this study since it does not vary with changing flow conditions.

The term hydraulic geometry refers to independent channel characteristics that, when graphed, have a simple geometric form (Leopold, 1994). At-a-station hydraulic geometry is the manner in which width, depth, and velocity increase with discharge. Recalling eq. 9,

$$Q = whU$$

each of the variables may be related to discharge, Q, using a power-law relationship:

$$w = aQ^b \tag{eq.18}$$

$$h = cQ^f \tag{eq.19}$$

$$U = kQ^m \tag{eq.20}$$

where $b, f,$ and m are the slopes of the lines fitted to Q vs. w, h, U data, respectively, on a log-log plot. The coefficients a, c, and k are the values of w, h and U, respectively, when $Q = 1$; they are the y-intercepts. In order to maintain eq. 9, $b, f,$ and m must sum to unity (1), and a, c, and k must multiply to unity, or within ± 5% of unity (Leopold and Maddock, 1953). It is important to note that the coefficients a, c, and k are theoretical values, with no physical reality (Dunne and Leopold, 1978). Their values depend on the fitting of a line to the data available. This is a significant weakness when only limited data are available.

If the equations do not balance when field data from the East Branch Perkiomen are inserted, the channel may not be adjusted to bankfull flows, or the derived values of the exponents and constants may be invalid. A weakness of hydraulic geometry as applied to the East Branch Perkiomen is that the concept of hydraulic geometry was determined in alluvial channels (Leopold and Maddock, 1953), whereas the East Branch Perkiomen is strongly influenced by bedrock. Though bedrock channels occasionally obey alluvial channel regularities, their forms are usually governed by lithologic and structural differences (Richards, 1982). For the East Branch Perkiomen, the relations may work at some discharges but not at others due to bedrock influence on channel form.

METHODS

FIELD

Channel Mapping

The study reach of the stream was mapped using a tape and compass method for the greater channel and hydraulic meander. Channel bed materials were mapped at the same time.

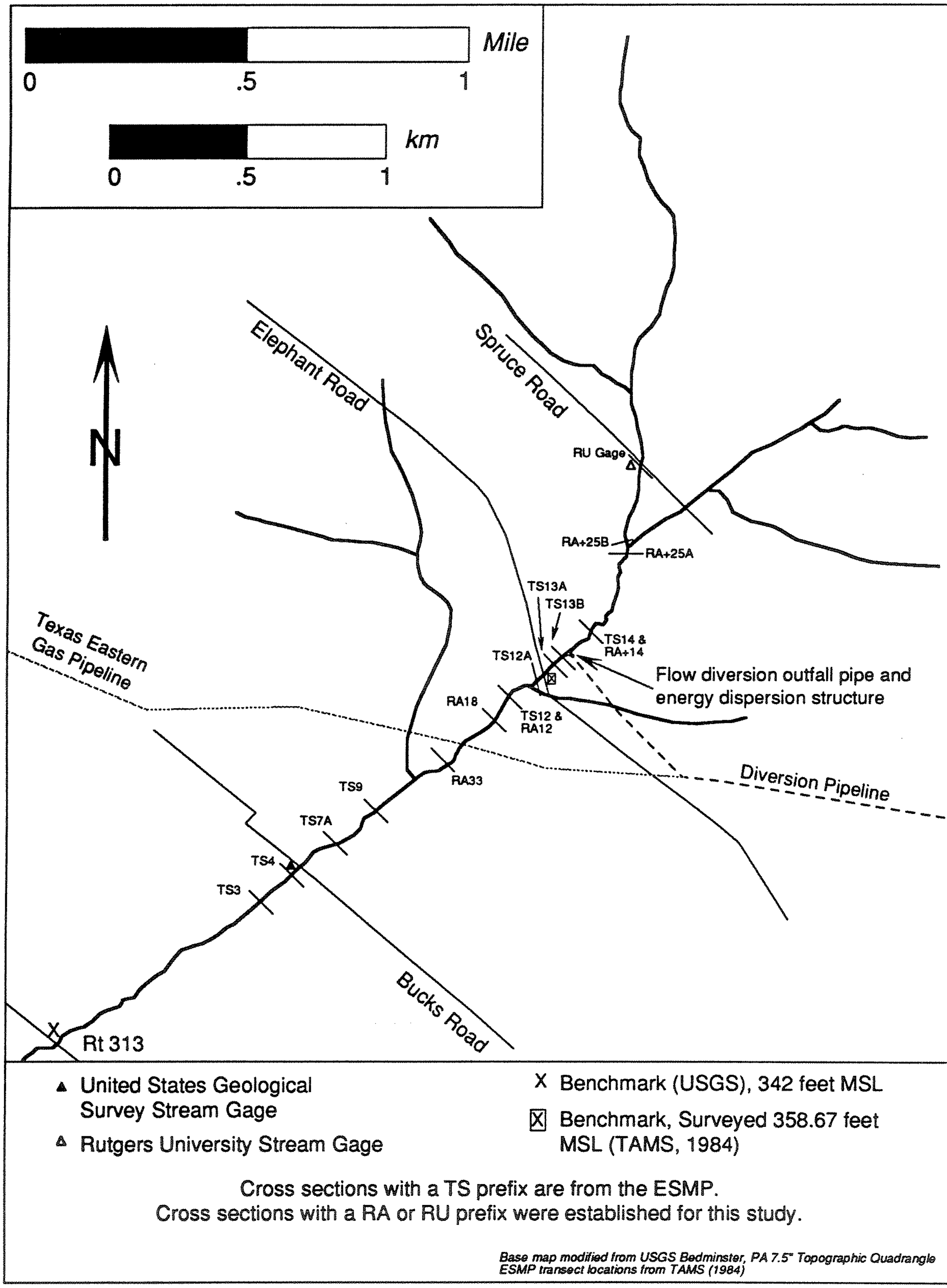


Figure 15: Locations of cross sections, benchmarks, and stream gages used in this study.

Channel Surveying

Several cross-sections were established specifically for this study. This was done because sufficient triangulation data were not available to re-establish the cross-sections used in the ESMP (Figure 15; Table 2). (When analyzing the ESMP data, the original numbering system has been retained for the sake of consistency.) The new cross-sections were surveyed using a Leitz/Sokkisha C3a automatic level and leveling rod to determine the elevation of the channel at specific intervals and salient points with reference to an established datum (methods are outlined in Appendix II). The locations of the new cross-sections are shown in Figure 15. The locations were surveyed at the beginning of this study (August 1993), again during low diversion flows (April 1994), and at the end of this study during summer (high) diversion flows (June 1994).

In order to survey the above cross-sections, it was necessary to establish several benchmarks. The true elevations of these benchmarks were determined by transferring the elevation of the known benchmark (Figure 15) to the new one using the automatic level (Appendix II). The known benchmark is a square chiseled into the northwestern abutment of the Elephant Road bridge over the creek (Figure 15). This benchmark was established by TAMS (1984), and is at 358.67 ft above mean sea level. The elevation of this benchmark was determined by TAMS (1984) using the same transfer method outlined above, from a benchmark located on State Route 313 (Figure 2). The locations and elevations of benchmarks used for this study are listed in Appendix II.

Natural Flow Measurement

In order to closely monitor the discharge of the stream without the additional diverted flow, a Steven's Type F water level recorder was installed on the creek upstream of the outfall pipe as a control (Figure 15). The recorder consists of a float which rises and falls with the water level, causing a drum to rotate accordingly. The drum is wrapped with paper, across which a recording pen moves, driven by a timer. The result is a record of stage (water elevation above some datum) versus time. The gage is located in a steel-reinforced wooden box atop a corrugated steel standpipe, attached to the Spruce Road bridge over the creek (Figure 15). This location was selected because it is the first bridge upstream of the outfall pipe. The stream channel was surveyed after installation of the gage in order to measure discharges. The gage is maintained weekly, when the timer is wound and the paper is changed.

Flow Velocities

Velocity data were collected for this study using a Marsh McBirney Model 201 electromagnetic current meter. The unit consists of a sensor probe attached to an electronic processor via a cable. The probe is mounted to a collar assembly which has a fin attached to it. The fin allows orientation of the sensor probe into the flow of water. The collar assembly swings freely with the current and is positioned at $0.4d$ (where d = depth of the stream at that location in the cross-section) measured from the channel bottom on a graduated wading rod. The setting of $0.4d$ for the swiveling collar assembly is generally accepted as the point in the water profile where the mean velocity of the stream may be measured (Leopold *et al.*, 1964). Measurements were taken at several points across the stream channel, and then averaged to achieve a mean velocity representative of the cross-section.

The probe consists of an electromagnet and two sensors located 180° apart. The magnet produces an electromagnetic field, which interacts with the water flowing around the sensor probe, producing a small voltage recorded by sensors in the probe. This voltage is processed by the unit into a flow velocity value. This value is averaged and integrated over time. The integration constant on the unit was set at maximum (20), to allow the greatest averaging of the data. An average flow velocity is then displayed on a meter on the instrument's panel. Readings were collected at 10-second intervals for 3 minutes at each measurement location, and then averaged. The instrument was calibrated to ±1% error by the manufacturer just prior to the study.

Water Sampling

Water samples were collected to determine suspended load at various points in the channel. Using a Nissen water sampler, approximately 1.5 liters were collected in the thalweg at approximately 0.4*d* measured from the channel bottom.

Depth to Bedrock and Soil Core Samples

In order to determine depth to bedrock on the banks and floodplain, a hand auger was used to core down through bank materials to bedrock. Coring was done on both sides of the channel at the cross-sections from the ESMP and those established for this study. Representative samples of both cutbank and point bar materials were collected from some of the cores.

Structural Data

Data on joint and bedding plane orientations were collected to characterize the structural geology of the bedrock flooring the stream channel. Because bedding is indistinct and most of the outcrop is actually underwater all year, only a limited number of bedding orientations were measured. Submerged outcrop also made it difficult to measure the dip angles of joints. Joints in the Newark basin (Schlische, 1992) and in the study area are sub-parallel, so it was not necessary to collect dip readings. Hence, it was possible to collect a large number (~600) of joint azimuths. All orientations were collected using a Brunton pocket transit.

Bed Material Characterization

The extent to which the bedrock liner outcrops within the channel banks was determined by walking along the creek and sketching the extent of bank bedrock outcrops onto the tape and compass map. Characterization of bed material was done by pebble-counts at the cross-sections established for this study. A grid was established (Figure 16) at each cross-section. One pebble was sampled at each grid line intersection, and measured for its b-axis (the short axis of the maximum projection plane of the pebble), for a total of 100 (optimally) pebbles at each cross-section. It was necessary to sample less than 100 pebbles in some places because of extensive bedrock exposure within the channel. Samples were not collected directly along the cross-section lines (Figure 16) so as not to artificially induce change. The shapes of the pebbles collected were characterized using Zingg's (1935) classification scheme.

At certain cross-sections (e.g. if the cross-section was not located in a straight reach, noted in a summary table presented later in this thesis), the grid had to be modified because it intersected the banks. In such cases, the grid was simply measured oblique to the cross-section. In areas where no control points were available (non-cross-section areas), a grid was simply paced out.

LABORATORY

Suspended Load

Suspended load water samples were filtered through P4 medium-fine porosity (particle retention = 3-5 µm), slow flow rate pre-weighed (to 0.001 grams) quantitative filter paper. This paper will retain material larger than clay. The paper with suspended load was then dried and allowed to equilibrate with ambient room humidity and temperature. The paper with load was then weighed to 0.001 grams. A suspended load value (mg/l) was then calculated.

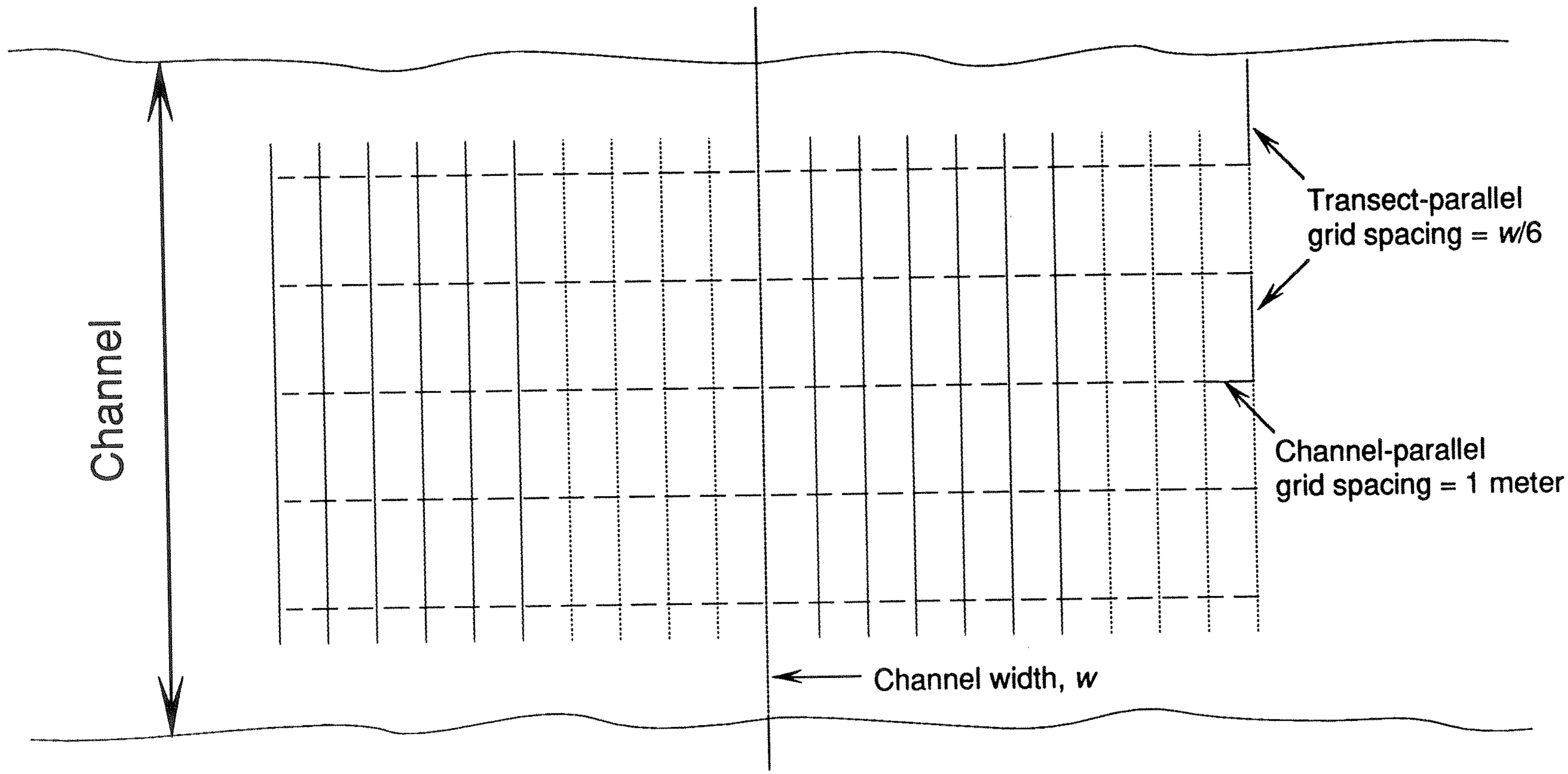


Figure 16: Bed materials sampling grid.
Samples collected at grid intersections were measured for intermediate (b) axis of clasts.
No samples were collected along the cross sections themselves.
100 pebbles were measured at each cross section.

Grain Size Analysis

Flood plain samples were processed using a wet sieving and pipette method to determine 1) percentages of gravel, sand, and mud, and 2) percentages of sand, silt, and clay. The complete procedure used is outlined in Appendix III.

ANALYTICAL

Natural Discharge

Using the records collected from the Rutgers University control gage, as well as discharges measured at the Rutgers University control gage cross-section, a rating curve was established after the method described in Dunne and Leopold (1978, p. 594 to 599), which utilizes a linear regression analysis of measured stage-discharge relationships to predict discharge at stages other than those measured. The least squares method is used to fit the predictive line to the measured data. This is the line where the sum of the y-deviations (the y-axis is the value being predicted) from measured data is at a minimum, and is called a least squares or regression line. Regression analysis was performed using the *Regression* function of Microsoft Excel v4.0, a statistical-spreadsheet program for the Macintosh microcomputer. Discharges were calculated using the velocity-area method (eq. 9). Discharge calculations at the cross-sections established for this study were calculated in the same manner.

Structural Data

Structural data were processed using Stereonet v4.6a to produce equal area plots for bedding orientations, and rose diagrams of joint azimuths. The data were corrected for declination (11.5°W) (1983 Bedminster, PA 7.5 minute United States Geological Survey Topographic Quadrangle).

Channel Form Analysis

Channel form analysis consisted of the calculation of channel sinuosity (eq. 10) and hydraulic meander wavelength (eqs. 11, 12), and the evaluation of cross-sectional form. Bankfull discharge (Q_{bkf}) was related to drainage area using eq. 13, and to mean annual discharge (Q_{ma}) using eq. 14. Hydraulic meander wavelength was calculated as the distance between inflection points on meander bends. A distinction will be made between broad hydraulic meander wavelength (L), which tends to follow the meander of the greater channel, and small hydraulic meander wavelength (λ) which swings back and forth within the greater channel.

Hydraulic Geometry

Hydraulic geometry relations were established using field data on width, depth, cross-sectional flow area, and velocity with eqs. 18-20, as well as published values of b (0.26), f (0.40), and m (0.34) (Leopold, 1994) for the purpose of comparison. The values of the exponents and coefficients for the hydraulic geometry relations were determined by plotting channel dimension, velocity and discharge data collected at the cross-sections established for this study. This was done in order to determine if the relationship is valid for diversion flows and for flows upstream of the outfall point. If it is not, this may be indicative of disequilibrium conditions. Empirical values for bankfull discharge were substituted into eqs. 18-20, along with data on bankfull channel dimensions and the empirically derived values of the exponents and coefficients, in order to see if the equations balance.

Hydraulic Analysis and Hydrology

Cross-sectional flow area and mean depth were calculated using top flow width (w), eq. 1, and Canvas on a Macintosh computer. Wetted perimeters (P) were calculated using top flow width (w) and a plot of a given cross-section using Canvas on a Macintosh computer. Hydraulic radius (R) was calculated using eq. 2, Reynold's numbers (Re) using eq. 3, and Froude numbers (Fr) using eq. 4.

Measured shear stress (τ) was calculated using field data and eq. 5. The water surface slope was measured using the methods outlined above. For flows measured in the field, the water surface slope was 0.0026. The value for density of water (ρ_w) varied because when velocities were collected, the water temperature was above 32° F (0° C, where $\rho_w = 1$ g/cm^3). The water temperature was about 70° F (21.1° C) when field data for this study were collected, except for one occasion when it was very close to 32° F (0° C). Water at 70° F (21.1° C) has a density of 0.997970 g/cm^3 according to the Handbook of Chemistry and Physics (Weast, 1971). Shear stresses for diversion flows will be referred to as τ_d in the discussion section. The maximum amount of applied shear stress was calculated as being 1.08τ for the banks, and 1.37τ for the bed (Chang, 1992).

Shear stress at bankfull flow (τ_{bkf}) were calculated using eq. 5, but mean flow depth (h) was substituted for R since the channel has a very high width:depth ratio (discussed later in this thesis) making P roughly equal to w, and making R roughly equal to h. Substituting eq. 1 and h into eq. 2, $R \sim wh/w \sim h$. Additionally, a bankfull water surface slope of 0.00329 (calculated from ESMP cross-sections) was used in eq. 5.

Critical tractive force (τ_c) was calculated using eq. 6. When determining τ_c for bed materials, a minimum value of 0.1 was used for θ_c, because of the highly imbricated nature of the armor lining the channel. The "rule of thumb" of $\tau_c = 0.97d_{50}$ (Gordon *et al.*, 1992) will not be used here because it uses a value of 0.06 for θ_c, which assumes a uniform, settled bed with random grain arrangements (Andrews, 1983; Church, 1978, cited in Gordon *et al.*, 1992), as well as a sediment density of 2.65 g/cm^3 (Gordon *et al.*, 1992). These values are not appropriate for the channel in the study area, where the bed materials are highly imbricated tabular pebbles of Brunswick/Passaic formation mudstone, which has a density of ~2.45 g/cm^3 (Sheridan *et al.*, 1991).

To determine the critical tractive force required for flushing surface fines from the channel bed, a value of $\theta_c = 0.021$ was used. A value of $\theta_c = 0.035$ was used for rearranging the channel bed. Critical tractive forces determined using these values of θ_c will be referred to as τ_f (flushing) and τ_r (rearranging) respectively. The d_{50} value used for calculating τ_f and τ_r is that of the armoring materials.

In order to determine the critical tractive force required to entrain bank (Bowmansville series alluvium) materials, a value of 0.05 was used for θ_c, and a density of 1.63 g/cm^3 (USDA SCS, 1975) were used. In light of considerable scatter in experimental data, a range of 0.04-0.06 for θ_c is suggested by Gordon *et al.* (1992) for materials similar to those that make up the banks of the East Branch Perkiomen.

Substituting τ_{bkf} for τ_c in eq. 6 and solving for d_{50} provides an estimate of the size of material bankfull flows can entrain and transport. Substituting τ_d for τ_c in eq. 6 also provides an estimate of the size material that diversion flows can entrain and transport. A limitation of applying these equations to this study is that they assume spherical grains, whereas the materials lining the channel of the East Branch Perkiomen Creek are tabular. It will thus be used as a 'best guess'.

Manning's "n" was back calculated using the DOS-based program *Manning*, which is part of the *Aquapak* software package by Gordon *et al.* (1992). Parameters required were average water surface slope (as a decimal), hydraulic radius, and mean flow velocity.

Stream power was calculated using eqs. 15 and 16.

Data sets on discharge (USGS, 1984-present; Rutgers control gage, June 1993-present) and volumes pumped (provided by PECo to DRBC, 1989-present) were utilized to 1) establish hydrographs (discharge or pumpage versus time); 2) calculate natural flows (discharge at the USGS gage minus volume pumped from Bradshaw to the East Branch Perkiomen); 3) compare hydrology of reaches upstream and downstream of the outfall point; and 4) perform flood-frequency analysis for the creek prior to and during flow diversion.

Flood frequency analysis was performed using the method outlined in Gordon *et al.* (1992, pp. 352-385). This method ranks the largest flow events for the period of hydrographic records, and then calculates an average recurrence interval for each flow, using the formula:

$$R.I. = (N+1)/m \qquad \text{(eq.21)}$$

where $R.I.$ = average recurrence interval of a given event, N = number of years of record, and m = rank of a given flow event.

Erosion and Sedimentation Monitoring Program Data

The data from the ESMP were initially in the form of graphical cross-sections. An example of one of these graphical cross-sections is provided in Appendix V. In order to determine changes in cross-sectional area over time, the cross-sectional area of each of the periodic surveys had to be determined. This was achieved using a vector-based object-oriented computer-aided drafting program, Canvas v3.5.1, from Deneba Software, Inc, using an Apple Macintosh IIfx and an Apple Macintosh Quadra 610. The plotted cross-sections were scanned into the computer individually using an AppleScanner and AppleScan software. Canvas was then used to manipulate the cross-sections (reverse vertical exaggeration, etc.) and determine bankfull cross-sectional areas. Microsoft Excel for the Macintosh was then used to manage the data set that resulted from this procedure. The complete procedure is outlined in detail in Appendix IV.

Potential Problems It is important to note two potential limitations and/or problems with the ESMP data set: The first is that the data from the ESMP were available only as photocopies of plotted cross-sections. Some of the spatial relations on the cross-sections may have been distorted by photocopying. In order to minimize such effects, any copies that showed obvious distortion (e.g. straight lines that had become warped) were rejected, and better copies were acquired. A second potential source of error is inaccuracy of the plots of the cross sections themselves.

The third, most important source of error is evidenced in the presentation of the data in Table 13, where final amounts of channel change have been presented both in a "raw" and "corrected" form. In their "raw" forms some of the data indicated decreases in bankfull cross-sectional area, whereas their respective cross-sectional surveys (discussed in detail below) show channel deepening with minimal deposition (e.g. TS13B and TS9; Figs. 38 and 42). The error arises from the elevations of the end points (on the lower bank) of the surveyed transects being inconsistent during the chronology. The reasons for the inconsistencies are unclear, but possible explanations include 1) surveying error, 2) vegetation changes, and 3) actual modification of the flood plain due to overbank flow. The inconsistencies result in artificial inflation or deflation of bankfull cross-sectional area values. For example, if the end point of the lower bank was lower in the final survey than in the original survey, the "top" of the bankfull cross-section will be lower, thus decreasing the area of the bankfull section (see Figure 37 as an example). Thus, a correction of some sort was necessary. The correction was performed by using the pre-operational surveying end-point as the end-point of the newer survey, if the end-point had changed. TS4, TS7A, TS9, TS13B and TS14 were significantly affected by this error (Table 13). The amount of change in the remainder of the transects was relatively unaffected.

Because the changes in the elevations of the affected end points of the given transects were erratic and not consistent through time, and the reasons for the inconsistencies are unknown, only the final data points have been corrected. When looking at trends of channel change, all values were uncorrected since the actual amount of correction in many cases is minimal. *Patterns* of change (e.g. erratic or steady) are unaffected even where the correction was significant (e.g. going from negative to positive change as in TS9 and TS13B). When attempting to predict future change, the models will use the average amount of change (from pre-operational conditions) over the length of the channel, which was not significantly affected by the correction. The complete data set, with cross-sectional areas, vertical exaggeration correction factors and final absolute correction factors may be found in Appendix V.

The error involved with the scanning - tracing method is ± ~ 5% for bankfull cross-sectional areas. This was determined by performing the procedure repeatedly (4 times) for several ESMP cross section surveys. This error is not significant in that the data are used primarily to determine general trends and rates of channel change with flow diversion.

Material Loss A rough estimate of total volume of material lost over the period of the ESMP was calculated by using the change in area (+ or -, in ft^2) at a given cross-section as the amount of material lost at that section. It was assumed that the change in area (+ or -, in ft^2) at a given cross-section was approximately the same as the change between that cross-section and halfway upstream to the previous cross-section, and halfway downstream to the next cross-section. The sum of the upstream and downstream distances (feet) was multiplied by the amount of material lost at the cross-section (ft^2), to obtain an approximate volume of material lost in that reach of the channel over the period of the ESMP. This was done for all nine of the ESMP transects, which cover just under a mile of stream distance, and summed to obtain a total volume of material lost. For end cross-sections, TS14 and TS3, the distance used in the direction where there is not another cross-section was the same as the half-distance to the next cross-section in the opposite direction.

The volume of material lost was multiplied by the density of the material of the Bowmansville alluvium (102 lbs/ft^3; 1.63 g/cm^3, SCS, 1975) to obtain the mass of the material lost. This mass was divided by the period of the ESMP (4.5 years) to obtain the average amount of material lost per year of the transfer thus far. This value was divided by the average amount of water diverted to the East Branch Perkiomen Creek per year (since the diversion flows more than dominate the natural flows) in order to obtain the average amount of suspended load in *g/l*, which was in turn compared to measured suspended loads as a cross-check.

DATA MANAGEMENT

Data management for the entire project was performed using Microsoft Excel v4.0. Data were graphed using Microsoft Excel v4.0 and CA CricketGraph III v1.5. Figures were created and/or modified using Deneba Software's Canvas v3.5.1, and AppleScan v2.0.2. Word processing was done using WordPerfect v3.0. All applications were used with an Apple Macintosh Quadra 610 or IIfx microcomputer.

RESULTS AND INTERPRETATION

HYDROLOGY

Pre-diversion

Figure 11 is the hydrograph for the period of record from the United States Geological Survey Gaging station located in the headwaters region of the East Branch Perkiomen Creek (Figure 15), downstream of the outfall pipe. The period prior to the phased start-up of pumping operations (1983-mid 1989) shows a normal, undistorted stream hydrograph, with a low baseflow and dominant storm peaks. Winter months are considerably wetter than summer months, which often have no flow.

Pumping Effects

The hydrograph begins to be distorted from its natural form during the phased start-up of pumping operations (August 1989-August 1990) (Figure 11). The form of the hydrograph becomes erratic as a result of several periods of sustained elevated flows, the magnitudes of which increased during the start-up period. Phase I flows were increased to 10, 20, and 27.1 cfs; Phase II flows were increased to 40, 50, and 67 cfs.

In August 1990, full pumping operations commenced, with diversion flows within project design parameters (normal 55, maximum 65 cfs). The hydrograph (Figure 11) takes on the distorted form of alternating high and low plateaus. This is the form that it will have for the duration of the transfer project. The yearly hydrograph is comprised of two plateaus: an elevated baseflow in the winter months and a substantially higher, sustained flow during the summer months (periods of high electricity demand). The normally negligible baseflow in the summer months is replaced with extended periods of sustained elevated discharges. Storm peaks appear to be less dominant. The baseflow of winter months (which is normally greater than that of summer months) has been elevated as well (in accordance with the Stream Encroachment Permit), although storm peaks are still discernable.

Two years of pumping data (Figure 4) show the same pattern as the flows recorded in the hydrograph from Bucks Road (Figure 11), suggesting that diversion flows more than dominate natural flows. The variability (although not great) in the hydrograph is due to the effects of natural storm flows. Storm hydrographs have also been distorted as a result of flow diversion. Comparing hydrographs of storms of similar magnitude prior to and during flow diversion (Figure 17), it is evident that storm peaks are less dominant, and waning storm flows are interrupted by the return of diversion flows. The end effect of the flow diversion is that the hydrograph of the East Branch Perkiomen Creek has been grossly distorted from its normal form, with the relative magnitudes of winter and summer flows being effectively reversed.

Table 3 summarizes the effect that the flow diversion has had on the hydrography of the creek. Mean annual discharge has increased from 6.8 cfs prior to flow diversion to 37.7 cfs, an increase of 454%. The mean discharge of the maximum month prior to pumping was 11.8 cfs (2/85). With the diversion project in place, it is now 58.3 cfs (9/92). Summer flows have increased from a mean of 0.87 cfs in 8/84 to 59 cfs in 8/93.

Flood Frequency

Flood frequency analysis reflects a further effect of the diversion flows. Given the limited period of record (10 years), there is an apparent increase in the magnitude of floods with a recurrence interval of 1.9 years from 145 to 150 cfs. The magnitude of the 2.3 year

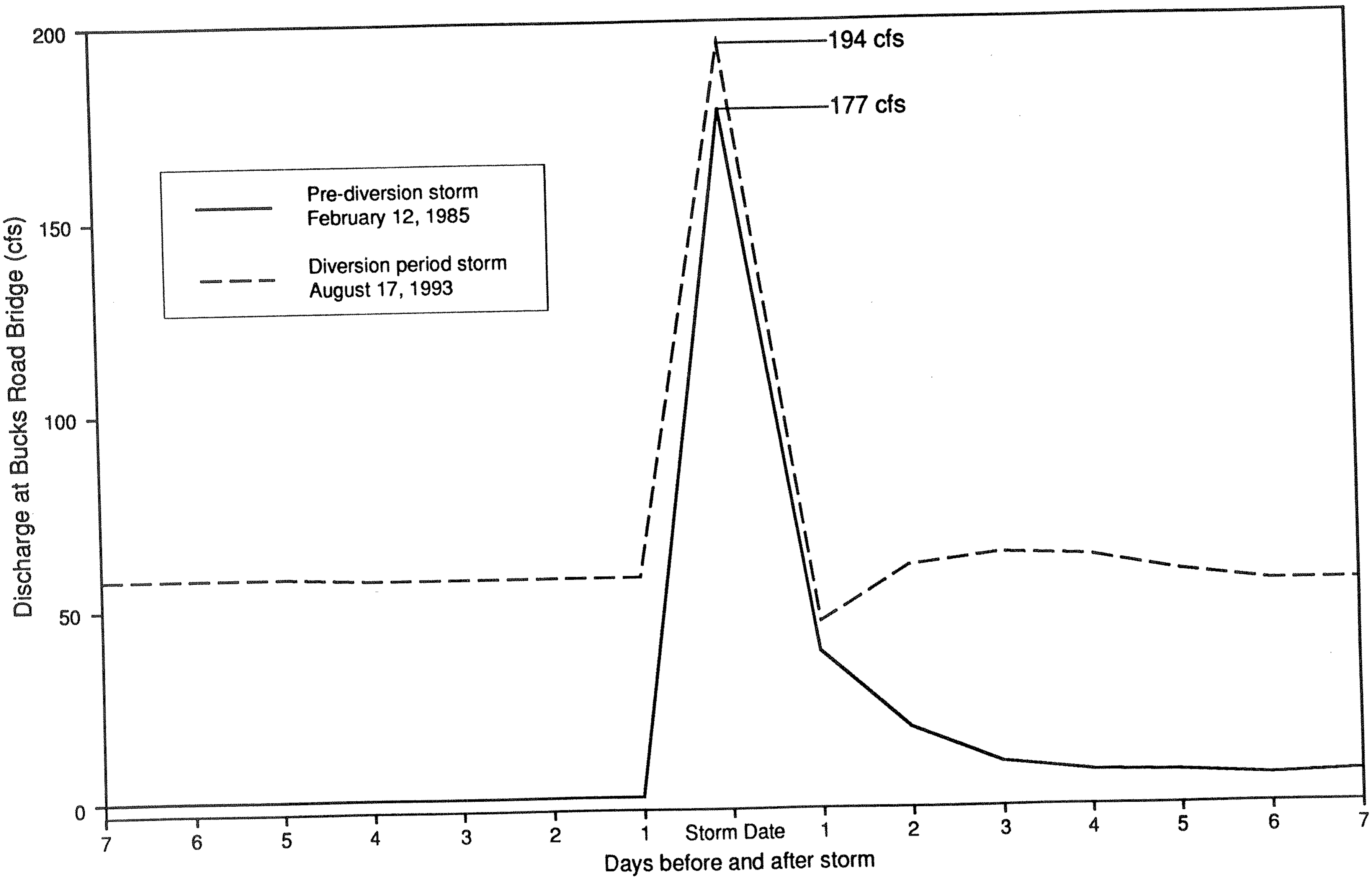


Figure 17: Comparative hydrographs for pre-diversion and flow diversion storms for the East Branch Perkiomen Creek.

event increased from 110 cfs to 245 cfs, and that of the 2.9 year event increased from 250 cfs to 280 cfs (Figure 18).

GEOLOGIC STRUCTURE

Bedding within the channel strikes ~055°, and dips gently NW (Figure 19). Stream flow is essentially along bedding planes. The mudstones are prominently jointed, and there are three joint sets that can be observed in bedrock that outcrops in the channel. The joints are spaced at intervals of less than 1 ft, making them closely spaced. The dominant joint set (set 1) within the channel trends ~025° (Figure 19), and is oblique to the strike of bedding. The second dominant joint set (set 2) is parallel to the strike of bedding. The channel generally trends ~225°, which is within ~15-20° of the dominant joint sets (sets 1 and 2) and bedding (Figure 19). There is a subordinate set (set 3) orthogonal (300°) to dominant set 2 (Figure 19). This subordinate set is better exposed in meander bends. Cutting of the channel into bedrock is apparent in Figure 20.

Structural controls on the position of the East Branch Perkiomen Creek at the regional scale are readily apparent. A map of the creek has been superimposed on the geology of the area in Figure 6. In the headwaters region (A), the stream channel follows the strike of the bedding closely, with sinuosity generally increasing from ~1.07 to ~ 1.27 as the creek enters the limb of an anticline (B). The channel continues to follow bedding closely in the limb of the anticline, but abruptly changes direction as it follows bedding through the hinge region, crossing the Chalfont fault (C). The channel again follows bedding closely through the hinge region and down the limb of the adjacent syncline (D). Sinuosity remains at ~1.27 from C to D. This agrees with Schumm *et al.*'s (1987) observation that channel sinuosity in bedrock controlled or influenced reaches increases when streamflow is in the opposite direction of the dip of bedrock (up-dip). An example of another creek in the area that exhibits structural control at the regional scale is Swamp Creek (Figure 6 (E)), which follows bedding closely down the limb and through the hinge

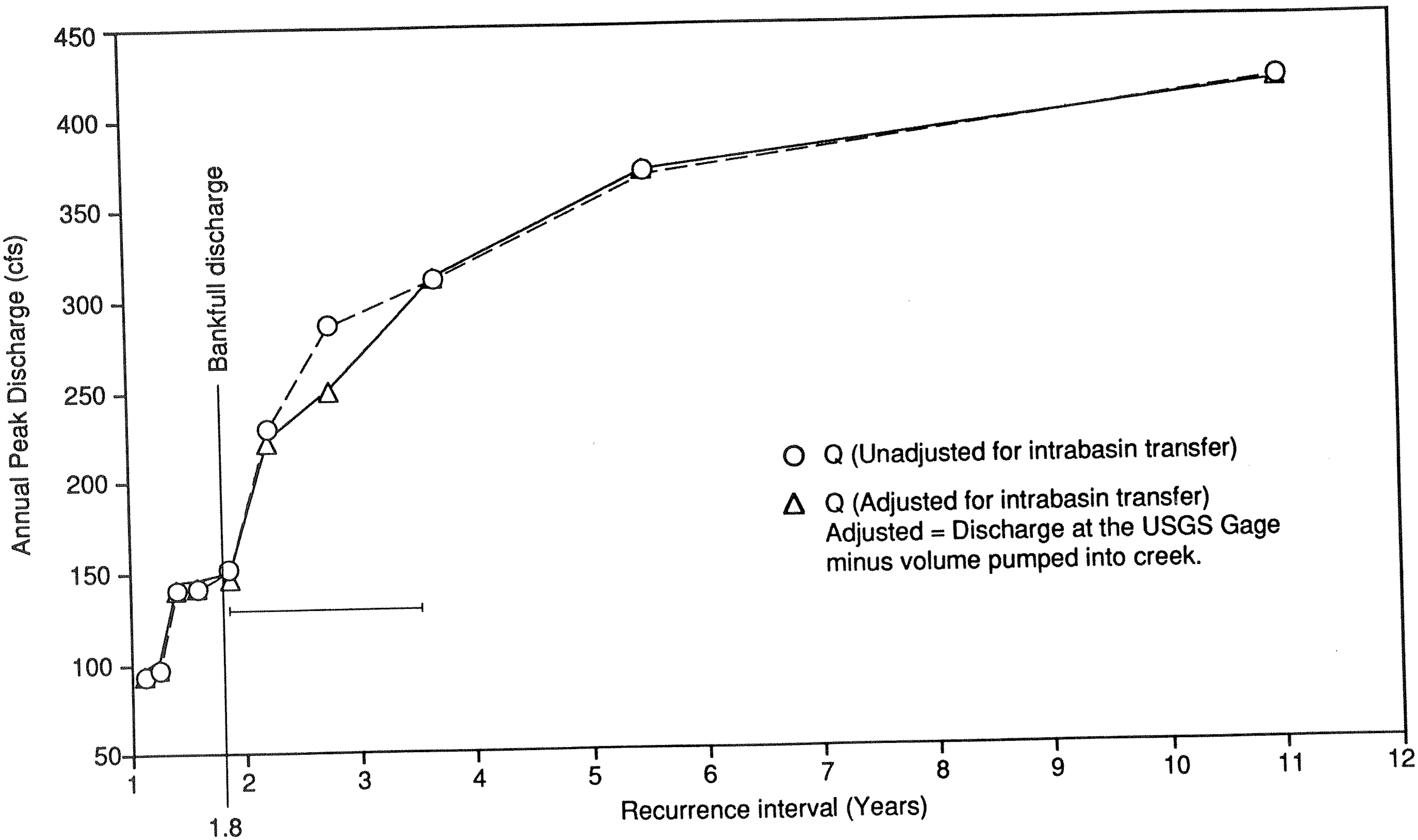


Figure 18: Flood frequency plot. Bar indicates the recurrence interval over which the magnitude of flows has apparently increased.

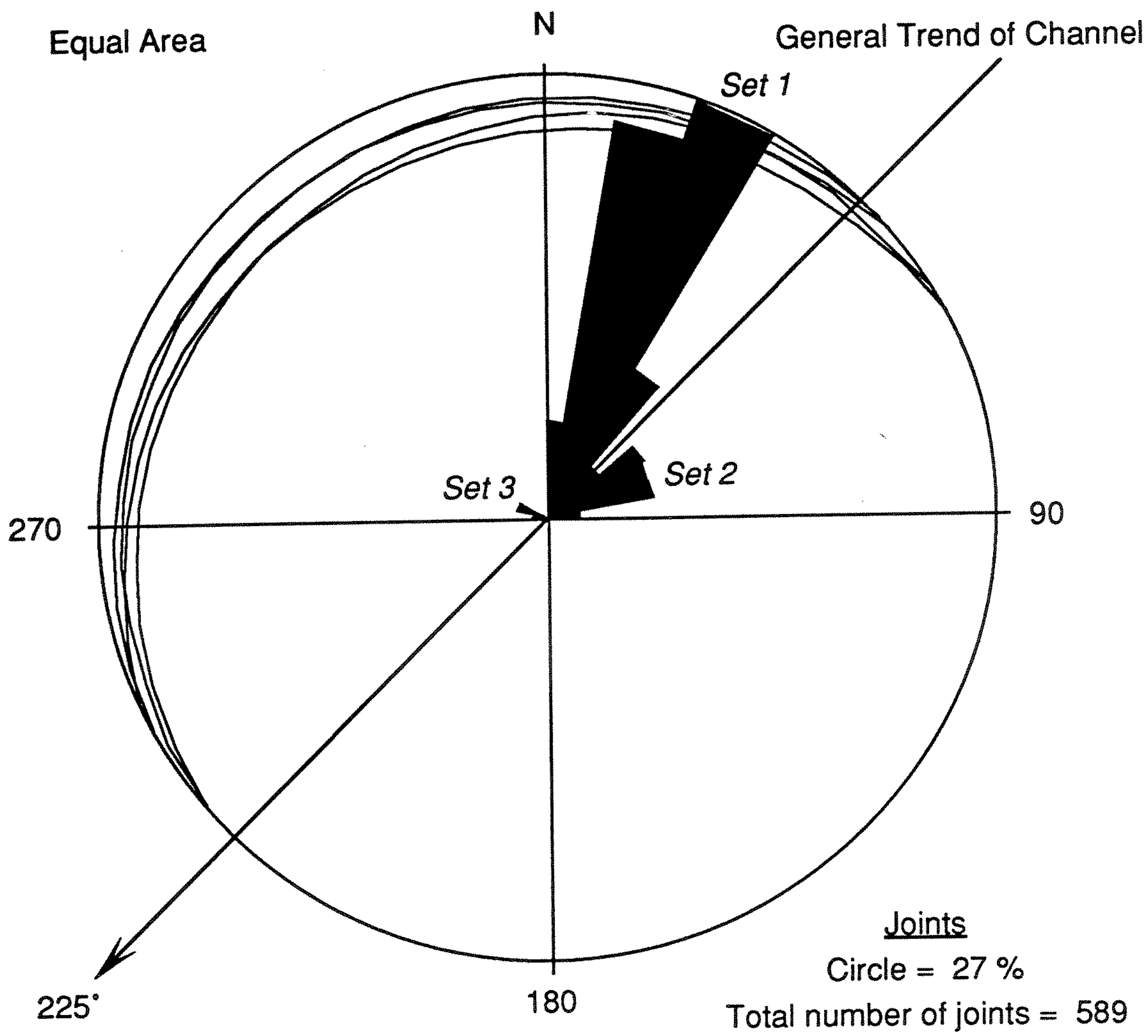


Figure 19: Equal-area stereonet of bedding planes and rose-diagram of sub-vertical joint azimuths with general channel trend.

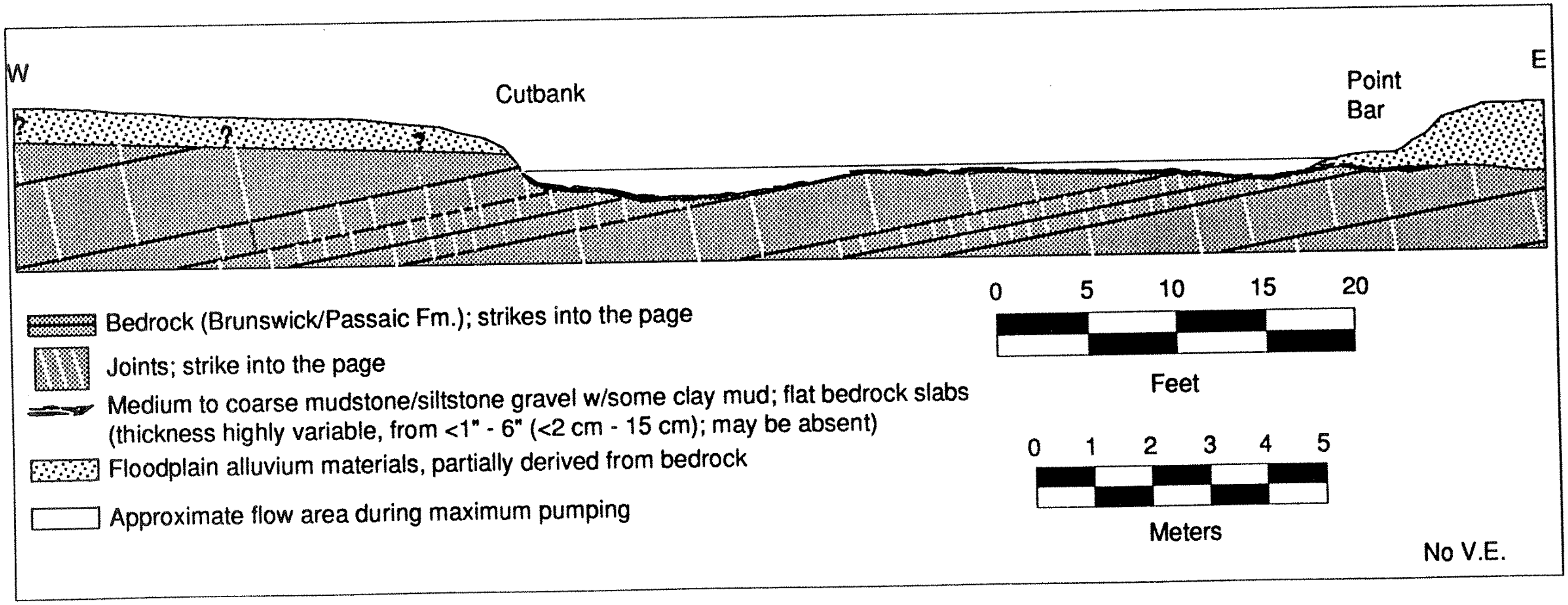


Figure 20: General geologic cross section (TS12) of the East Branch Perkiomen Creek.

of a syncline. The channel is oriented perpendicular to the local structure where the East Branch Perkiomen Creek joins the main stem Perkiomen Creek. The general tendency of the East Branch Perkiomen to parallel structure also agrees with an observation by Schumm *et al.* (1987) that bedrock channels show alignment with regional structure and joint patterns.

SEDIMENTOLOGY

Bed Materials

Bed materials range from mud (generally limited to quiet backwater areas) to coarse gravel armor (especially in the thalweg). The materials armoring the bed cover finer-grained materials. They are angular to sub-angular tabular mudstone pebbles and cobbles, and are highly imbricated (dipping upstream). This orientation provides maximum stability (Briggs, 1977, cited in Gordon *et al.*, 1992). Table 4 summarizes d_{16}, d_{50}, and d_{84} values for bed materials. The values of d_{50} represent the median intermediate (b) axis for the pebble samples, while d_{16} and d_{84} represent one standard deviation below and above the median. The set grid (Figure 16), modified grid, and paced grid methods produced virtually identical results (Table 4). The average d_{50} value upstream of the outfall pipe is 20 mm; downstream d_{50} values average 26 mm. Upstream of the outfall point d_{16} values average 9 mm; downstream d_{50} values average 15.2 mm. Upstream of the outfall pipe, d_{84} values average 26 mm; downstream d_{84} values average 55.2 mm.

The difference in d_{50} and d_{16} values between the reaches upstream and downstream of the outfall pipe is likely a result of diversion flows flushing finer-grained materials from the channel. d_{16} values are the most consistent from section to section downstream of the outfall point, most likely an indication of the competence of the diversion flows. The larger size of the larger clasts downstream of the outfall pipe is the result of a smaller population of small clasts, as well as more bedrock outcropping along the banks (Figure 21), which produces larger bed material. d_{84} values were the least consistent from section to section

Table 4: Streambed materials size summary.

Transect	RU Gage	RA+25A	RA+14/TS14	**Upstream Average**	Near TS12A	RA12	Just upstream of TS12	Just upstream of RA18	RA33	**Downstream Average**
Method	Paced Grid	Paced Grid	Paced Grid		Paced Grid	Grid	Paced Grid	Paced grid	Modified Grid	
d16	12	6	8	**9**	14	15	18	14	15	**15**
d50	20	12	27	**20**	23	26	30	25	26	**26**
d84	25	23	60	**36**	40	85	56	40	55	**55**

All values are pebble b-axes in mm
Pebbles are tabular

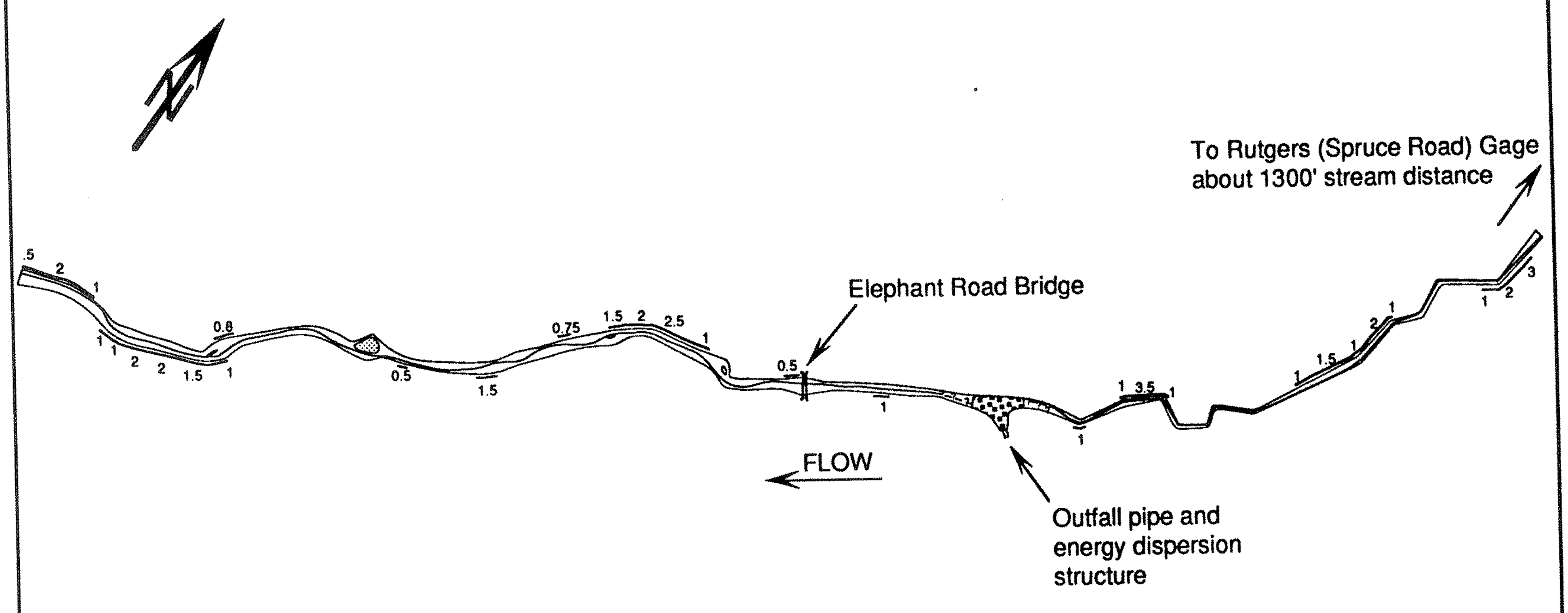


Figure 21: Bank bedrock outcrop on the East Branch Perkiomen Creek. Highlighted areas contain 0.5 feet or more of bedrock at their base. Most of the banks have 3 - 4 inches of bedrock at their base. 20.6% of the banks contain 0.5 feet or more of bedrock at their base.

downstream of the outfall point. The d_{84} value for just upstream of TS12 (Figure 15, Table 4) is higher (85 mm) than most of the other sections downstream of the outfall pipe (avg. = 55 mm), again the result of extensive bedrock outcrop along the banks. The data thus suggest that downstream of the outfall pipe d_{16} values are governed by flow competence, whereas d_{84} values are governed by channel geology. Channel materials are governed by lithology and structure in bedrock channels (Schumm, 1977).

Bank Materials

Bank materials are mostly alluvium with some bedrock. Bedrock outcrops (greater than six inches in height) line 21% of the banks (Figure 21). Alluvium in the study area is mostly mud and sand with some gravel. It is thin, ranging from 2-3 ft along the stream banks up to 6 ft away from the floodplain (USDA SCS, 1975). Two soil horizons are often clearly visible in the channel banks. These were identified by Hepner (1991) as the Bt (upper) and Bx (lower) soil horizons. The lower of these two horizons is so dense that plant roots cannot penetrate it (Hepner, 1991). Cutbank materials are considerably finer-grained than point bar materials (Figure 22, Table 5). Cutbank materials are predominantly silty mud, whereas point bar materials are mostly sand with gravel. Point bar materials are very sticky, dense, and coherent when wet. Overburden in the area dries to brick-like hardness during extended dry periods. Fine gravels in cutbank materials are angular to subangular in shape, and similar in color to the underlying bedrock. Fine gravels in point bar materials are more rounded and weathered than those found in cutbank materials, suggesting that whereas the unconsolidated materials on the point bars were deposited during waning flood flows, some of the cutbank materials are derived from the in-place weathering of the shallow bedrock.

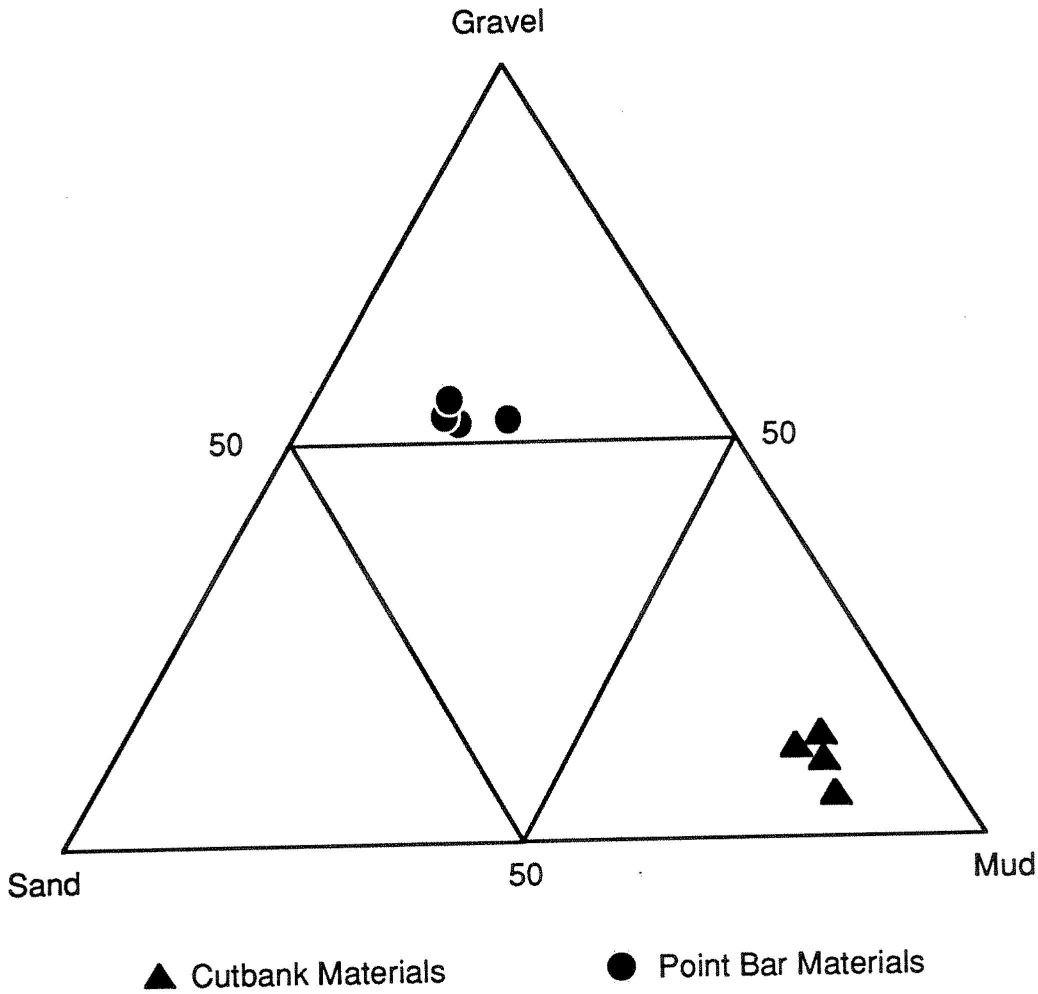


Figure 22: Bank materials composition diagram.

Table 5: Bank materials grain-size summary.

Percents are by weight

Date	Sample #	% Clay	% Silt	% Sand	% Gravel	Bank
21-Dec-93	TS12 WB	10.18	63.12	11.42	14.20	Cutbank
	RA18 EB	9.62	59.69	13.51	16.66	Cutbank
	TS12 EB	4.02	12.32	29.22	54.12	Point Bar
	RA18 WB	4.22	12.91	28.21	54.31	Point Bar
27-Dec-93	TS12 WB	12.40	63.51	10.99	12.65	Cutbank
	RA18 EB	10.85	55.62	15.84	17.30	Cutbank
	TS12 EB	1.59	14.26	29.17	54.76	Point Bar
	RA18 WB	1.73	15.51	27.35	55.18	Point Bar

Date	Sample #		% Sand	% Gravel	% Mud	Bank
21-Dec-93	TS12 WB	Cutbank	11.40	14.18	73.18	Cutbank
	RA18 EB	Cutbank	13.49	16.64	69.20	Cutbank
	TS12 EB	Point Bar	29.17	54.04	16.32	Point Bar
	RA18 WB	Point Bar	28.17	54.24	17.10	Point Bar
27-Dec-93	TS12 WB	Cutbank	10.95	12.60	75.62	Cutbank
	RA18 EB	Cutbank	15.78	17.23	66.22	Cutbank
	TS12 EB	Point Bar	29.10	54.63	15.81	Point Bar
	RA18 WB	Point Bar	27.29	55.05	17.20	Point Bar

Suspended Load

Samples collected for suspended load analysis (Table 6) indicate that suspended load downstream of the outfall point (0.02 mg/l) is about half of that upstream of the outfall pipe (0.04 mg/l). This is the result of the water being discharged into the stream is free of sediment.

GEOMORPHOLOGY

Fluvial Geomorphology

Within the study area (the headwaters region of the East Branch Perkiomen), the drainage pattern is a combination of dendritic and trellis (Figure 9), but is more dendritic than trellis. Farther downstream it is a hybrid of dendritic and trellis (Figure 2), likely a result of bedrock controls. Channel form is meandering within the headwaters region, though not blatantly so (Figures 9 and 17). The sinuosity index is low. The greater channel has a sinuosity of 1.2; that of the hydraulic meander is 1.1. The thalweg (hydraulic meander) can be seen to meander back and forth within the greater channel (Figure 23). It generally correlates with broad channel bends, but still swings back and forth within straight reaches (Figure 23). Broad hydraulic meander wavelength (L) upstream of the outfall pipe is ~230 ft, downstream it is ~700 ft. The small hydraulic meander is poorly defined. Average small hydraulic meander wavelength (λ) is ~175 ft. Channel slope is gentle at 0.00287.

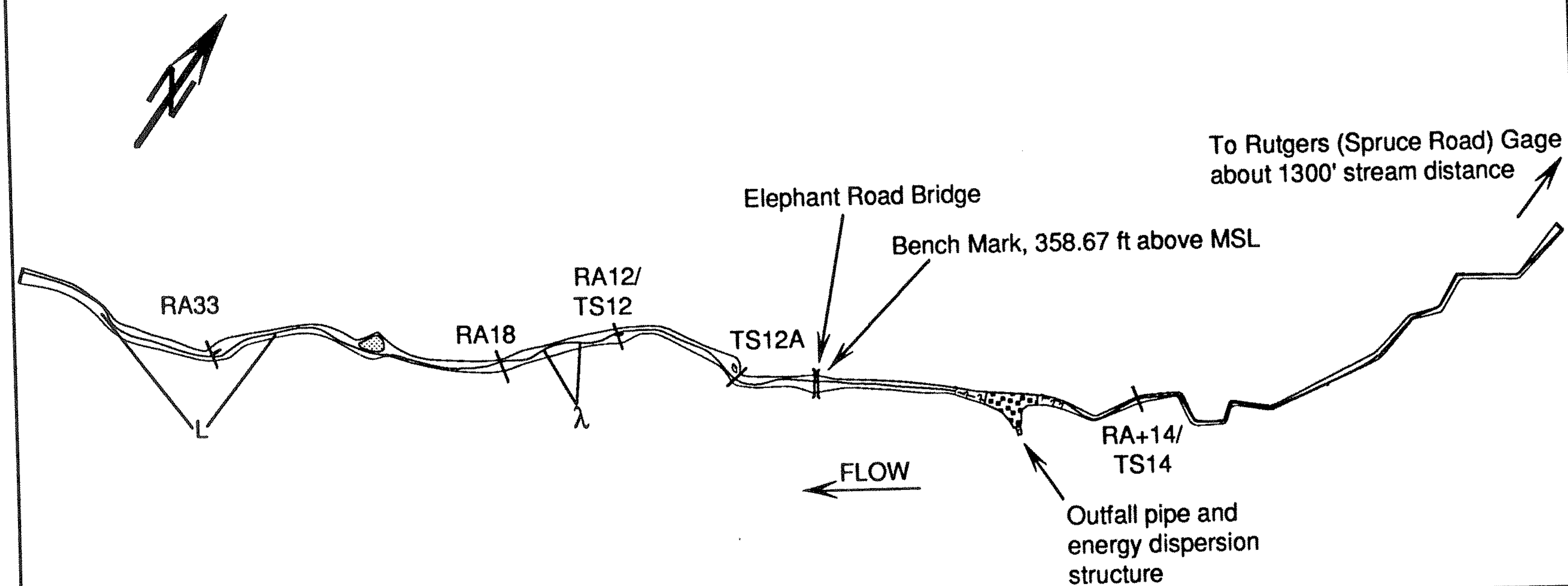
The channel itself is about 42 ft wide (22-80 ft, Tables 7 and 8). The stream flows over bedrock and alluvium. Average bankfull channel depth is about 3 ft. Plots of cross-sections used in this study (Figure 24) show that channel form is trapezoidal, with an average width:depth ratio of 19.5 (Table 7), which is large. Trapezoidal form is typical of bedrock-floored streams where bedrock is weak (Braun, 1983; Allen and Narramore, 1985). The relationship between geology and channel form is apparent in Figure 20, which

Table 6: Suspended sediment load summary.

Date	Sample #	Filter Wt Pre	Filter Wt After	Suspended Wt	Vol of water (liters)	Susp Load (g/L)
9/14/93	Rutgers Gage	1.17	1.19	0.02	1	0.02
9/14/93	RA+7	1.16	1.19	0.03	1	0.03
9/14/93	Outfall	1.25	1.25	0	1	0
9/14/93	**RA12**	1.25	1.26	0.01	1	**0.01**
9/14/93	**RA18**	1.22	1.23	0.01	1	**0.01**
9/14/93	**RA33**	1.24	1.25	0.01	1	**0.01**
9/26/93	Rutgers Gage	1.20	1.22	0.02	1	0.02
9/26/93	RA+25B	1.12	1.18	0.06	1	0.06
9/23/93	RA+25A	1.17	1.21	0.04	1	0.04
9/23/93	RA+14	1.17	1.21	0.04	1	0.04
9/23/93	**RA33**	1.16	1.18	0.02	1	**0.02**
9/23/93	**RA12**	1.19	1.21	0.02	1	**0.02**
9/23/93	**RA18**	1.18	1.18	0	1	**0**

All weights in grams
Samples downstream of the discharge point are in boldface type

Figure 23: Tape and compass map of East Branch Perkiomen Creek
Bedminster Twp., Bucks Co., PA.
Rolf V. Ackermann
1994



L = Broad hydraulic meander wavelength
λ = Small hydraulic meander wavelength

— Hydraulic Meander
Rip-rap
Island

0 Feet 300
0 Meters 100

Sinuosity Index: Thalweg ~ 1.08
Greater Channel ~ 1.12

Wavelength of greater channel and broad hydraulic meander (L):
Downstream of outfall: ~ 700 ft
Upstream of outfall: ~ 230 ft

Average small hydraulic meander wavelength (λ) ≈ 175 ft

Table 7: ESMP channel dimensions summary.

Cross Sect	A ft^2	P ft	P/A	W ft	avg d ft	W/d
TS14	56.61	28.03	0.50	21.77	2.60	8.37
TS13B	83.07	56.54	0.68	24.74	3.36	7.36
TS13A	115.51	49.61	0.43	26.72	4.32	6.19
TS12A	173.84	122.45	0.70	67.29	2.58	26.08
TS12	192.58	71.55	0.37	56.41	3.41	16.54
TS9	129.00	87.49	0.68	81.15	1.59	51.04
TS7A	156.41	73.60	0.47	62.35	2.51	24.84
TS4	107.29	51.09	0.48	45.52	2.36	19.29
TS3	101.91	44.54	0.44	39.58	2.57	15.40
Average	**124.02**	**64.99**	**0.53**	**47.28**	**2.81**	**19.46**

A Bankfull cross sectional area
P Bankfull wetted perimeter
W Bankfull channel width
avg d Bankfull average depth

Table 8: Summary of meander wavelength calculations.

	Mean Annual Q (cfs)	Bankfull Q (cfs)	Drainage Area (mi^2)	Bankfull channel width (ft)	Meander Wavelength (L) (ft)
Prior to flow diversion	5.5	*219*		***57.6***	**692**
Independent of flow diversion		*192*	4.05	***53.2***	**638**
Measured		*223*		**58.3**	700
Measured		**130**		42	*504*
With flow diversion	37.7	*1508*		***190.8***	**2290**

Values in plain type are raw data

Values in italic type are calculated from data in plain type

Values in bold type are calculated from italic values

Values in bold italic are calculated from bold values

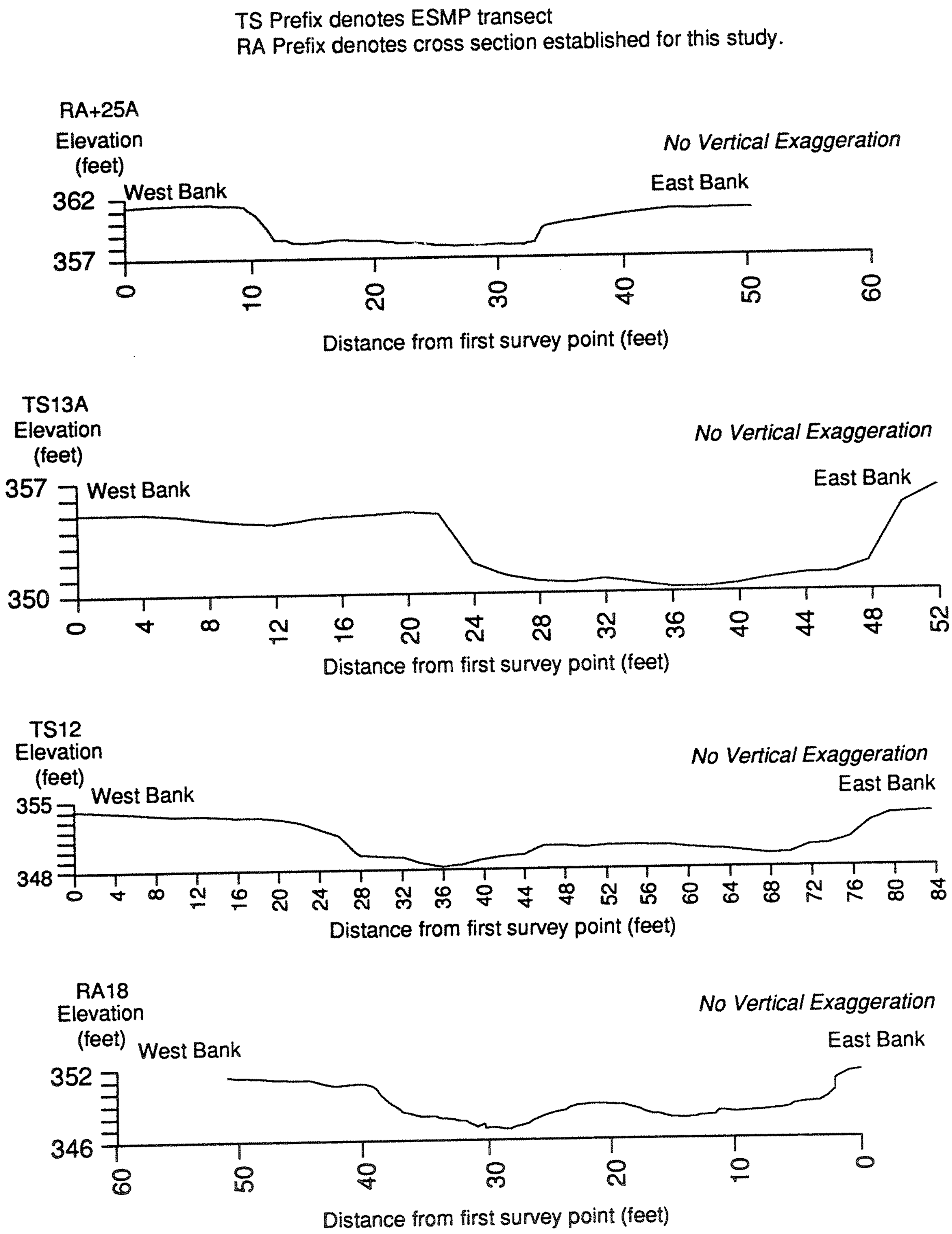


Figure 24: Sample cross sections of the East Branch Perkiomen Creek showing general trapezoidal form. Cross sections are presented in downstream order. Average width to depth ratio ≈ 20. See Figure 15 for cross section locations.

shows the channel cutting to bedrock, especially at the cutbank. Bedding thickness (and thus joint spacing) is diagrammatic.

Bedrock outcrops approximately 4 in. high can be found at the edge of the channel along much of the stream, at times covered with alluvium. About 21% of the channel banks contain more than 6 in. of bedrock, frequently 1-2 ft, in places as much as 3 ft. Most of the prominent outcrops within the banks occur along cutbanks, suggesting that the stream is up against bedrock, cutting into it, rather than being incised. Figure 21 shows where bedrock outcrops within the banks are higher than 3-4 in.

Most of the channel is lined with a discontinuous veneer (armor) of mudstone chips and bedrock slabs. This veneer ranges from 1-5 in. in thickness. Pebbles are tabular and angular to sub-angular. Bedrock is often exposed without any veneer. The materials armoring the bed cover finer-grained materials, and are highly imbricated (dipping upstream). There are no obvious potholes present in the channel bed.

The majority of the channel banks are clayey alluvium and overburden derived from the in-situ weathering of bedrock. There are two distinct soil horizons visible. There are limited areas, mostly downstream of the outfall pipe and on the outside of meander bends, where part of the channel bed flows over ledges of very compact mud. This is clearly the remainder of the denser lower (Bx) horizon after the upper (Bt) more erodible horizon has been stripped away. This is indicative of greater resistance to erosion by the denser, more compact lower horizon. The mud ledges frequently contain small potholes (<10 in. diameter). There occasionally are small potholes (<10 in. diameter) present in the alluvium of the lower channel banks (Bx horizon).

Several different scenarios were calculated using eqs. 12-14 to relate hydraulic meander wavelength, drainage area, mean or annual discharge, respectively, to bankfull discharge. These calculations are summarized in Table 8.

Prior to flow diversion, mean annual discharge was 5.5 cfs (Table 3), excluding Water Year 1984 because it was an unusually wet year. This translates to a bankfull discharge of 219 cfs using eq. 14, which in turn translates into a hydraulic meander wavelength of 692 ft. using eq. 12. Using the drainage area above the USGS gage at Bucks Road, (4.05 mi^2) to calculate bankfull discharge yields a value of 192 cfs using eq. 13, which translates into a hydraulic meander wavelength of 638 ft. using eq. 12. Mean annual discharge and drainage area produce similar results in this case. These results are consistent with an measured broad hydraulic meander wavelength (L) of ~700 ft, but inconsistent with an measured small hydraulic meander wavelength (λ) of ~175 ft. 192 cfs is inconsistent with the bankfull discharge of 100-150 cfs calculated by TAMS (1984). 192 cfs is close to the magnitude of the one-year flood calculated by TAMS (238 cfs), but significantly more than the one year flood *calculated* in this study (~130 cfs) using a longer period of record (Figure 18). With reference to Figure 11, it is clear that 100 cfs is exceeded several times per year. A bankfull discharge of 223 cfs can be back-calculated from the measured broad hydraulic meander wavelength of ~700 ft (Table 8) using eq. 12, which is consistent with the bankfull discharges calculated from mean annual discharge and drainage area. A bankfull discharge of 23.6 cfs can be back-calculated using the measured small hydraulic meander wavelength ($\lambda = 175$ ft) and eq. 12. This is not consistent with any of the above calculations. Relating the three broad hydraulic meander wavelength values discussed above to bankfull channel width using eq. 11, a value of ~56 ft is obtained. Using small hydraulic meander wavelength, a value of 14.5 ft is obtained for bankfull channel width. However, both surveying data collected for this study and the ESMP indicate an average bankfull channel width of 42 ft (Table 8). Eq. 11, also suggests that hydraulic meander wavelength should be 504 ft, which it is not. If 10 is substituted for 12 as the coefficient in eq. 11 (Ashley *et al.*, 1988), a hydraulic meander wavelength of 420 ft is obtained, which is still inconsistent with an measured hydraulic meander wavelengths of $L \approx 700$ ft, and $\lambda \approx 175$ ft. Using a hydraulic meander wavelength of 504 ft in (eq. 12) indicates that bankfull discharge should be ~130 cfs, which is significantly less that the first three scenarios produced. A bankfull discharge of 130 cfs, however, is consistent with Figures 11 and 18 (assuming a recurrence interval of 1.8 years).

These calculations suggest that broad hydraulic meander wavelength (L) is adjusted to mean annual discharge and drainage area, whereas bankfull channel width is adjusted to bankfull flows. Small hydraulic meander wavelength cannot be correlated using established relationships. These calculations also suggest that the relationship between bankfull channel width and hydraulic meander wavelength (eq. 11) does not hold for the East Branch Perkiomen, even when Ashley *et al.'s* (1988) coefficient of 10 is used. Broad hydraulic meander wavelength (L) is too large relative to channel width, whereas as small hydraulic meander wavelength (λ) is too small. This could be the result of the bedrock exposed within the channel inhibiting meander development. Gordon *et al.* (1992) noted that in streams with bedrock, much of the work (stream power) is expended as frictional dissipation of energy. As Richards (1982) observed, bedrock-influenced channels sometimes do not adhere to alluvial channel regularities. Studies have shown, however, similarities between bedrock and alluvial channel hydraulic meander geometries (Ashley *et al.*, 1988). In the case of the East Branch Perkiomen, there is agreement between bankfull channel width and bankfull discharge, and no agreement between bankfull channel width and hydraulic meander wavelength.

Substituting mean annual discharge during the period that the flow diversion has been in place into eqs. 11, 12, and 14 should predict the extent to which the channel will adjust to the imposed flows. Mean annual discharge during the diversion period has been ~37.7 cfs, which predicts a hydraulic meander wavelength of 2290 ft, and a bankfull channel width of ~191 ft. This prediction might be more realistic if this were a purely alluvial system. It also assumes that there would be no change in slope due to increased discharges, which is more realistic in bedrock than alluvial channels. As will be discussed below, the bedrock and alluvial controls on this system prohibit radical morphologic change. Also, the flow diversion will only be in place for a brief instant on a geologic time scale, and fluvial geomorphic theory assumes a time scale longer than that of human beings and flow diversions. It is more probable that limited adjustment will occur, depending on local variations in channel geology and geometry.

Hydraulic Geometry

Hydraulic geometry relations are valid for the East Branch Perkiomen Creek both upstream and downstream of the outfall pipe. The values used for *w*, *h*, *U*, and *Q* in eqs. 18-20 are presented in Table 9. The exponents *b*, *f*, and *m* sum to 1, and the coefficients *a*,*c*, and *k* multiply to 1 within ± 5% (Table 9). Leopold (1994) presents common values for *b*, *f*, and *m* of 0.26, 0.40, and 0.34 respectively. The values of *b*, *f*, and *m* determined for this study (Table 9) are significantly different from these averages. This may be a function of the channel being floored with bedrock instead of alluvium. Using field data on discharge (*Q*) measured in the field, values for *w*, *h*, *U*, were calculated using the empirically derived coefficients and exponents, and then compared to actual values for *w*, *h*, and *U* for that given discharge. The calculated values for *w*, *h*, and *U* came fairly close to the actual values (Table 9).

Bankfull cross-sectional areas from surveying data and empirically-derived bankfull discharges were used to determine bankfull velocities for some of the cross-sections surveyed for this study. Using the empirically-derived bankfull discharge and the empirically derived exponents and constants, bankfull values for *w*, *h*, and *U*, were calculated and compared to values from surveying data (Table 9). A bankfull discharge of 130 cfs (3.68 m^3/s) was used (See Table 8).

The calculated values are significantly different than the measured values. These differences are readily explained by the fact that the plots used to derive the empirical exponents and constants lack data points with high discharges. Hence the equation calculated by the computer was based on low (natural) to moderate (diversion) discharges

Table 9: Hydraulic Geometry Summary.

Cross Sec	b	f	m	b+f+m	a	c	k	a*c*k	Q (m^3/s)	w (m)	h (m)	U (m/s)	*Calc w* m	*Calc d* m	*Calc U* m/s
RU Gage	.079	.347	.597	1.023	4.328	.314	.778	1.057	.264	3.975	.223	.297	*3.896*	*.198*	*.351*
RA +25B	.049	.164	.791	1.004	3.730	.387	.700	1.010	.248	3.505	.280	.253	*3.484*	*.308*	*.232*
RA12	.311	.176	.516	1.003	8.662	.190	.607	.999	1.459	9.881	.212	.697	*9.742*	*.203*	*.738*
RA18	.081	.504	.415	1.000	9.740	.368	.279	1.000	2.777	10.769	.656	.393	*10.580*	*.616*	*.426*
RA33	.533	-.229	.693	.997	9.242	.201	.538	.999	2.343	13.180	.203	.874	*14.550*	*.165*	*.971*

Using field data, 9/26/93

b, f, m; a, c, k are calculated from field data.

Calculated w, d, and u are based on bank-full discharge; b, f, m; and a, c, k, for purpose of comparison with published values given in the text.

Cross Sec	b	f	m	b+f+m	a	c	k	a*c*k	Bkf Q m^3/s	Bkf Area m^2	Bkf w m	Bkf h m	Bkf U m/s	*Calc Bkf w* m	*Calc Bkf h* m	*Calc Bkf U* m/s
RU Gage	.079	.347	.597	1.023	4.328	.314	.778	1.057	3.682	5.862	10.546	.556	.628	*4.797*	*.494*	*1.694*
RA +25B	.049	.164	.791	1.004	3.730	.387	.700	1.010	3.682	7.756	9.677	.802	.475	*3.976*	*.479*	*1.963*
RA12	.311	.176	.516	1.003	8.662	.190	.607	.999	3.682	10.431	15.545	.671	.353	*12.991*	*.239*	*1.189*
RA18	.081	.504	.415	1.000	9.740	.368	.279	1.000	3.682	11.154	15.240	.732	.330	*10.825*	*.710*	*.479*
RA33	.533	-.229	.693	.997	9.242	.201	.538	.999	3.682	7.592	18.288	.415	.485	*18.512*	*.149*	*1.328*

Using empirical bankfull discharges and velocities (from bank-full discharge, and bankfull cross sectional area)

Calculated w, d, and u are based on bank-full discharge; b, f, m; and a, c, k, for purpose of comparison.

Ubkf (130 cfs = 3.682 m^3/s) from empirical Qbkf/bankfull cross sectional area.

Qbkf does not work because values of exponents determined without high discharge data.

and extrapolated to bankfull conditions. Additionally, 130 cfs is probably more than the bankfull discharge in the extreme upstream (e.g., RU Gage) reaches of the study area. The differences may also be due to bedrock controls on the system.

HYDRAULICS AND SEDIMENT TRANSPORT

Hydraulics

Natural Flows A rating curve was created for the Rutgers University Gage at Spruce Road (Figure 25). The hydrograph constructed from this rating curve and records from the gage are presented in Figure 26. A number of mechanical problems occurred which resulted in several data gaps, which can be seen in Figure 26. The original purpose of the gage was to 1) provide independent empirical flow data for the stream upstream of the outfall pipe, 2) exclude the western tributary upstream of the USGS Bucks Road Bridge gage (Figure 8), 3) determine pumping rates by comparing the Rutgers gage discharge with that from the USGS gage at Bucks Road. Actual daily records of volumes pumped to the East Branch Perkiomen became available during the course of the study, minimizing the need for the Rutgers gage data.

Field measurements of stream velocities for varying flow conditions upstream of the outfall point are summarized in Table 10 (complete tables can be found in Appendix VI). During non-storm and non-runoff flows, Reynold's numbers ($Re \approx 300$) and Froude numbers ($Fr = 0.03$) are well within the very low turbulence (laminar) subcritical flow regime (Figure 12). Shear stresses ($\tau \approx$ 2-3 N/m^2) are not great enough to entrain materials found within the channel upstream of the outfall point (d_{50} = 20 mm; τ_c = 29 N/m^2) during such flows (Table 4). Back-calculated Manning's "n" for reaches unaffected by diversion flows during non-storm conditions are high ($n \approx 0.8$) because the relative prominence of obstructions (e.g., mudstone slabs) is greater at lower stages (Allen, 1985). Stream power was calculated to be ~ 0.02-0.12 watts/m^2 for $\omega 1$ and ~ 0.00-0.30 watts/m for $\omega 2$.

Figure 25: Rating curve for Rutgers University stream gage on the East Branch Perkiomen Creek (Spruce Road).

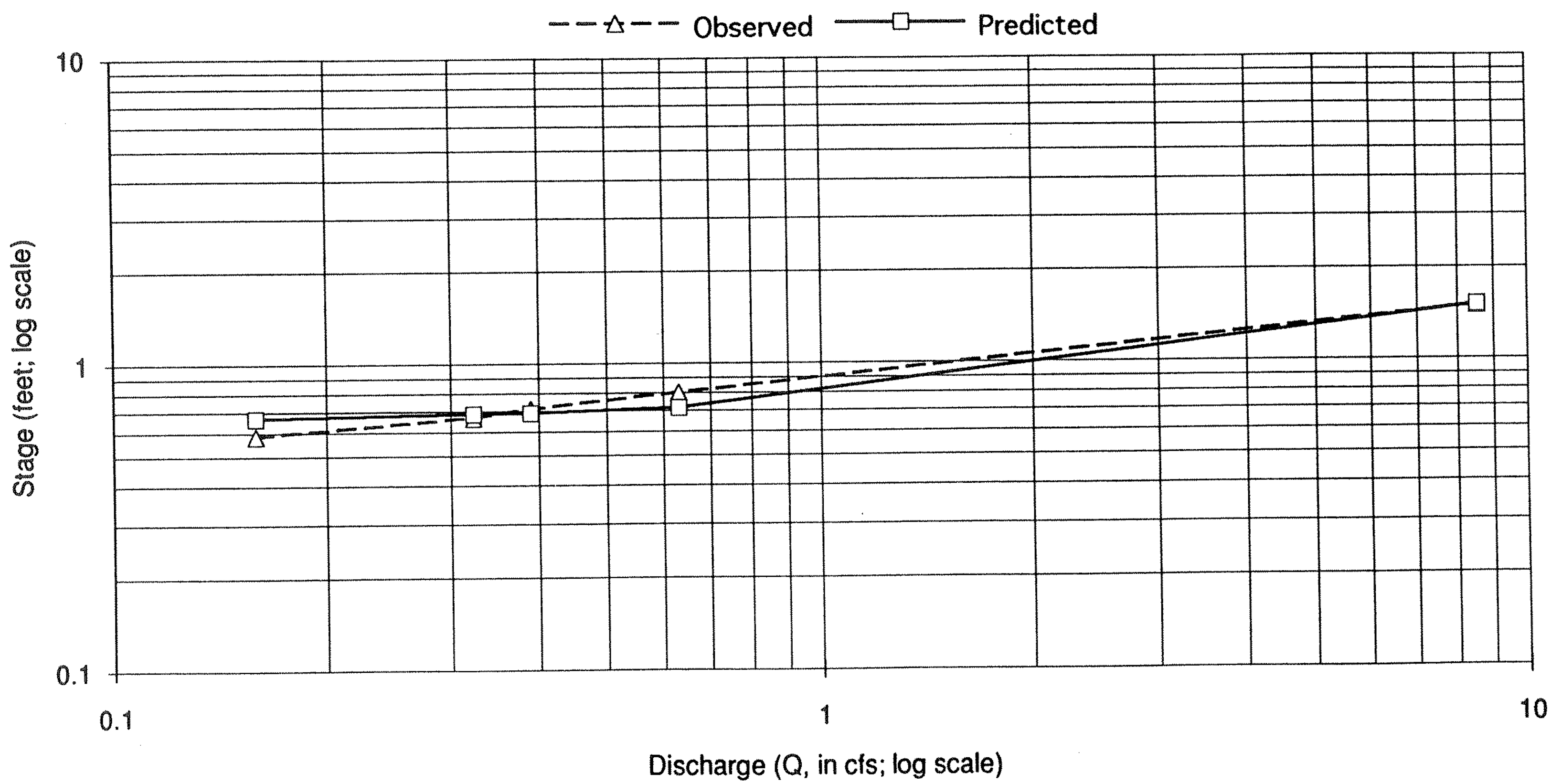


Figure 26: Period of record hydrograph for Rutgers Uinversity stream gage on the East Branch Perkiomen Creek (Spruce Road).

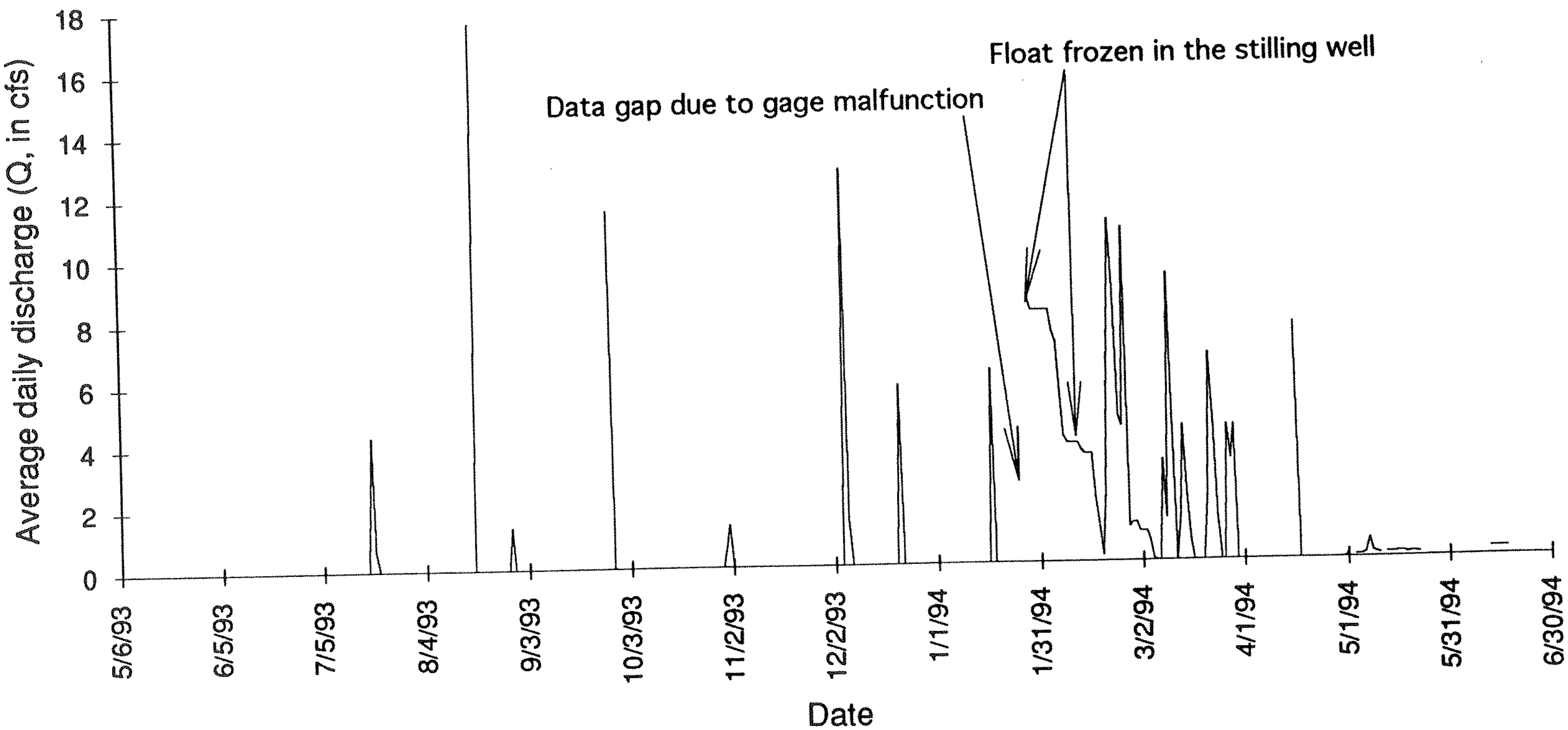


Table 10: Hydraulics summary.

Date	Reach Upstream or Downstream	Q Discharge cfs	V Velocity ft/s	Re # Reynold's #	Fr# Froude #	τ Shear Stress N/m^2	n Manning's "n"	ω1 Stream Power watts/m^2	ω2 Stream Power watts/m
19-Aug-93	Upstream	0.35	0.03	466	0.03	3.20	0.36	0.12	0.38
7-Sep-93	Upstream	0.35	0.02	144	0.01	2.66	1.03	0.04	0.19
	Downstream	**43.08**	**0.69**	**17807**	**0.46**	**6.86**	**0.03**	**4.46**	**31.70**
14-Sep-93	Upstream	0.09	0.02	89	0.03	1.20	0.37	0.02	0.00
	Downstream	**57.91**	**0.74**	**21932**	**0.49**	**8.31**	**0.04**	**5.33**	**42.76**
26-Sep-93	Upstream	9.35	0.25	5690	0.17	7.29	1.44	1.65	8.32
Rain	**Downstream**	**69.91**	**0.65**	**19403**	**0.42**	**10.26**	**0.05**	**5.63**	**61.07**
8-Oct-93	**Downstream**	**57.91**	**0.58**	**13300**	**0.40**	**6.50**	**0.04**	**3.34**	**42.76**
8-Apr-94	Upstream	1.41	0.09	1284	0.11	4.61	0.02	0.35	1.05
Melt runoff	**Downstream**	**18.36**	**0.32**	**6585**	**0.23**	**5.04**	**0.02**	**1.60**	**11.72**
	Pre-op Mean Q	6.8							4.87
	Pump Mean Q	37.7							27.00
	Min Pump	10.0							7.18
	Avg Pump	55.0							39.39
	Max Pump	65.0							46.55

Reynold's numbers ($Re \approx 5690$) calculated for a rain event (Table 10) indicate that flow is much more turbulent, but Froude numbers ($Fr \approx 0.17$) still fall well within the subcritical flow regime. Shear stress is higher during storm flows ($\tau \approx 7.3$ N/m^2), which is enough to entrain grains with a b-axis of less than 5-7 mm. Stream power increased significantly during the rain event (~ 1.7 watts/m^2 for $\omega 1$ and ~ 8.3 watts/m for $\omega 2$).

Hydraulic parameters calculated for discharges associated with runoff of meltwater are also summarized in Table 10. Reynold's numbers ($Re \approx 1284$) fell within the boundary between low turbulence (laminar) and turbulent flow, whereas Froude numbers ($Fr \approx 0.1$) remained within the subcritical flow regime. Shear stresses ($\tau \approx 4.61$ N/m^2) were less than those experienced during the rain event discussed above. Manning's "n" values decreased to ~0.02 as the relative prominence of obstructions decreased.

Anthropogenic Flows

Field measurements of stream velocities for varying flow conditions downstream of the outfall pipe are summarized in Table 10 (complete tables can be found in Appendix VI). With summer diversion (non-storm) flows, Reynold's numbers ranged from 13,000-22,000, indicating that the flow is very turbulent (Figure 12). Under the same conditions, Froude numbers at various cross-sections ranged from ~ 0.2-0.7, indicating that flow is subcritical (Figure 12). In the area of TS13A and TS13B (immediately downstream of the outfall pipe), there are often standing waves, which are characteristic of critical flow (Fr = 1). Although much of the creek downstream of the outfall pipe is characterized by hydraulic jumps resulting from obstructions within the channel (e.g. mudstone slabs), it is believed that these standing waves are the result of critical flow conditions. Manning's "n" values calculated were ~ 0.03-0.05. These values agree with those calculated by TAMS in 1984, and those used by DER in 1985.

Shear stresses during summer diversion flows averaged ~ 6-8 N/m^2. During the rain event (with summer diversion flows), shear stresses were in excess of ~ 10.2 N/m^2, but Reynold's ($Re = 19{,}400$) and Froude ($Fr = 0.42$) numbers remained within the summer diversion, non-storm range (Table 10). Stream power was significantly greater during summer diversion (non-storm) flows, with values of ~ 3-5 watts/m^2 for $\omega 1$ and ~ 30-42 watts/m for $\omega 2$. During diversion with rain flows, $\omega 1$ = 5.6 watts/m^2, and $\omega 2$ = 61 watts/m. During winter diversion flows, Reynold's numbers, Froude numbers, and stream power were significantly lower than during summer diversion flows (Table 10). Shear stresses, however, remained closer to summer diversion values (Table 10). The data suggest that the erosive power of the stream during non-storm diversion flows is greater than it would be naturally. The data also suggest that reaches of the stream downstream of the outfall pipe experience sustained elevated flow turbulence, with shear stresses approaching those of moderate storm conditions.

Manning's "n" values during non-storm diversion flows are within the normal to high range for winding lowland streams with some stones (Gordon *et al.*, 1992). Manning's "n" for reaches unaffected by diversion flows during non-storm conditions are high because the relative prominence of obstructions (e.g. mudstone slabs) is greater at lower stages.

Sediment Transport

Bed Materials (Armor) Measured diversion shear stresses (τ_d), critical tractive forces (τ_c), calculated bankfull shear stresses (τ_{bkf}), and eqs. 5 and 6 (to determine the mean grain size (d_{50}) movable by both diversion (d_{50d}) and bankfull (d_{50bkf}) flows) illustrate that the channel armor is reducing the erodibility of the stream channel. The results of these calculations are summarized in Table 11.

The shear stress produced by bankfull flows (τ_{bkf}) are calculated to be approximately 20.3 N/m^2. Substituting this value for (τ_c) in eq. 6 and solving for d_{50} to obtain d_{50bkf} indicates that bankfull flows are capable of moving material up to ~11.5 mm. Upstream of the outfall pipe, this is smaller than d_{50} values, but larger than d_{16} values.

Table 11: Sediment transport summary

Shear Stress Condition	Value in N/m^2	d_{50}/Material (mm)
Diversion (τ_d)	6 - 8 (measured)	4.2 - 5.6 (calculated)
Bed critical (τ_c)	36.9 (calculated)	26 (measured)
Bed maximum during flow diversion	8.2 - 10.9 (measured)	5.7 - 7.7 (calculated)
Flushing (τ_f)	7.8 (calculated)	[surface fines]
Rearranging (τ_r)	12.9 (calculated)	30% of armor & flushing of deep fines
Bankfull (τ_{bkf})	20.3 (calculated)	11.5 (calculated)
Bank critical (τ_c)	point bar 0.038 cutbank 0.009 (calculated)	point bar 0.125 cut bank 0.031 (measured)

This is consistent with finer grained materials settling out during waning storm flows. Downstream of the outfall pipe, the d_{50bkf} is smaller than measured d_{16} values.

Shear stress produced by diversion flows (τ_d) is 6-8 N/m2 (eq. 5). Substituting this value for (τ_c) in eq. 6 and solving for d_{50} to obtain d_{50d} indicates that diversion flows are capable of moving material between 4.2-5.6 mm in diameter. The intersection of the measured values for diversion flow shear stresses (6-8 N/m2) and d_{50} armor values of 26 mm falls well above the absolute stability limit line on Church and Gilbert's (1975) diagram that depicts the relationship between critical tractive force and spheroidal particle size for incipient motion (Figure 27). The imbricated nature of the armor makes it even more stable than Figure 27 suggests. The maximum shear stress applied to the channel bed during diversion flows is 8.2-10.9 N/m2, which is capable of moving material with a d_{50} between 5.7-7.7 mm in diameter.

The d_{50} values calculated for both diversion (d_{50d}) and bankfull (d_{50bkf}) flows are less than the measured d_{16} of 15 mm downstream of the outfall point (Tables 4 & 11). The maximum shear stress applied to the beds during diversion flows produces a d_{50} (5.7-7.7 mm) that is also less than the d_{16} (15 mm) measured downstream of the outfall pipe. Using a d_{50} of 26 mm (Table 4), critical tractive forces (τ_c) are approximately 37 N/m2. This is actually a minimum shear stress required to entrain the bed materials because increasing dimensionless critical shear stress (θ_c) from 0.1 (the value used here) will increase the critical tractive force (τ_c). The critical tractive force (τ_c) is greater than the shear stresses produced by either diversion or bankfull flows, as well as the maximum shear stress applied to the channel bed during diversion flows.

Solving eq. 6 for τ_f and τ_r by changing the value of θ_c indicates that the shear stress required to flush surface fines (τ_f) from the armor is 7.8 N/m2, which is within the range of diversion flows ($\tau_d \approx$ 6- 8 N/m2) (Table 11). The shear stress required to move (rearrange) 30% of the armor material and deep-flush trapped fines (τ_r) is 12.9 N/m2, which is greater than shear stresses during diversion flows, but is exceeded by shear stresses during

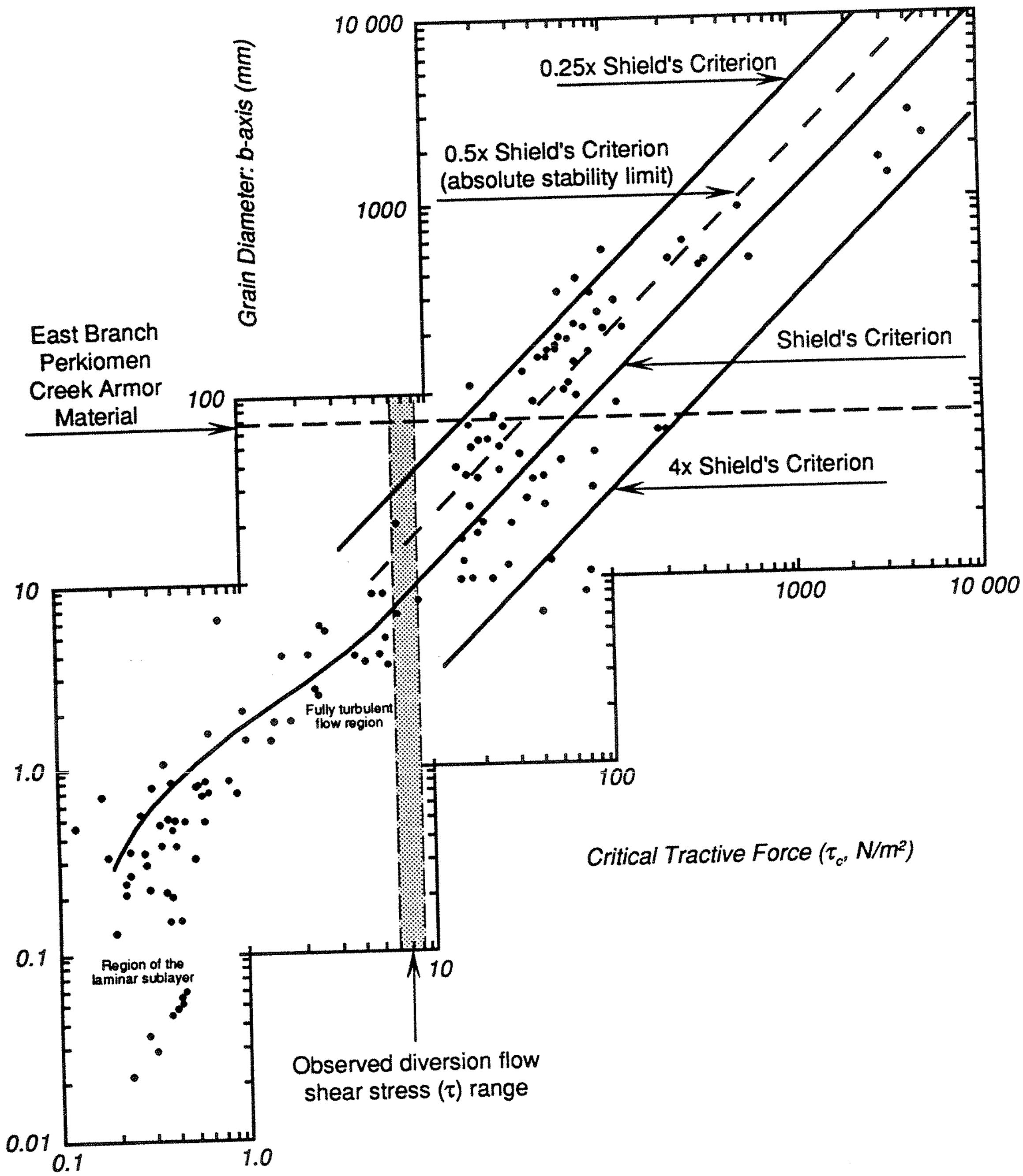


Figure 27: Relationship for tractive force at the streambed and particle size for incipient motion. Modified from Church and Gilbert (1975), who compiled the data points above from various authors.

bankfull conditions (τ_{bkf} = 20.3 N/m2) (Table 11). Recall that the magnitude of the 1.9 - 2.9 year flood events has increased from 145 and 250 cfs to 150 and 280 cfs, respectively. These flows are in the range that produce shear stresses capable of rearranging channel armor and deeply flushing trapped fines (τ_r, Table 11).

The implication of these calculations is that the bed materials that are present downstream of the outfall pipe cannot be moved by diversion flows, although any surface fines associated with the armor can be flushed out. Bankfull conditions provide enough shear stress to rearrange the armor downstream of the outfall pipe, but they do not exceed the critical tractive force required to entrain them.

The d_{50} values of bed materials upstream of the outfall point (Table 4) suggest that shear stresses in excess of 28.45 N/m2 are required to move bed materials. Such shear stresses would be associated with flows not measured during this study.

Bank Materials (Alluvium) For the purpose of calculation, a d_{50} of 0.031 mm (medium silt) was used for cutbank materials, and a d_{50} of 0.125 mm (fine sand) for point bar materials, in order to conservatively estimate the critical tractive force required to entrain flood plain materials. A minimum of 0.038 N/m2 is required to entrain point bar materials, whereas a minimum of 0.00957 N/m2 is required to entrain cutbank materials. Both of these values are significantly less than the maximum shear stress exerted on the banks during diversion flows (6.5-8.6 N/m2) and bankfull flows (21.9 N/m2), suggesting that bank materials would be easily entrained by diversion flows.

Fine grained materials present a smoother surface profile to flow than coarser materials, making them less affected by turbulence (Gordon *et al.*, 1992). This increases their resistance to entrainment, and thus erosion. Hjulström (1935, cited in Gordon *et al.*, 1992) found that critical tractive force is greater in fine-grained materials (Figure 28). Additionally, the silt and clay content of the consolidated bank materials may be making it more difficult to erode due to electrochemical forces binding them together (Gordon *et al.*,

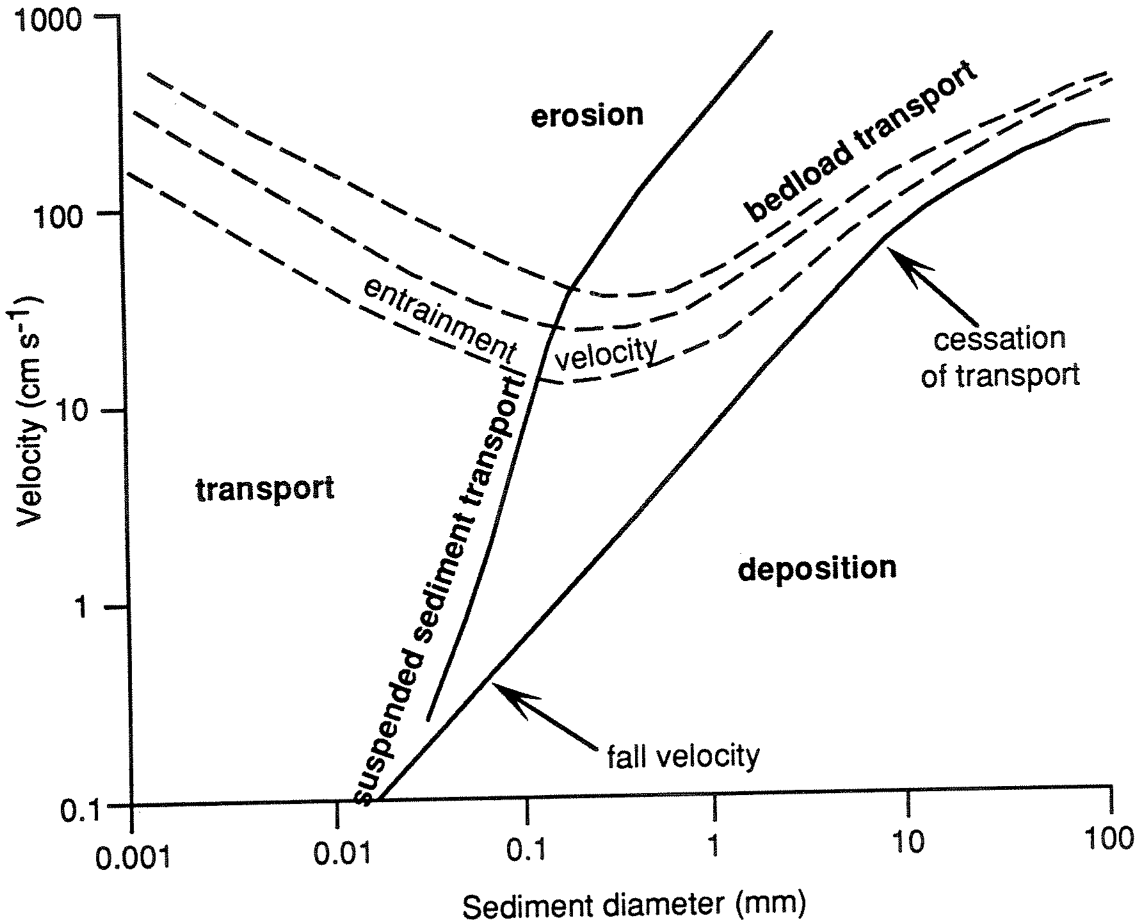


Figure 28: Threshold velocities (after Hjulström, 1935), and transport regimes (modified from Richards, 1982; Gordon *et al.*, 1992).

1992). Recall that plant and tree roots cannot penetrate the dense, lower (Bx) soil horizon, and thus cannot loosen it.

The bank materials are saturated for extended periods of time due to elevated water levels. These periods of time during the summer are significantly longer than they would be naturally, since upstream of the outfall pipe the creek is dry and the banks are hard as "bricks" during the summer months. Such extended periods of saturation downstream may make the banks more prone to failure by rotational slump (e.g., Ashley, 1991). It was observed in the field that the surfaces of the saturated banks are sticky and very coherent, perhaps from being constantly saturated. Channel bank collapse often occurs during rapid draw-down of the water surface after storm events as water drains towards the channel from the banks, creating pressure within the banks (Leopold, 1994). This pressure is directed out towards the channel, and reduces the ability of bank materials to stand as a vertical free face, resulting in slumping (Leopold, 1994). If water levels are high for extended periods of time (Figure 4), this problem should be eliminated because of little or no movement of water from the banks to the channel and vice versa, with pressure between the two being nearly equal. The reduction in channel-ward pressure in the banks combined with theoretical electrochemical attractions between silt and clay particles inhibiting entrainment is most likely making the stream banks more resistant to erosion than they may readily appear.

CHANNEL RESPONSE

Erosion

Surveyed Cross-Section Data Channel changes in the cross-sections established for this study are shown in Figures 29-35, and are summarized in Table 12. Change between the initial survey (August 1993, during summer diversion flows) and the second survey (April 1994, after one season of transfer) was limited to a small increase or decrease in channel cross-sectional area (±1-3%) upstream of the outfall point. Downstream of the outfall pipe, channel cross-sectional area increased as much as 4.5%.

The cross-sections were surveyed a third time in July 1994, to continue to monitor change and to determine if the materials that appeared to be deposited downstream of the outfall pipe during the months of lowered discharge (April survey) had been flushed out by the return of elevated summer flows. The results of these surveys are presented in Figures 29-35 and Table 12. Over the entire study area, change in bankfull channel cross-sectional area between the first and third surveys averaged +4.3%, whereas change in bankfull channel cross-sectional area between the second and third surveys averaged +3.8%. Upstream of the outfall pipe, bankfull channel cross-sectional area between the first and third surveys increased by 4.1%, whereas between the second and third surveys it increased by 5.3%. Downstream of the outfall pipe, bankfull cross-sectional area changed by +4.57% between the first and third surveys, and by +1.81% between the second and third surveys.

Over the period of this study, cross-sections located upstream of the outfall pipe experienced some erosion along their banks, and in one instance in the channel itself. The cross section located at RU Gage (Figure 29) deepened within the channel and widened along the west bank. There was erosion along the west bank of RA+25B (Figure 30), and deposition within the channel. The west bank is the cut bank for cross-section RA+25B (Figure 15). Erosion on RA+25A (Figure 31) was limited to the east bank, which is the cut bank for that cross-section (Figure 15). RA+14 (Figure 32) experienced some erosion along the west bank, which is the cut bank for that cross-section (Figure 15). There was also deposition within the channel at cross-section RA+14.

Downstream of the outfall pipe, cross-section RA12 (Figure 33) deepened along the western side of the channel (which is the thalweg, Figure 23), and accreted along the eastern side. RA18 (Figure 34) experienced erosion along the west bank and within the channel itself. The erosion within the middle of the channel (Figure 34) is the result of the

Table 12: Summary of changes in cross-sections established for this study.

Survey Date	**RU Gage**	**RVA +25A**	**RVA +25B**	**RVA +14**	**Upstream Average**	RVA 12	RVA 18	RVA 33	Downstream Average
Aug-93	-	-	-	-		-	-	-	
8/93 - 4/94	1.32	-0.94	-1.64	-3.36	-1.16	2.97	4.49	0.79	2.75
4/94 - 6/94	5.00	-1.43	11.30	6.32	5.30	1.20	-0.85	5.07	1.81
8/93 - 6/94	6.44	-2.36	9.50	2.75	4.08	4.21	3.59	5.91	4.57

All values are percent increase (+) or decrease (-) in cross-sectional area from original survey

Sections located upstream of the outfall pipe in boldface type
See Figure 15 for cross-section locations

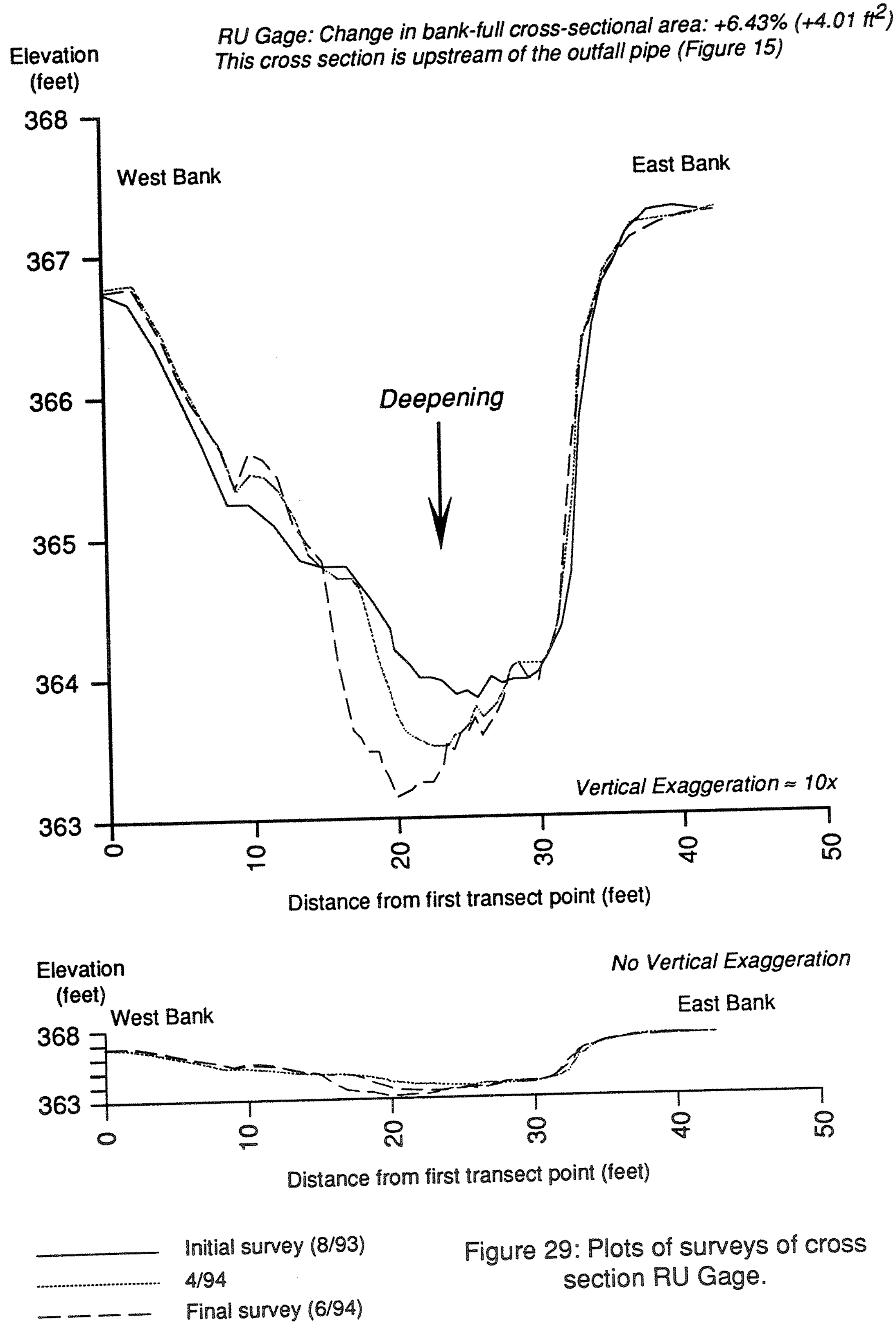
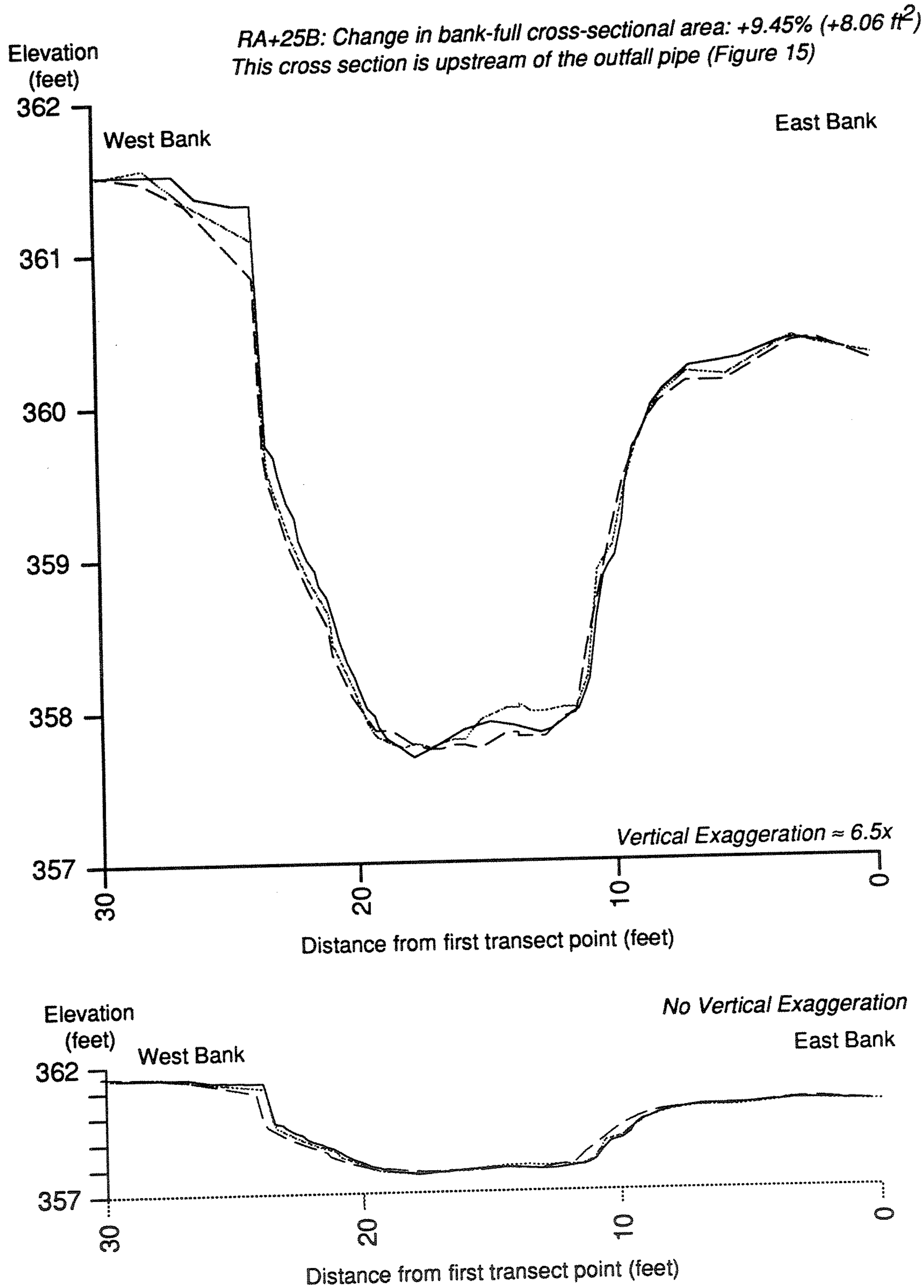
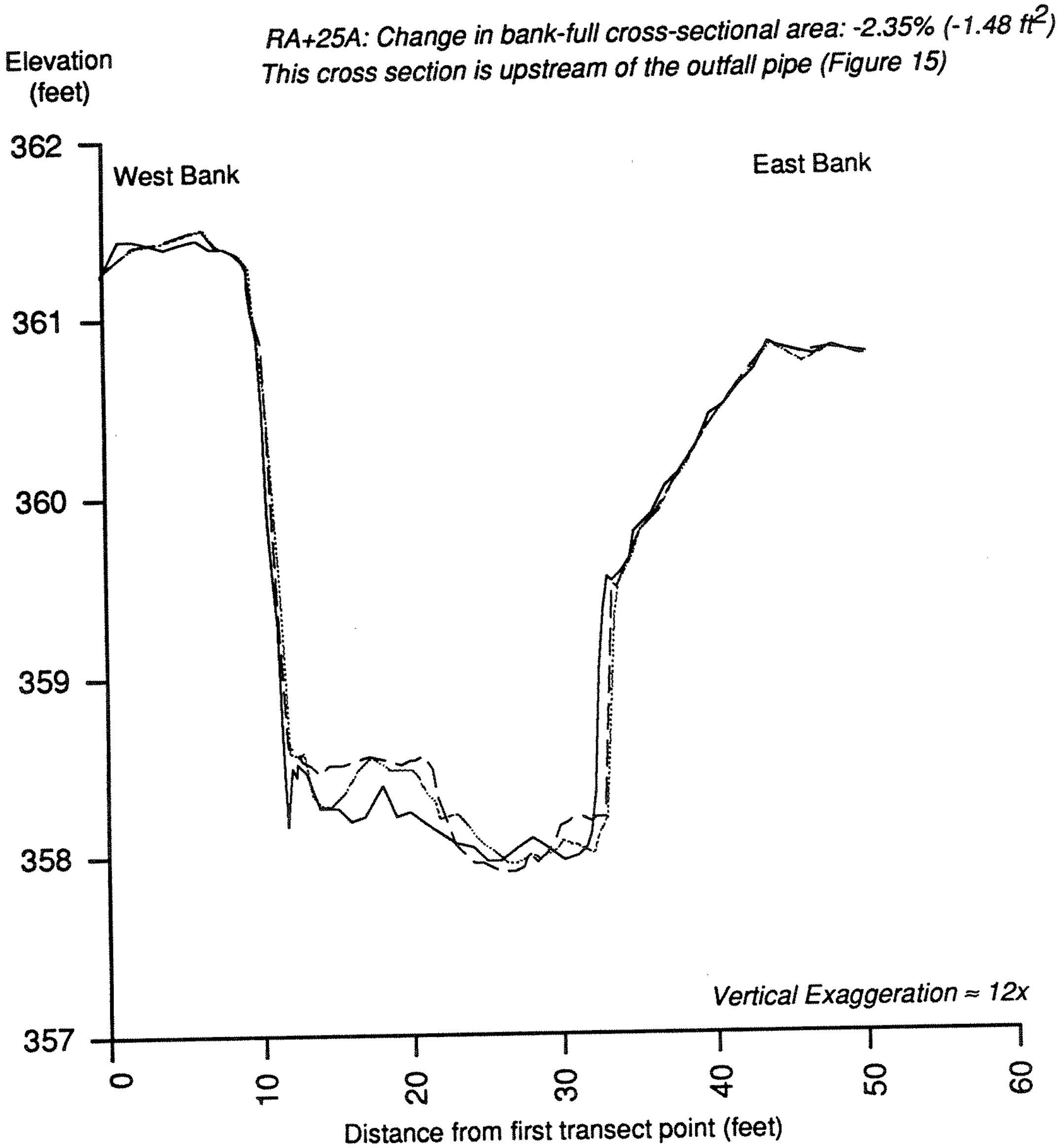


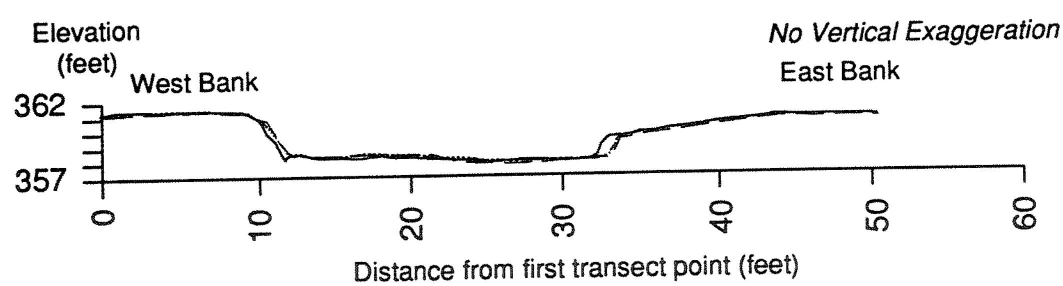
Figure 29: Plots of surveys of cross section RU Gage.



Initial survey (8/93)
4/94
Final survey (6/94)

Figure 30: Plots of surveys of cross section RA+25B.





———— Initial survey (8/93)
.... 4/94
— — — — · Final survey (6/94)

Figure 31: Plots of surveys of cross section RA+25A.

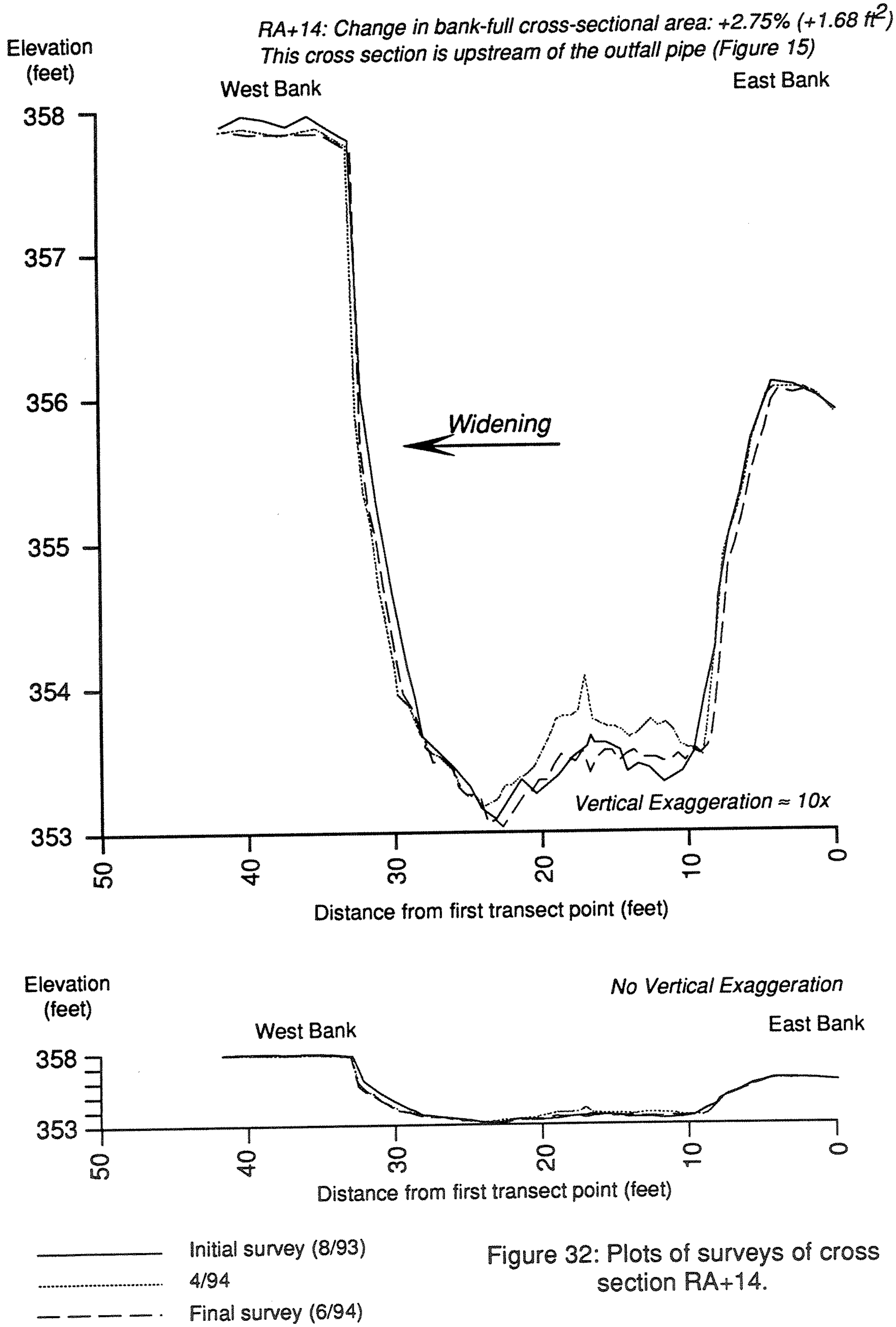


Figure 32: Plots of surveys of cross section RA+14.

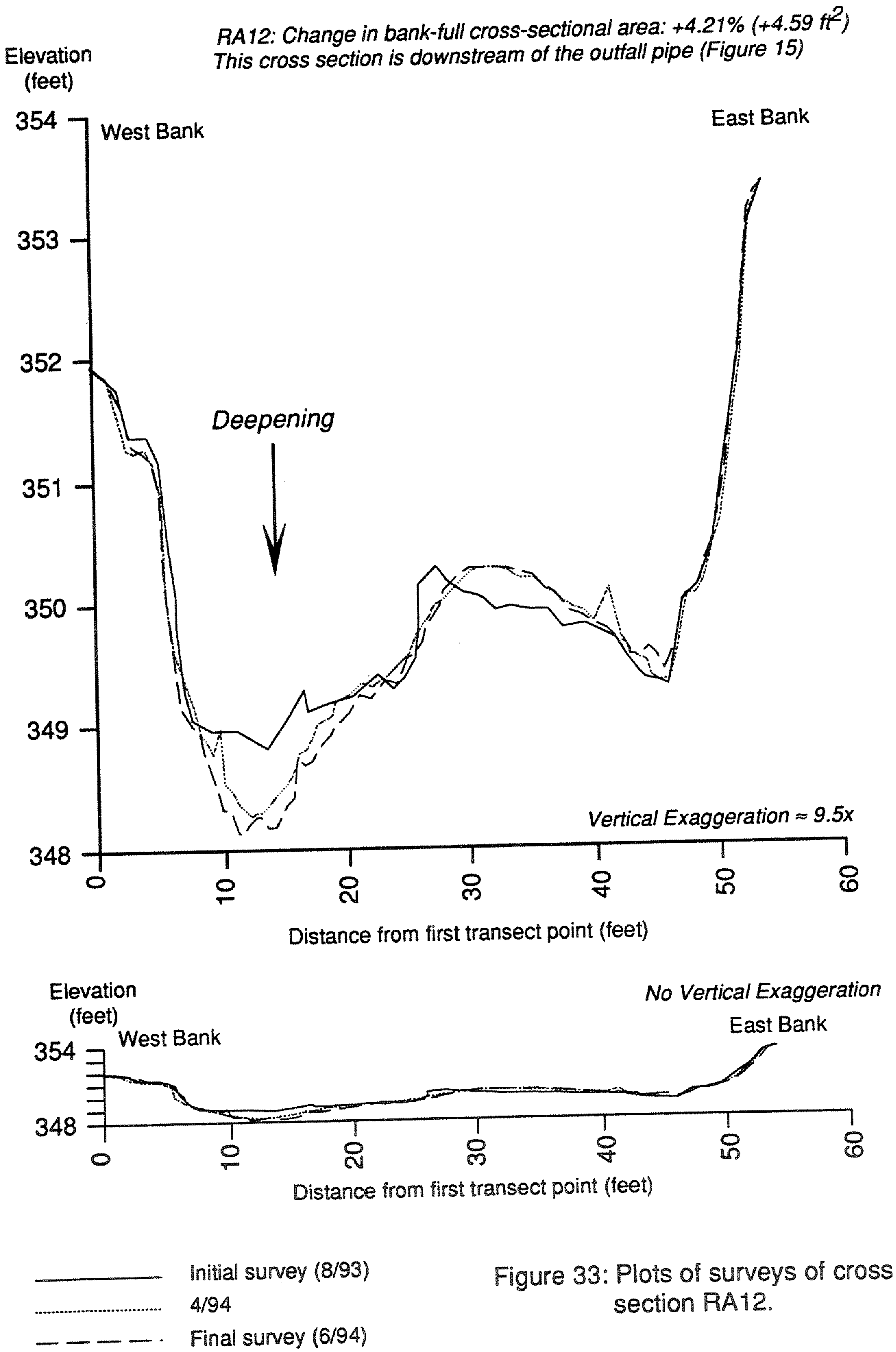
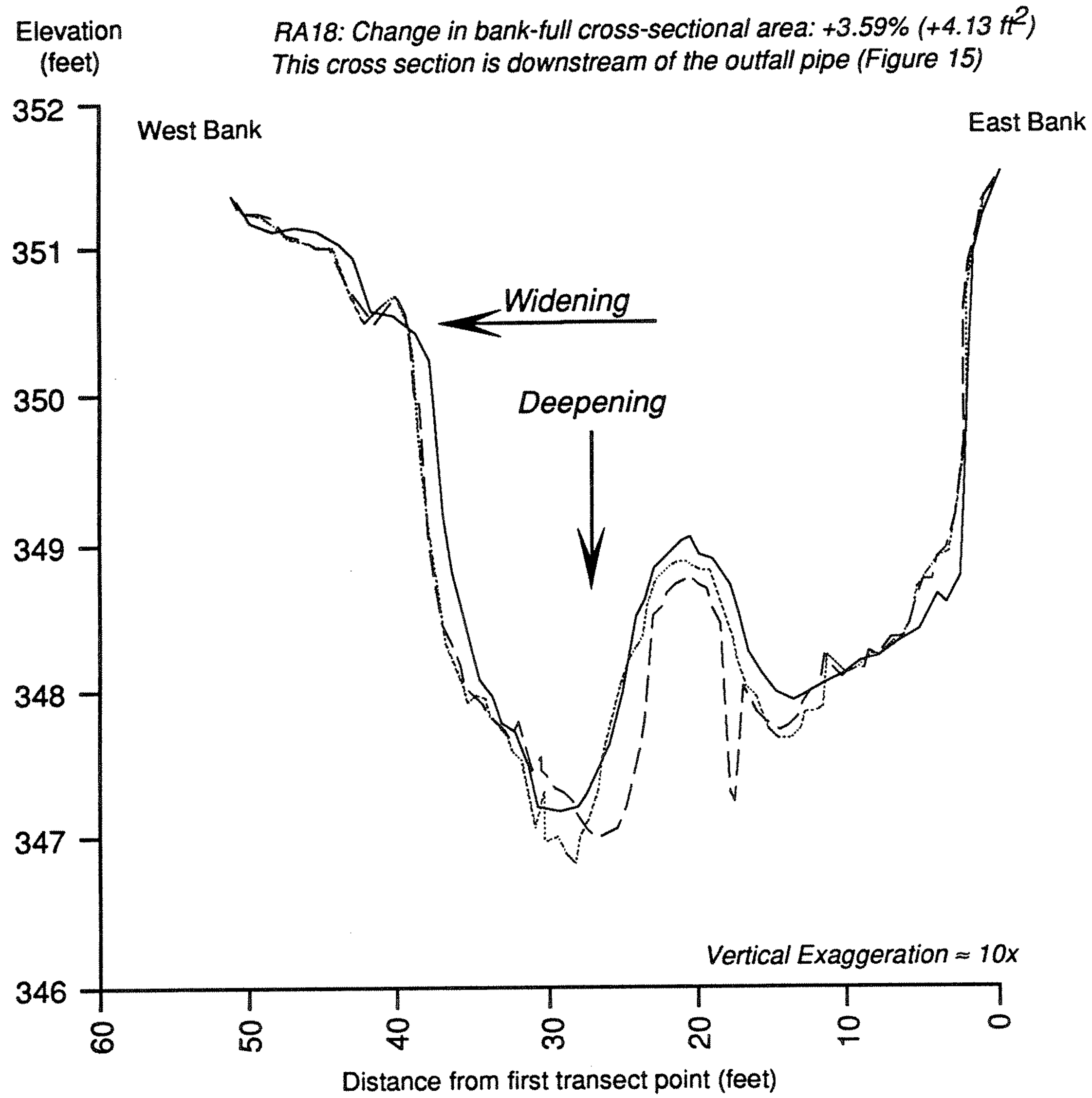


Figure 33: Plots of surveys of cross section RA12.



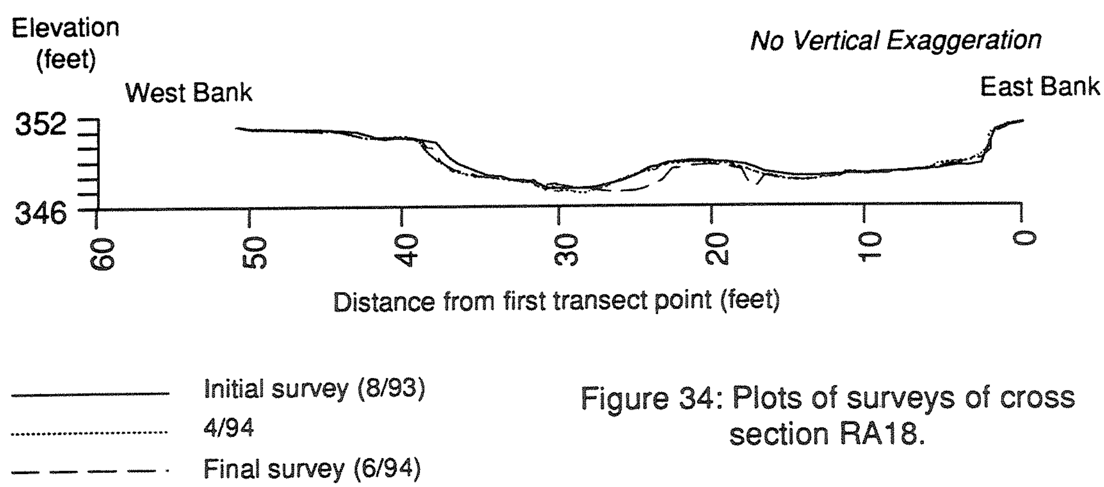


Figure 34: Plots of surveys of cross section RA18.

progressive removal of unconsolidated materials held in place by a tree which was eventually washed away. Cross-section RA33 (Figure 35) experienced erosion along the west and east banks, and on either side of the island in the middle of the channel.

In general, channel deepening can be seen in cross-sections RU Gage, RA12, RA18, and RA33 (Figs. 31, 33, 34, and 35), whereas channel widening can be seen in cross-sections RA+25B, RA+25A, RA+14, RA12, RA18, and RA33 (Figures 30-35). Note in cross-sections RA12 and RA33 (Figures 33 & 35) that the channel bed has been built up. This is likely the result of winnowing and deposition of finer grained materials during waning flood flows, such as those experienced early in December 1993 (Figure 11).

Erosion and Sedimentation Monitoring Program Data

Results of Data Analysis The complete data set from the ESMP analysis is provided in Appendix V. The amount of channel change downstream of the outfall point over the 4 1/2 years of the ESMP varies from a slight increase in channel cross-sectional area (+1.17%) at TS7A, to an increase of +44.34% at TS12A (Table 13). There is a general trend toward smaller changes (with some exceptions) with increasing distance downstream from the outfall pipe (Table 13). The average total amount of channel change downstream of the outfall point was ~ +13%. This translates to about +4%/year when averaged over the life of the diversion thus far. The cross-sectional area change of the ESMP control section (TS14) upstream of the outfall point was 22.45%.

The control section, TS14, experienced both deepening and widening during the period of the monitoring program (Figure 36). Bankfull cross-sectional area increased by 22.45% (uncorrected = +17.91%). This apparently substantial amount of erosion (compared to the rest of the transects, with the exception of TS12A) will be addressed later in this thesis. The need for a final correction value can be seen on the east bank of the transect (Figure 36).

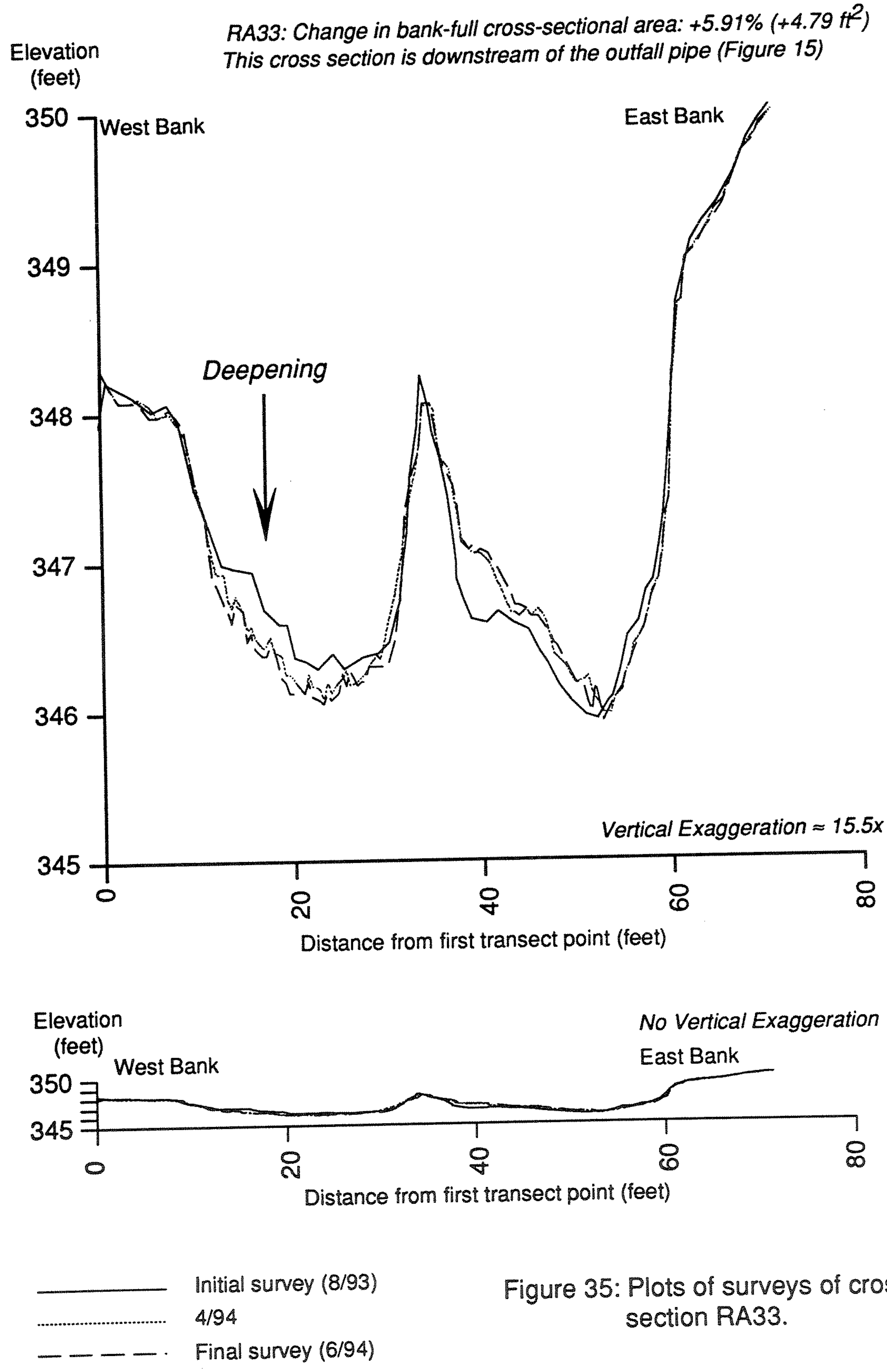


Figure 35: Plots of surveys of cross section RA33.

Table 13: Summary of results of ESMP data analysis.

Date	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	Control (TS14)	Average
Pre-op (7/89)	0	0	0	0	0	0	0	0	0	0
Aug-89	5.62	7.07	1.21	-.64	-.02	-.62	1.02	2.41	5.01	2.34
Sep-89	3.86	8.31	-.65	.33	.02	2.00	-.89	3.59	3.46	2.23
Sep-89	-.13	5.37	3.73	-2.24	-1.73	3.60	3.29	2.39	-.85	1.49
Oct-89	-1.51	2.79	.20	-3.75	-1.63	-1.50	4.57	-21.55	.87	-2.39
Nov-89	1.32	5.72	2.84	-1.10	-3.22	2.87	9.94	-8.90	13.97	2.60
Jan-90	2.39	2.52	1.58	1.38	4.33	31.68	6.89	-14.37	-1.22	3.91
Feb-90	2.58	4.20	2.98	-3.08	5.94	30.60	10.05	-14.37	8.23	5.24
Feb-90	2.46	4.16	1.27	-5.37	4.82	29.14	4.84	-17.97	13.16	4.06
Mar-90	-.16	2.96	3.37	-1.18	7.65	29.58	.48	-13.74	11.83	4.53
May-90	.64	3.32	.89	-1.14	4.86	28.52	5.92	-17.22	13.58	4.38
May-90	2.97		-.60	3.33	7.98	29.82	7.79	-12.53	13.33	6.51
Jun-90	2.07	5.74	3.22	1.24	6.33	32.78	6.87	-8.18	10.25	6.70
Aug-90	1.21	.59	2.68	-1.27	5.85	33.58	7.29	-19.32	10.56	4.57
Sep-90	2.70	4.31	4.89	-3.75	7.69	35.71	9.12	-12.72	16.58	7.17
Oct-90	3.83	1.98	1.74	-3.63	4.32	33.30	3.53	-10.76	12.29	5.18
Dec-90	8.39	4.30	4.12	2.62	5.34	32.56	4.47	-13.67	13.97	6.90
Mar-91	6.64	6.33	5.03	-2.12	6.32	31.17	2.92	-12.33	13.58	6.39
Jun-91	7.23	9.87	5.30	1.93	7.08	35.42	6.20	-12.98	13.74	8.20
Sep-91	9.10	7.18	6.22	5.87	10.10	44.39	10.45	-6.89	15.24	11.30
Dec-91	10.67	10.56	6.26	4.04	9.50	39.42	7.30	-6.24	16.41	10.88
Mar-92	8.74	8.38	4.94	1.79	9.91	36.90	6.09	-6.58	18.95	9.90
Jun-92	8.88	8.50	5.55	1.63	11.32	37.45	7.12	-4.83	19.12	10.53
Aug-92	10.15	8.65	5.40	5.75	12.74	43.08	9.50	-7.07	20.41	12.07
Nov-92	8.92	6.47	5.05	3.55	10.70	38.14	9.19	-5.97	18.00	10.45
Dec-92	10.13	7.38	5.91	-.79	12.46	37.63	6.60	-7.28	17.47	9.95
Apr-93	14.71	7.47	4.45	.27	11.66	39.11	10.72	-8.29	24.00	11.57
Aug-93	16.13	9.61	2.17	1.14	13.39	38.91	10.76	-5.14	21.37	12.04
Dec-93	16.18	8.62	7.41	-1.66	11.22	38.95	11.31	-.33	17.98	12.19
Dec-93	**14.25**	**9.15**	**5.92**	**-1.41**	**10.65**	**41.34**	**11.25**	**-2.55**	**17.91**	**11.83**
Corrected 12/93	***10.04***	***3.53***	***5.93***	***10.32***	***10.65***	***44.24***	***11.25***	***5.94***	***22.45***	***13.29***

All values are percentage increase (+) or decrease (-) in cross-sectional area since original (pre-op) survey.
See Figure 15 for transect locations

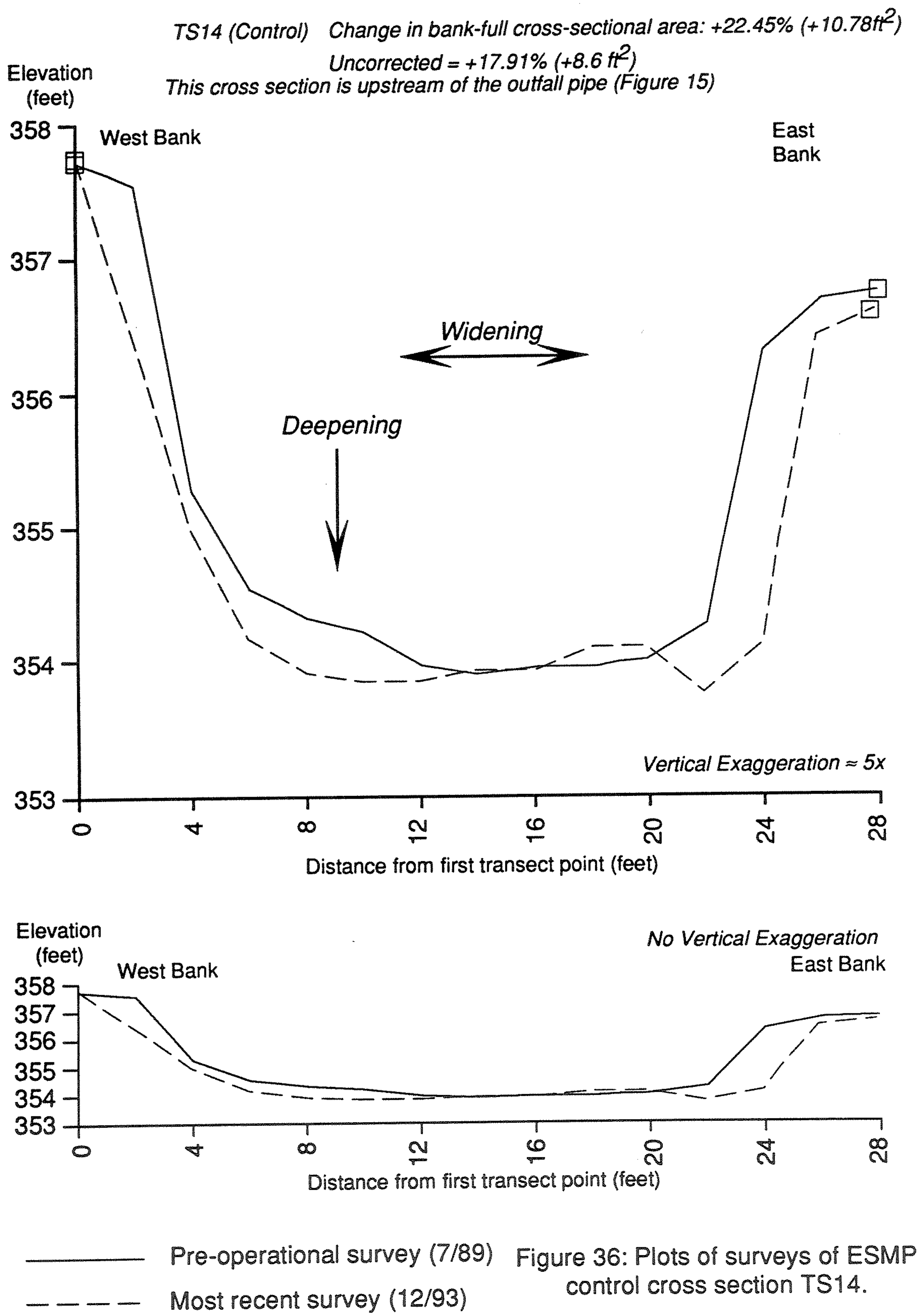


Figure 36: Plots of surveys of ESMP control cross section TS14.

TS13B (Figure 37) experienced an increase of bankfull cross-sectional area of 5.94%. The need for a correction for this transect is evident on the west bank of the section (Figure 37). Channel deepening is responsible for the increase in channel area. TS13A (Figure 38) also experienced deepening, but experienced widening and flood plain loss as well. Bankfull cross-sectional area increased by 11.25%. A correction was unnecessary for this transect. Both TS13B and TS13A are located along straight reaches of the channel (Figure 15), which accounts for the even distribution of change (TS13A, Figure 38) or lack thereof (TS13B, Figure 37) along the channel banks.

TS12A both widened and deepened (Figure 39), and experienced the most dramatic change of all of the ESMP transects (+44.24%). Substantial erosion occurred only on the west bank and its adjacent flood plain (Figure 39). The effect of the correction factor for this section was minimal (Figure 39). The channel is very deep at this point (4 ft, Figure 39), with steep sides. Diversion flows are only 2 ft deep, which correlates with the areas of erosion within the main channel (Figure 39). Floodplain modification (Figure 39) is likely a result of flows with high velocities during overbank events. The west bank at this section is the point bar of a very tight meander bend (Figure 23), directly in the path of oncoming flows from the straight reach directly upstream (Figure 23).

Channel modification at TS12 was limited primarily to deepening on the west side of the channel (Figure 40), with some deposition on the east side. TS12 is located on a gentle meander bend (Figure 15), the cutbank of which is on the east bank (Figures 15, 40). The channel is divided here by a small island (Figure 23), which experienced some deposition (Figure 40). Channel area increased by +10.65%. No correction was necessary. TS9 experienced a similar amount of change (+10.32%, Figure 41), in the form of channel deepening. This transect is located along a fairly straight reach of the channel (Figure 15). The need for a correction to the final change value of TS9 is can be seen on the east bank of the section (Figure 41).

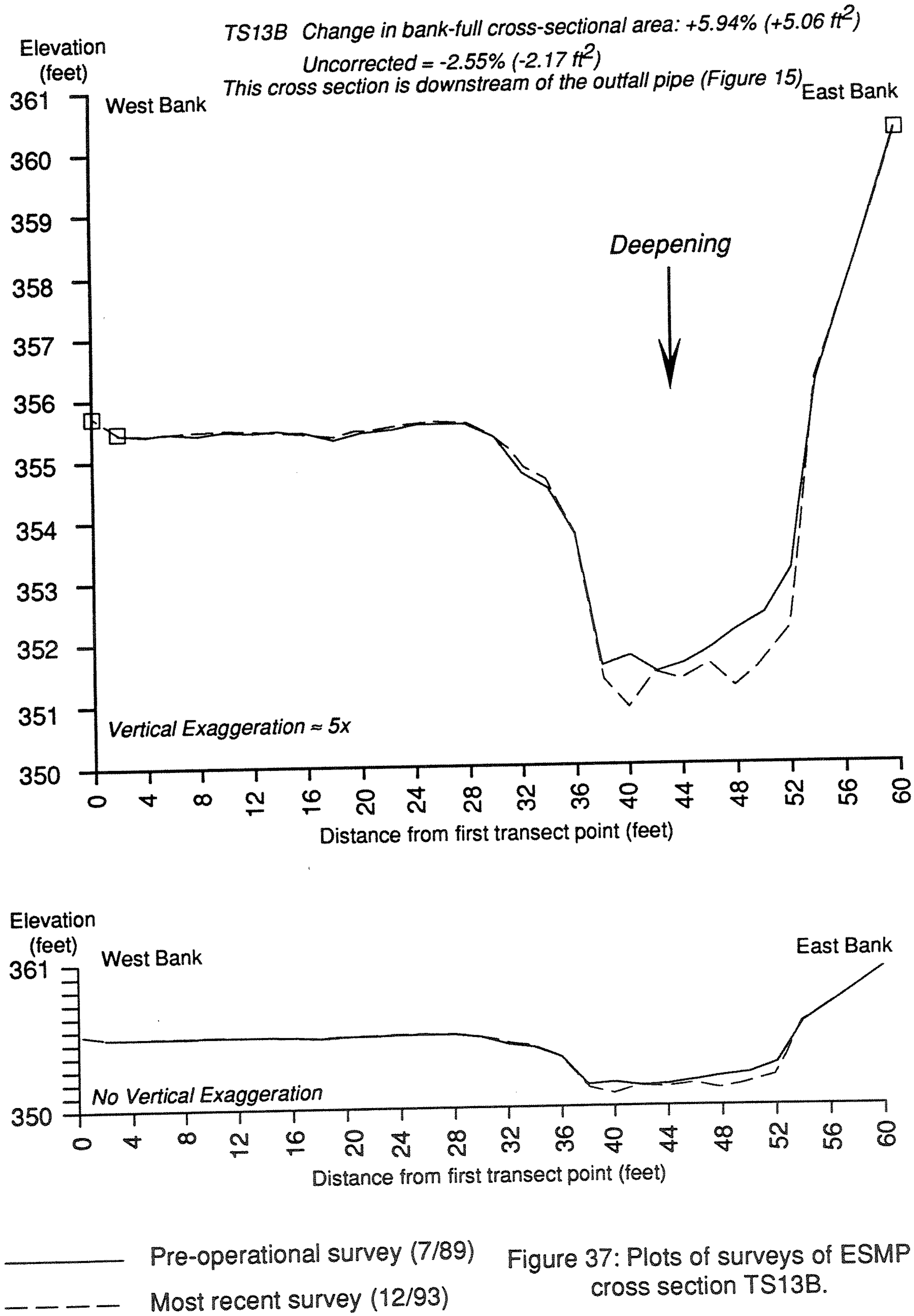


Figure 37: Plots of surveys of ESMP cross section TS13B.

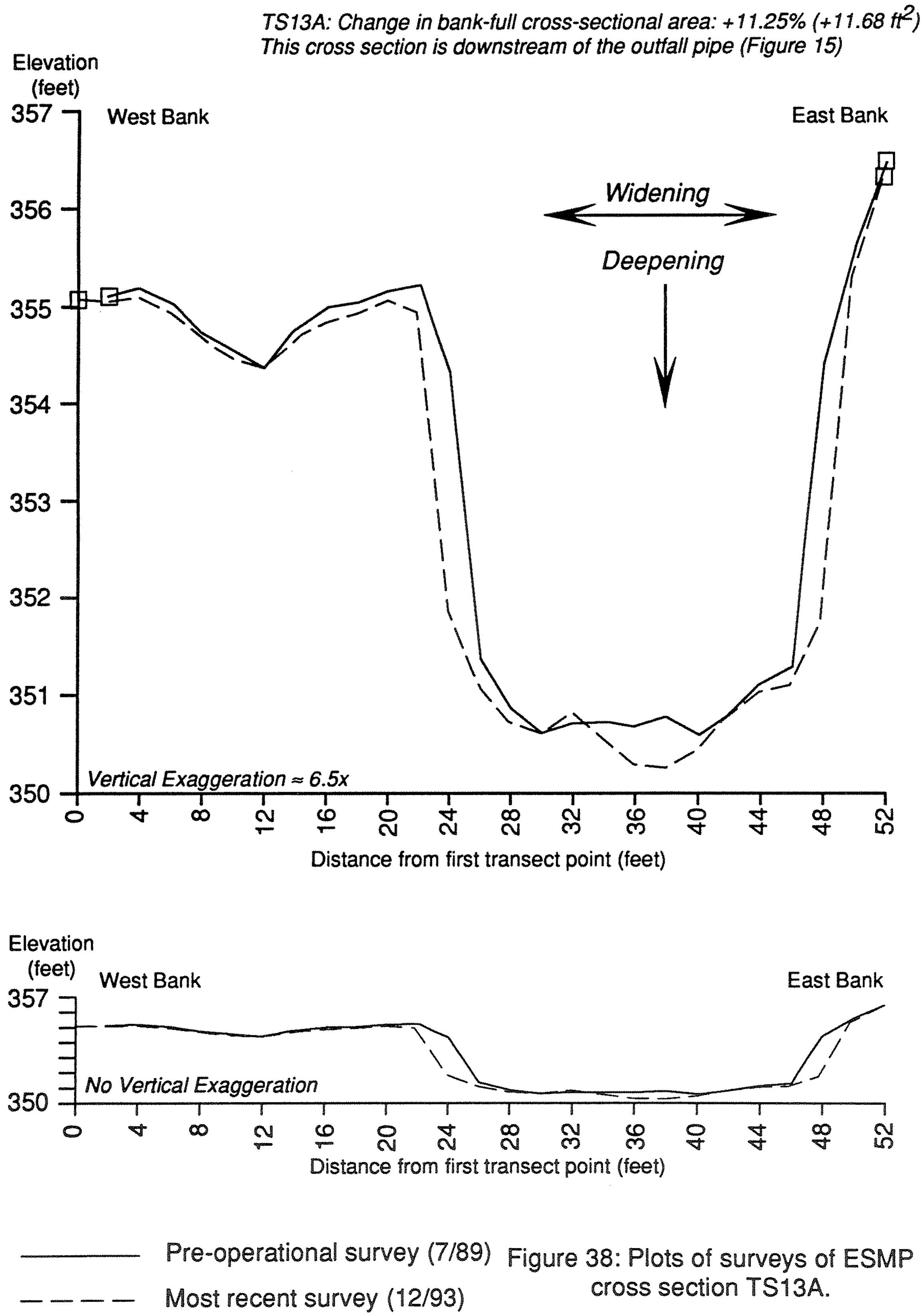
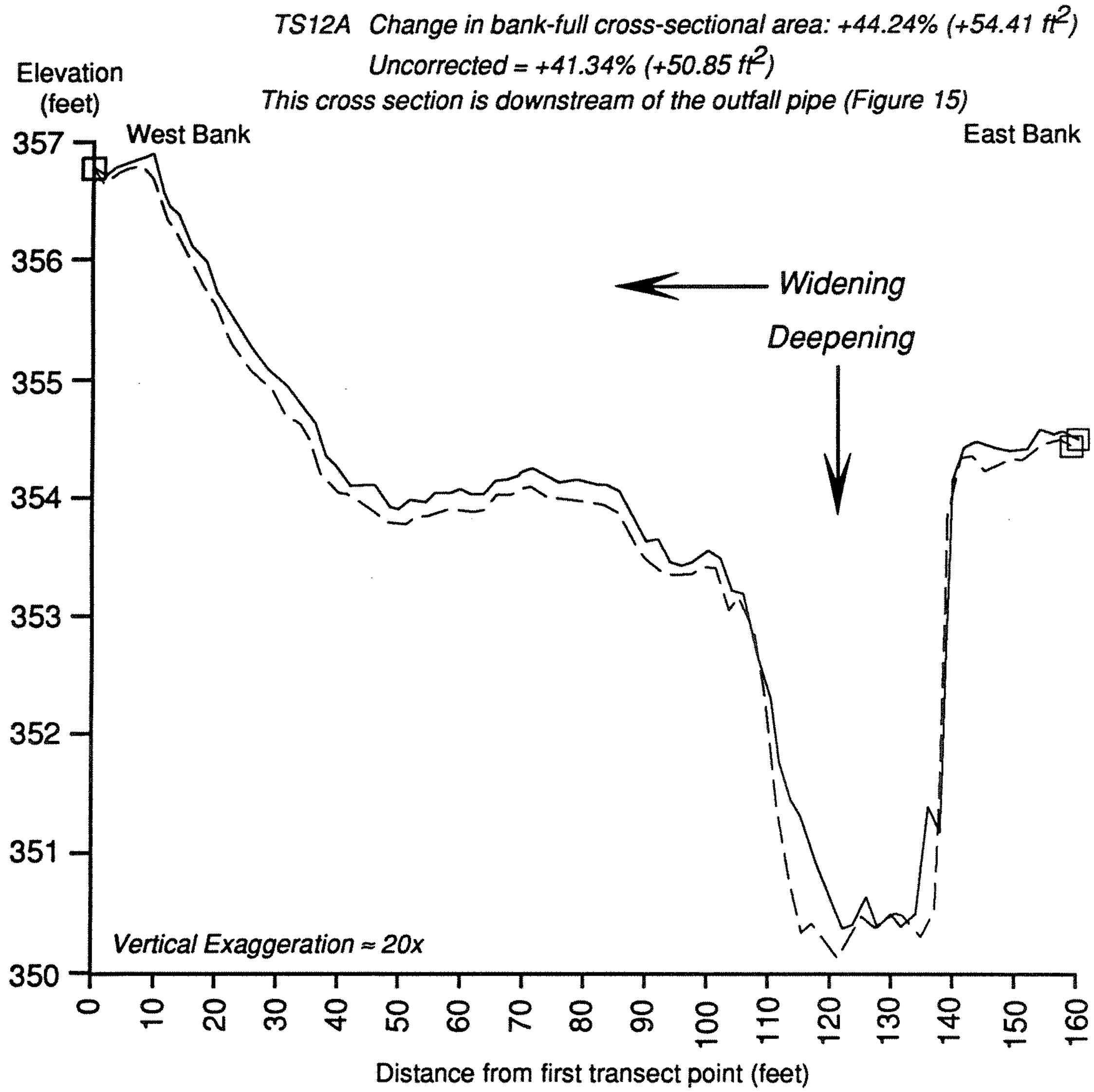


Figure 38: Plots of surveys of ESMP cross section TS13A.



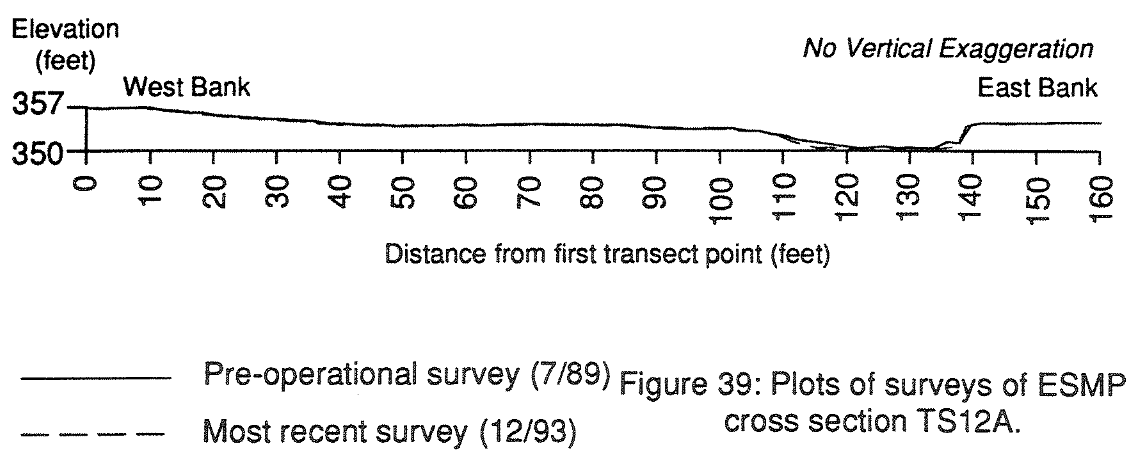
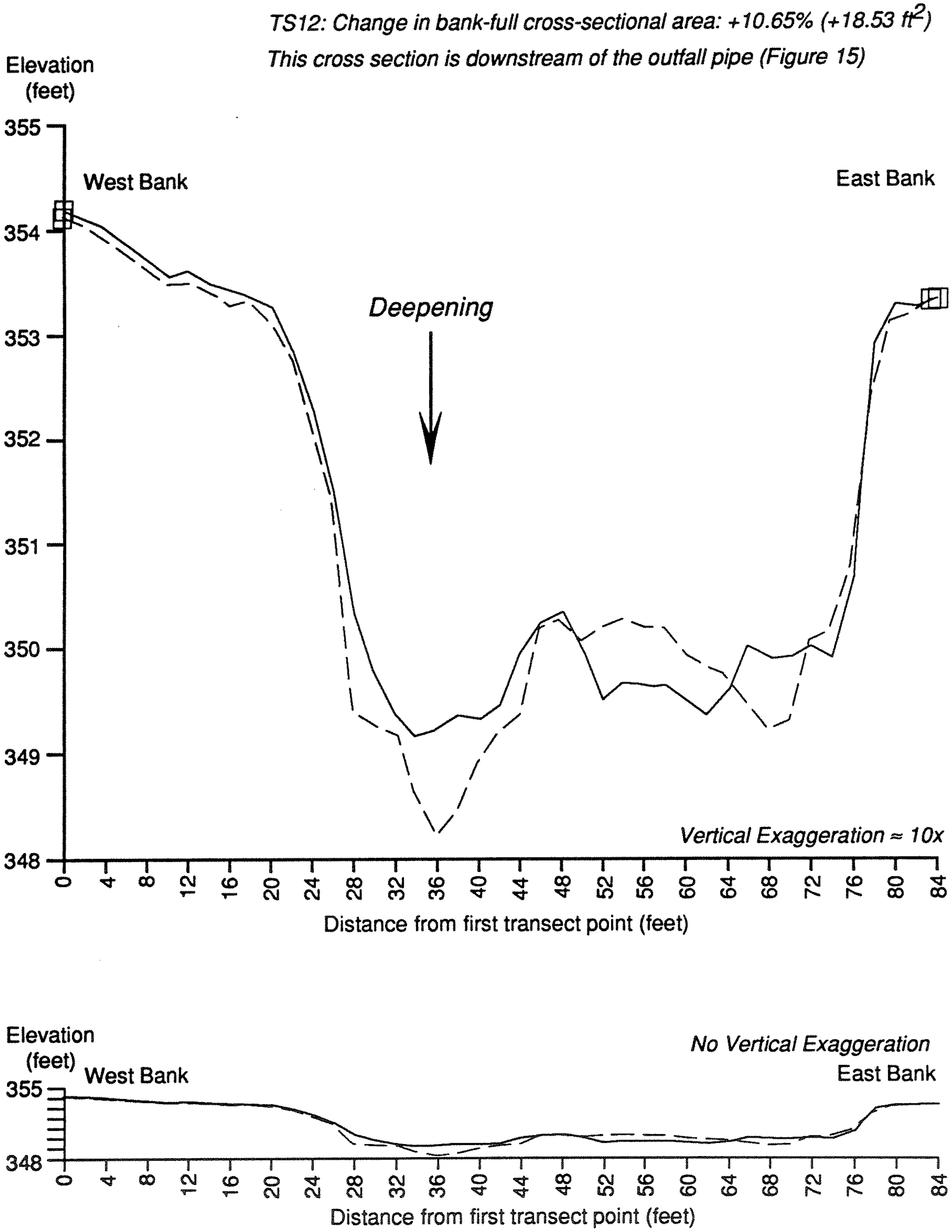


Figure 39: Plots of surveys of ESMP cross section TS12A.



Pre-operational survey (7/89)

Most recent survey (12/93)

Figure 40: Plots of surveys of ESMP cross section TS12.

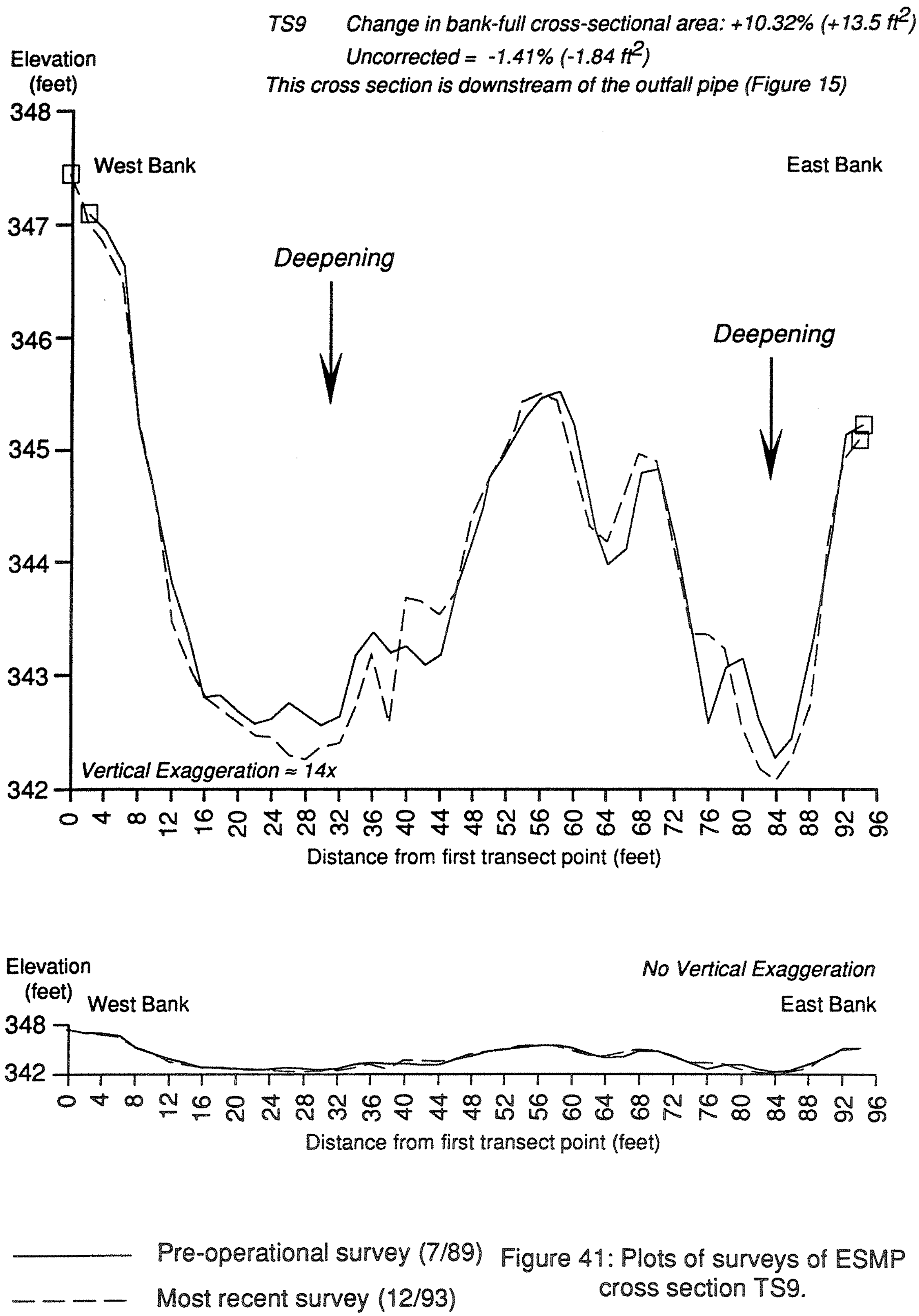


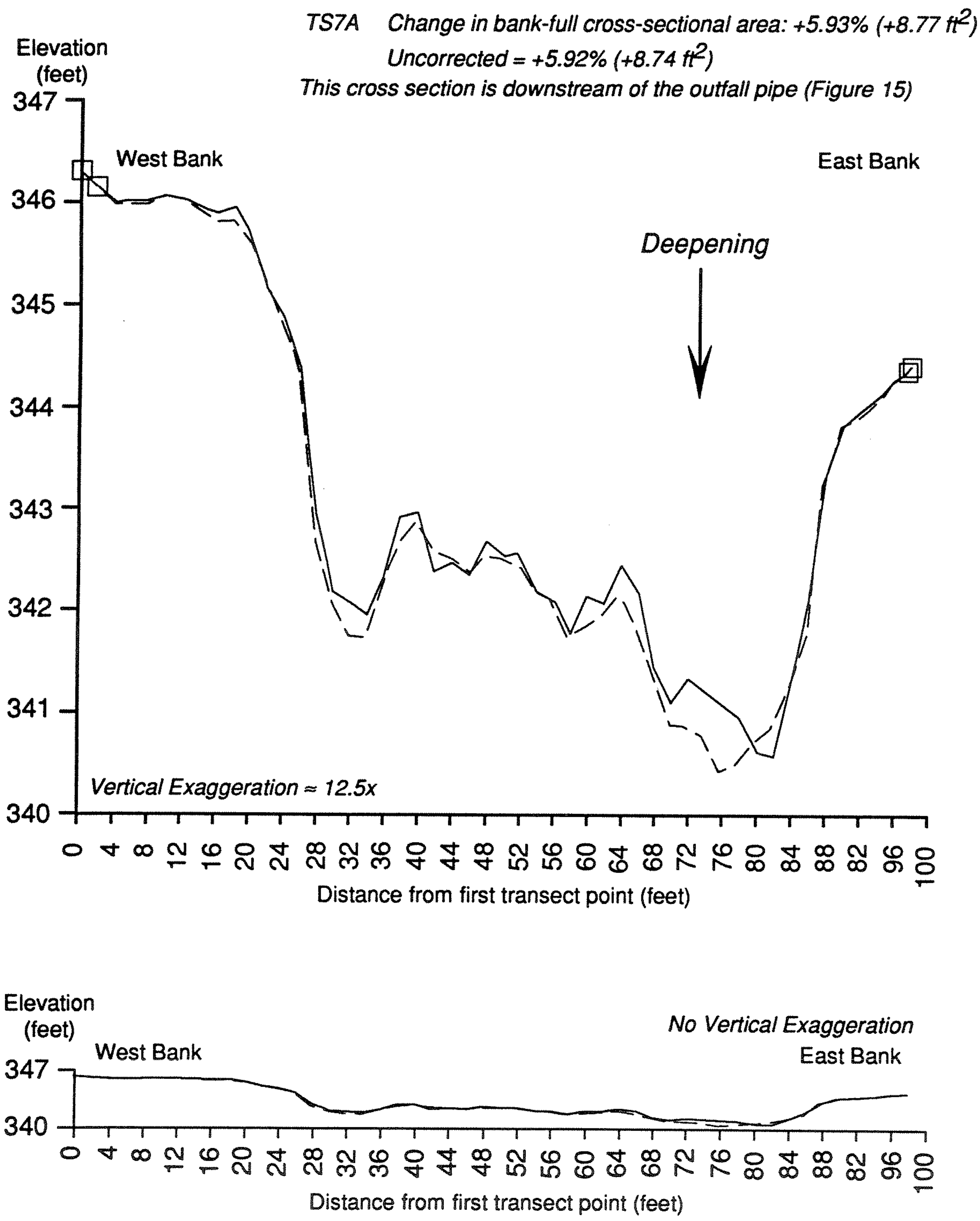
Figure 41: Plots of surveys of ESMP cross section TS9.

The correction factor for TS7A had virtually no effect. Change in bankfull cross-sectional area was +5.93%. Again, channel modification was restricted to deepening (Figure 42). The area of the most erosion in Figure 42 corresponds with the cutbank (east bank) of the meander bend that TS9 is located on (Figure 15). TS4 (Figure 43) also experienced a limited amount of channel change (+3.53%), with minor deepening on the west side of the channel, and some deposition along the east side of the channel. TS4 appears to be along a fairly straight reach of the channel (Figure 15).

The bankfull cross-sectional area of TS3 changed by +10.04%, with significant widening along the west bank (Figure 44) and significant deepening along the east side of the channel, balanced by deposition in the center of the channel and along the east bank. TS3 appears to be along a fairly straight reach of the channel (Figure 15), just downstream of TS4. The west bank was progressively undercut in 1991 and 1992, and then collapsed after a high flow event in early 1993, perhaps the result of rotational slump during rapid drawdown of stream levels after a storm, since a low area adjacent to the collapsed bank appears to have been filled in (Figure 44).

Examination of the cross-sections presented in Figures 36-44 reveals that channel modification has been primarily in the form of deepening (all transects experienced deepening). Cross-sections TS14, TS13A, and TS3 appear to have experienced significant erosion according to the standards set by the ESMP (a change of more than 0.75 ft in overall channel depth, or of more that 1.5 ft in overall channel width, PECo (1989)). Part of this erosion probably includes the flushing fines discussed earlier. No channel stabilization means have been put into place, however.

The ESMP Control Section The apparently large amount of change (22.45%) in the control section may be the result of lower width:depth ratio than the other ESMP cross-sections. TS14 has the lowest width:depth ratio (8.37) of all of the ESMP sections (Table 7), as well as the smallest bankfull cross-sectional area.



——— Pre-operational survey (7/89)

– – – – Most recent survey (12/93)

Figure 42: Plots of surveys of ESMP cross section TS7A.

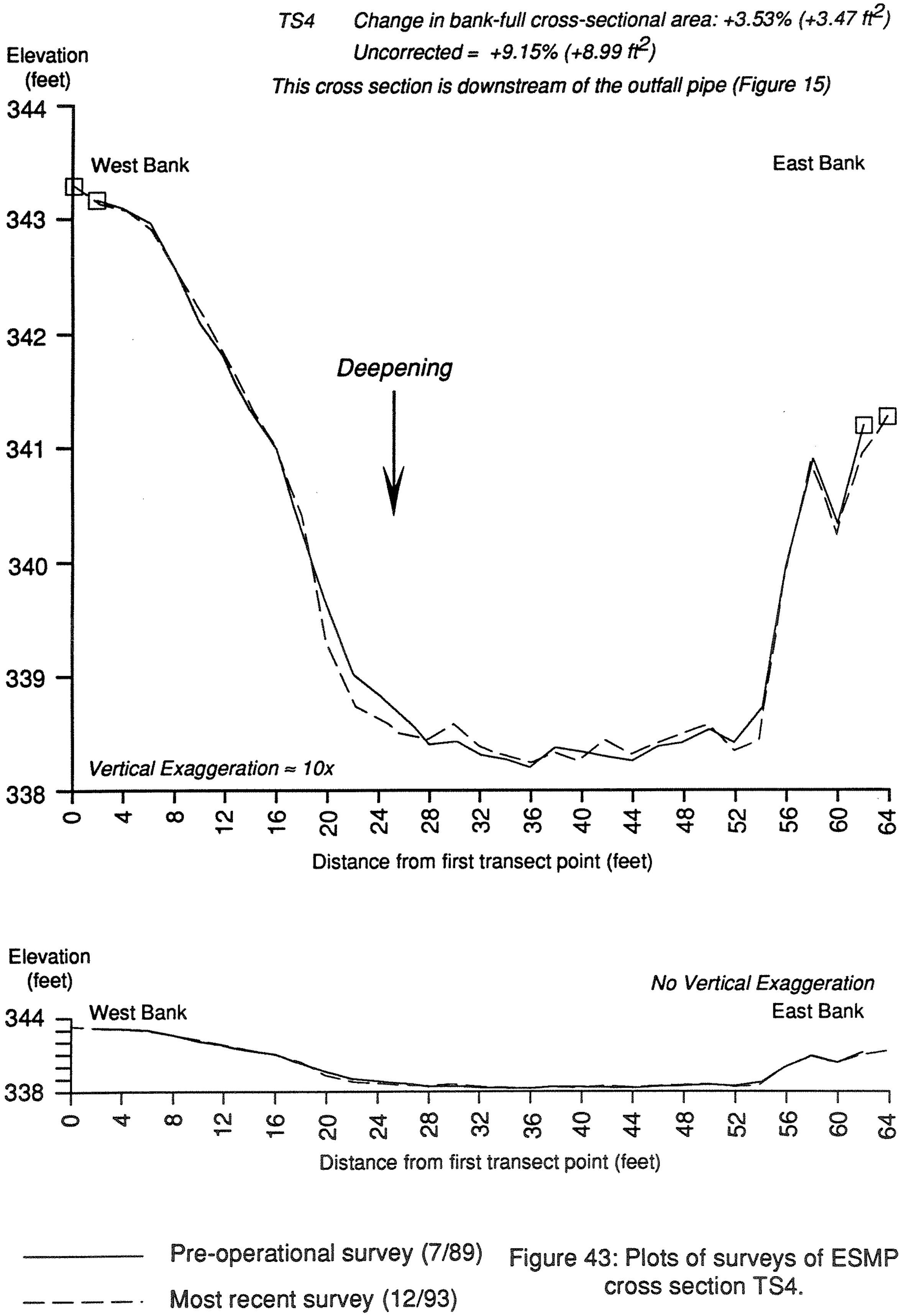
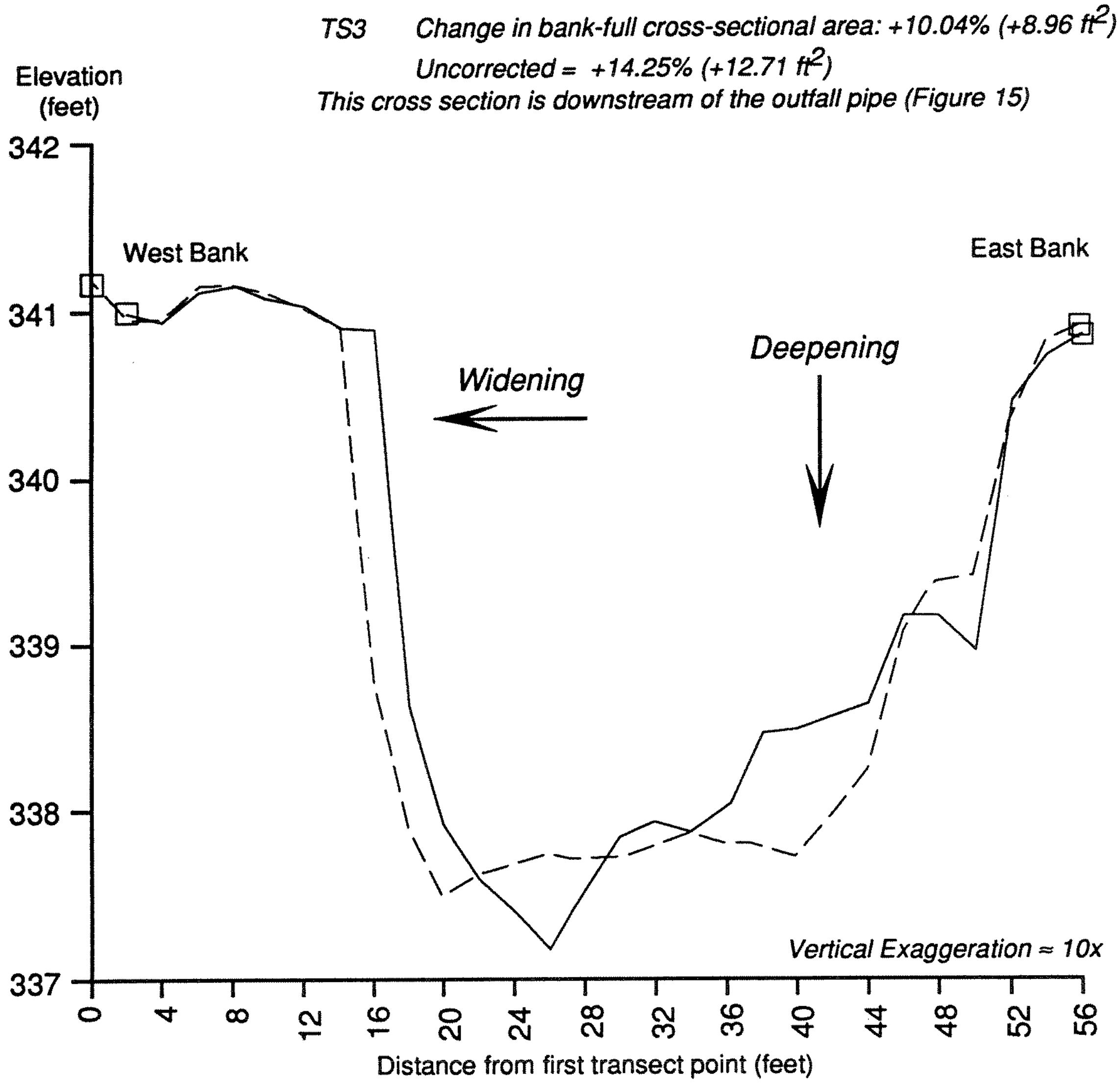


Figure 43: Plots of surveys of ESMP cross section TS4.



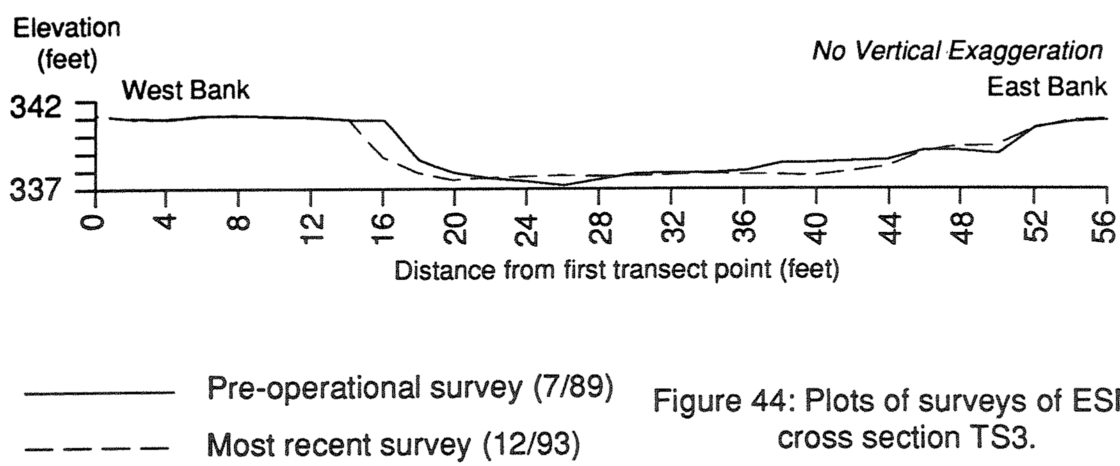


Figure 44: Plots of surveys of ESMP cross section TS3.

ESMP sections with a higher width:depth ratio are wider (Table 7), and thus have a greater proportion of bedrock and armor. Hence the control section is morphologically unlike the downstream sections. The ESMP sections with higher width:depth ratios also happen to have larger cross-sectional areas (Table 7), making a given amount of change in the control section appear to be greater than in the other sections. If one calculates the amount of cross-sectional area lost over the period of the ESMP (Table 13), the control section lost 8.6 ft^2, which is less than the overall average total loss of 13.5 ft^2, and closer to the loss of those sections with an average (11%) total amount of increase in channel cross-sectional area. The *actual* amount of change in the control section (which seems higher than it should be) is discussed below.

The amount of change (+22.45%) seen in the control section (TS14) upstream of the outfall pipe is consistent with larger storm flows being associated with significant channel modification, since the control section does not have sustained flow to flush loose materials free. This, however, creates a problem: It is unreasonable to suggest that a third order bedrock-influenced stream with fairly coherent bank materials will increase in cross-sectional area by nearly 20% every 5 years. This implies that the channel would double in size in just 25 years, which is not realistic, even for purely alluvial systems. In addition to the mathematical reasons addressed above, the key to this problem may lie in the location of the control section.

The control cross-section is located approximately 200 ft upstream of the outfall pipe, on a meander bend (Figures 15, 17) where the thalweg abruptly shifts. The bend appears to be rapidly eroding when compared to other reaches of the stream. Water backs up close to this point during the summer months, causing the banks to be more saturated than they would be normally. However, they are not completely saturated like the banks downstream of the outfall point (which are of similar composition) because the water level is not high enough to completely saturate them. Rather, the banks are just moist and loose. Recall that coherent fine-grained saturated (Gordon *et al.*, 1992) or brick-hard materials are more resistant to entrainment than loose, fine-grained materials. Thus, at high discharges (storm flows), these banks may be prone to entrainment. After the storm has passed, they are prone to slumping as water levels drop after storm events (since water levels are not continuously high). The comparative hydrograph presented in Figure 17 illustrates this point by comparing a pre-diversion storm hydrograph with one from the diversion period. The high, steep banks at the control section (Figure 36) probably amplify this problem since banks with high face angles are inherently unstable.

Figure 36 shows that the foci of change in the control section are the banks. Surveys of the control section from July 1989 (pre-operational survey), January 1990, and March 1991 are presented in Figure 45. It is apparent that the banks failed, filling in the channel bottom. With time, storm flows flushed the excess loose materials from the channel. The banks here are very high and steep (unlike much of the rest of the stream), such that the failure of a lower portion of the bank (perhaps saturated due to back-up of flow) will cause the collapse of the material above it, further increasing the calculated amount of channel cross-sectional area increase.

The problems associated with the control section of the ESMP that have been discussed here suggest that perhaps this was not an ideal location for a control cross-section. In addition, there are several reaches upstream of the control section (e.g. the two reaches below RA+25A, Figure 15) that are likely to be less affected by diversion flows and morphologically similar to the areas of concern (downstream of the outfall pipe). For example, cross-section RA+25A is far enough upstream of the outfall point to be unaffected by diversion flows. The slight amount of change (-1.43%) seen in cross-section RA+25A is probably an adjustment to a system in dynamic equilibrium.

Material Loss Approximately 72,995 ft^3 (2,150 m^3) of material has been lost over the last 4.5 years, which is approximately 3,720 tons (3,780 metric tonnes). This translates to about 825 tons (838 metric tonnes) per year thus far. Converting metric tonnes

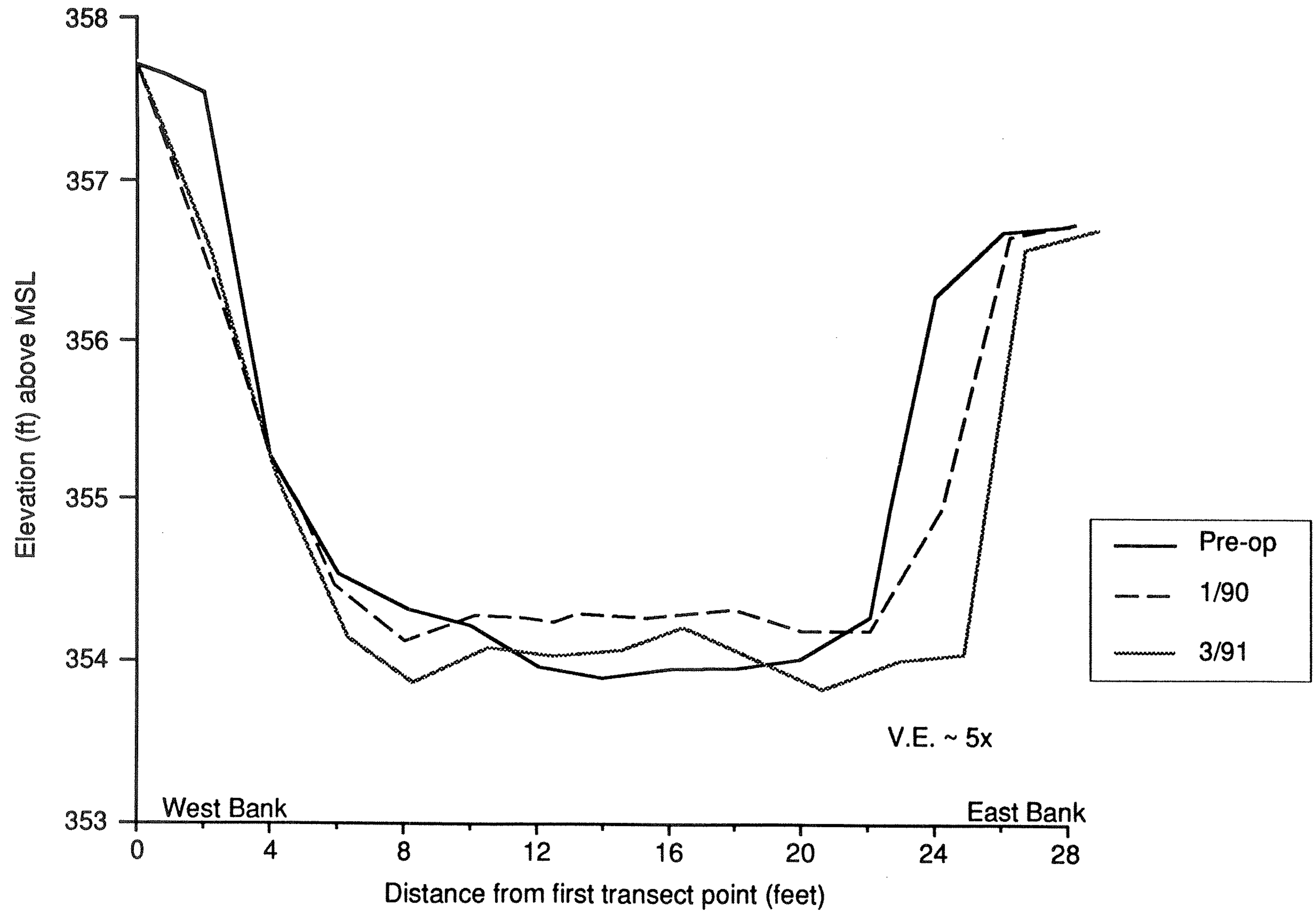


Figure 45: Progressive erosion of the ESMP control section (TS14).

to g and dividing by the average yearly diversion (~20,000 acre ft (6,518,000,000 gallons), which is about 24,672,585,400 l) gives an average suspended load of ~0.034 g/l. Downstream of the outfall pipe, suspended loads during diversion flows were measured as 0.01 g/l, during storm flows 0.02 g/l (Table 6). By performing the above calculation for only that portion of the channel upstream of the area where suspended load was measured, an average suspended load of ~.03 g/l is obtained. This value is consistent with the suspended load measured in the field. Hence the estimate of volume and mass of material lost over the life of the diversion thus far may be considered reasonable.

CHANNEL CHANGE WITH TIME

Figure 46 is a plot of channel bankfull cross-sectional area and discharge against time (survey dates are labeled). Channel adjustment (uncorrected) was greatest during the phased start-up (Phase I & II Testing) of the transfer, and then leveled off when normal pumping operations began. Channel adjustment (uncorrected) in response to varying testing conditions is evident (e.g. November-December 1989). The control section was less affected by the testing period. Channel response to storms is also apparent (e.g. 6/90, 12/90, & 12/92). Though erratic, changes in cross-sectional area during the phased start-up of the diversion appear to level off after the diversion was fully operational, with significant changes in cross-sectional area often being associated with major storm events ($Q > \approx 250$ cfs) (Figure 46).

Minor amounts of channel change (± 1- 2 %) are probably easily induced by having a slab of mudstone that is not oriented in the hydrodynamically efficient position (dipping upstream) being flipped over, exposing finer-grained materials it was protecting from entrainment. Because of the flashy nature of the drainage basin and the apparently resistant nature of the stream channel, large storm flows may be those responsible for major channel modification (>8%). Diversion flows appear to have less of an effect on channel cross-sectional area, perhaps a result of their lesser magnitude ($Q \approx 65$ cfs) compared to storm

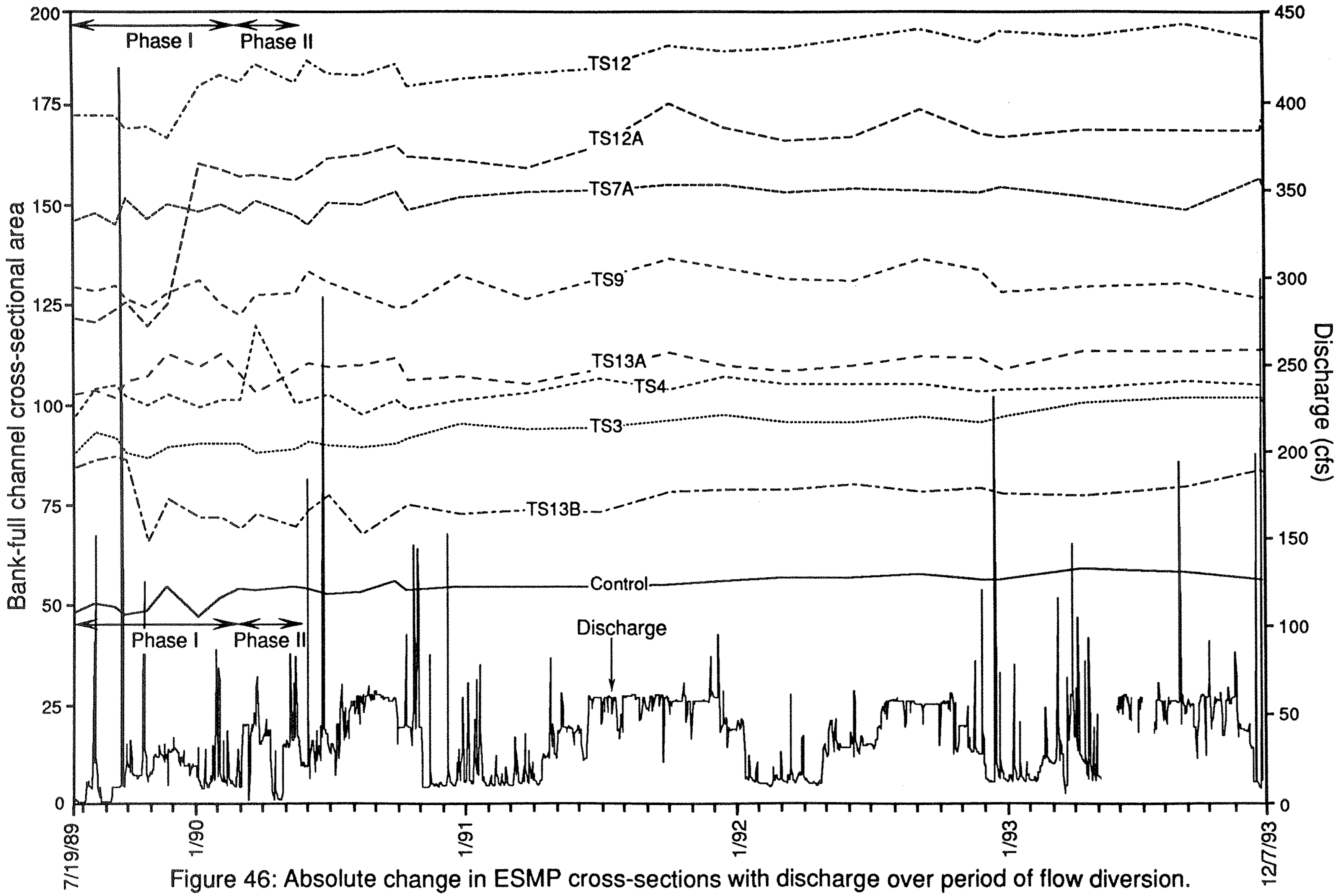


Figure 46: Absolute change in ESMP cross-sections with discharge over period of flow diversion.

flows. Diversion flows also are much more regular than start-up flows, which may also be conducive to channel stability (e.g. continuous saturation).

Plotting channel change (uncorrected) as a percentage increase (+) or decrease (-) in bankfull cross-sectional area accentuates (but reflects accurately) relative changes, especially during Phase I & II testing (Figure 47). The channel appears to have become more stable after the beginning of normal operations, with the average total amount of change (uncorrected) being ~ +11% over a four year period. Plotting average total percentage increase or decrease (uncorrected) in bankfull cross-sectional area and discharge against time (Figure 48) however, reveals a fairly steady overall increase in bankfull cross-sectional area, with a less prevalent leveling-off after mid-1991.

This curve looks very much like the dynamic equilibrium curve in Figure 14B, with system adjustment clustering around a central mean, which is tending towards an asymptote. The 130 cfs line represents bankfull conditions. Note that channel change is associated with events where discharge crossed over this line.

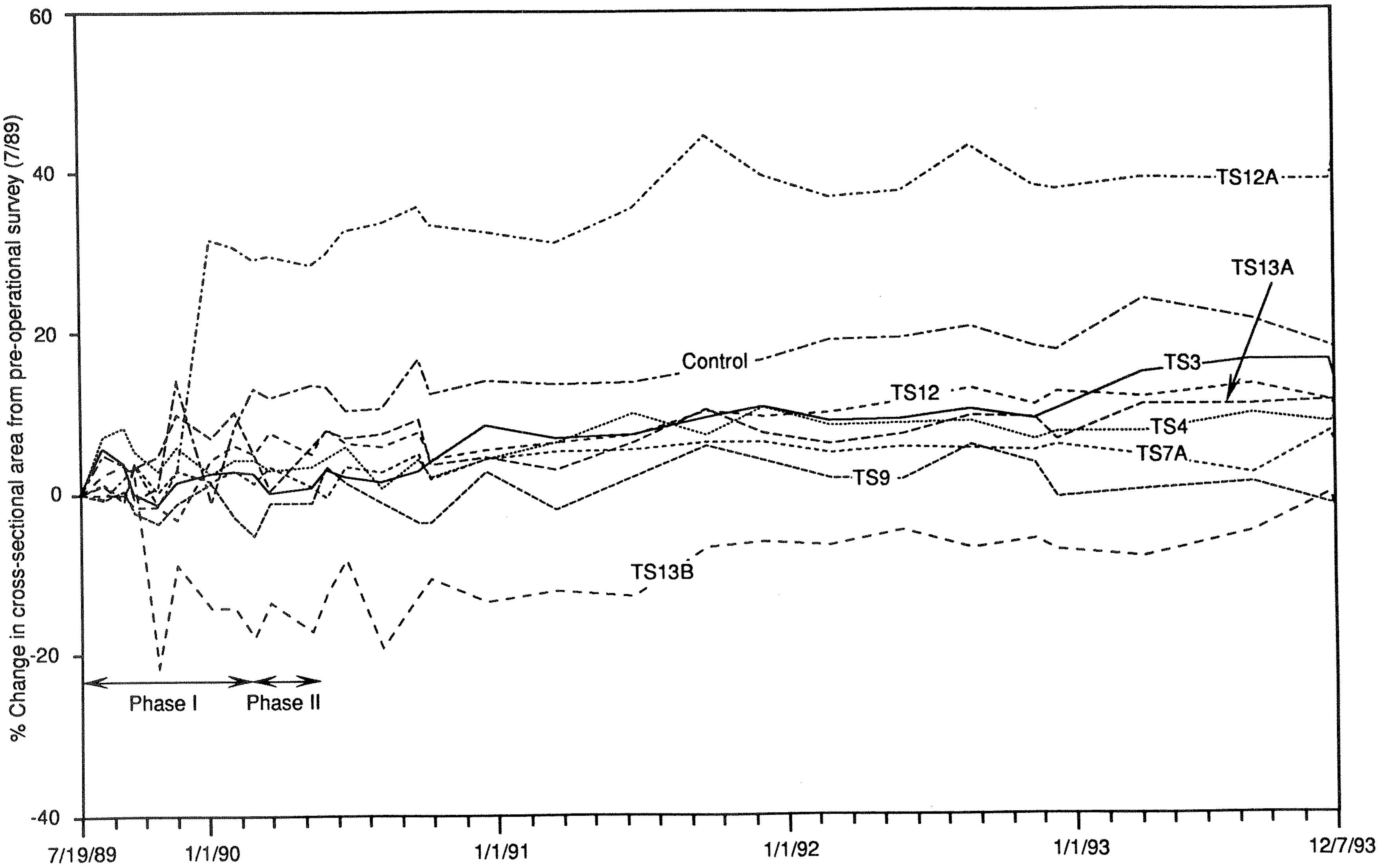


Figure 47: Average change in ESMP cross-sections during flow diversion period.

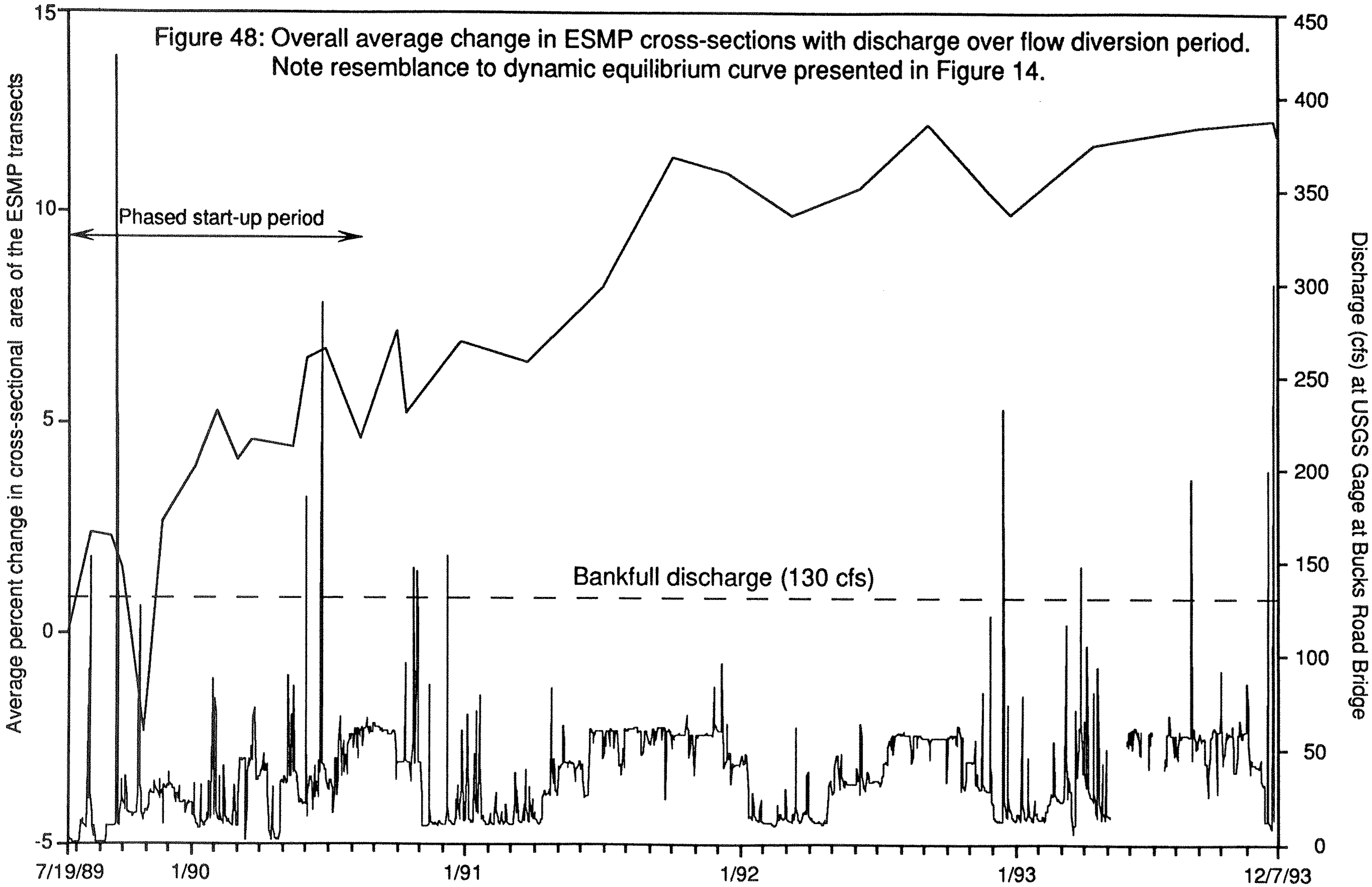


Figure 48: Overall average change in ESMP cross-sections with discharge over flow diversion period. Note resemblance to dynamic equilibrium curve presented in Figure 14.

FUTURE CHANGE: AN EMPIRICAL FORWARD MODEL

Assumptions and Basis

In order to predict general trends and magnitudes of channel change in the future, forward (predictive) models (ones that extrapolate from measured data) using empirical equations derived from field data were developed. These models are in the form of power-law relations ($y=bx^m$). Many of the empirical relations (based on field data) in fluvial geomorphology theory are in power-law or logarithmic form (e.g. eqs. 11, 13), most notably hydraulic geometry (eqs. 18-20). Many hydrologic relations may be expressed as power law functions (Leopold, 1994). In addition, the theme of systems that express change tending towards equilibrium is fairly universal in geomorphology (i.e. dynamic equilibrium). In the case of the ESMP data for the East Branch Perkiomen Creek, the curve produced by channel change against time (Figure 48) is best expressed by power-law relations. Exponential and linear relations cannot be used to characterize this particular system. Power-law relations produced higher correlation coefficients that logarithmic relationships. The equations of these models were derived by simply plotting (using Cricket Graph) the average total percent change in bankfull cross-sectional area data against time. A power-law curve was then fitted to the data using a computer. The computer was then used to calculate the equation of the curve fitted to the data, which had the form of

$$percent\ change = b(time^{m}) \qquad \text{(eq. 22)}$$

where *b* is a coefficient, and *m* is the exponent which governs how rapidly the curve flattens out (approaches equilibrium). This equation was used to predict future change by plugging in different values for time, and solving for average total percent change.

Basing the model on power-law relations of measured field data makes several assumptions, which are grounded in some of the concepts that are basic to landform analysis. The model assumes uniformity of process to extend current observations into the future (eg. hydraulic relationships will not change (Chorley *et al.*, 1984)). It is important to recognize, however, that the "snapshot" of today may not be representative of the bigger picture. Thus the model will not be used to predict change beyond a few decades into the future.

Over an extended period of time, landforms evolve (Chorley *et al.*, 1984; Bloom, 1991). However, changes in landforms are seemingly erratic, or complex (Chorley *et al.*, 1984). Geomorphic systems are complex, influenced by different levels of independent (e.g. geology, time, climate) and dependent (e.g. catchment and channel morphology) variables (Chorley *et al.*, 1984). Rivers are ultimately the products of processes occurring on the landscape (Wolman *et al.*, 1990). The system studied here is part of a larger system, which is tending towards equilibrium, with its own sets of independent and dependent variables. Two aspects of equilibrium that make the model developed here fairly reasonable are statistical stability of form and overall correlation of form and process throughout geomorphology (Chorley *et al.*, 1984). It is, however, impossible to pigeon-hole channel change beyond the near future with a simple power-law relationship.

But, as a best-guess, power-law seems the most appropriate in light of the tendencies of rivers to be in a steady-state equilibrium (Figure 14A) over the short term, and dynamic equilibrium (Figure 14B) over the long term. The idea that a channel is adjusting to its flows gives rise to the fact that if the flows are changed, then the channel will adjust. Hence a dynamic equilibrium, where the channel continually adjusts as it would under steady-state conditions (Figure 14A, no anthropogenic change of discharge), but these changes are clustered around a mean that itself is tending towards some sort of equilibrium (Figure 14B). That Figure 48 (short term change) so closely resembles Figure 14B reinforces the use of power-law relationships for short term predictions (less than 50 years) of channel change. Limiting the model to short term change is prudent in light of the tendency for bedrock-influenced channels not to be able to adjust to their discharge as freely as alluvial channels (Schumm, 1977), with their form being dictated primarily by structure and lithology. In addition, the models are based only on four and a half years of surveying data and flow diversion. As noted earlier, channel trend of the East Branch Perkiomen is sub-parallel to strike of bedding and joints.

The data collected on average total channel change over the past 4.5 years from the ESMP transects have been utilized in order to predict longer-term trends and approximate magnitudes of change in the future. The models derived from this data are simply a "best guess", and do not attempt to determine absolute change in the future. Rather, they represent a mean about which continuous adjustments of the system will cluster, i.e. dynamic equilibrium (Figures 49-54).

Two models were constructed and run, Model A and Model B. The difference between the two is the length of the data set used. Model A uses the full ESMP data set, from pre-operation (July 1989) through December 1993, whereas Model B uses a limited data set, from January 1991 to December 1993. The rationale for the limited data set in Model B is that between July 1989 and August 1990, pumping patterns were relatively erratic due to the phased start-up program, and unrepresentative of pumping patterns expected for the future (Figure 48). Consequently, channel change was erratic as well (Figure 48), with the channel finally settling in to period of consistent change at the end of 1990. Both models use the amount of channel change (uncorrected) from all of the transects averaged together.

Both models have advantages and disadvantages, which stem from their data sets. Model A uses a longer data set, and the equation has a higher correlation coefficient ($r^2 = 0.901$) (see Table 14) than Model B, which has a correlation coefficient of $r^2 = 0.75$, and a shorter data set. However, the data set in Model B is from the period of the flow diversion when pumping patterns were the same as they will be in the future. Thus, Model B may well be a better predictive tool for future change.

The error for each model was calculated by determining the maximum deviation of the field (ESMP) data from the predicted line on each of the two models. The error of Model A is +2.5 and -5.3 percentage points. The error of Model B is +2.1 and -0.8

percentage points. For example, if Model B were to predict 20% change, the calculated error suggests a range of 19.2 - 22.1%. The narrower error range of Model B suggests that it is a better predictive tool for the future.

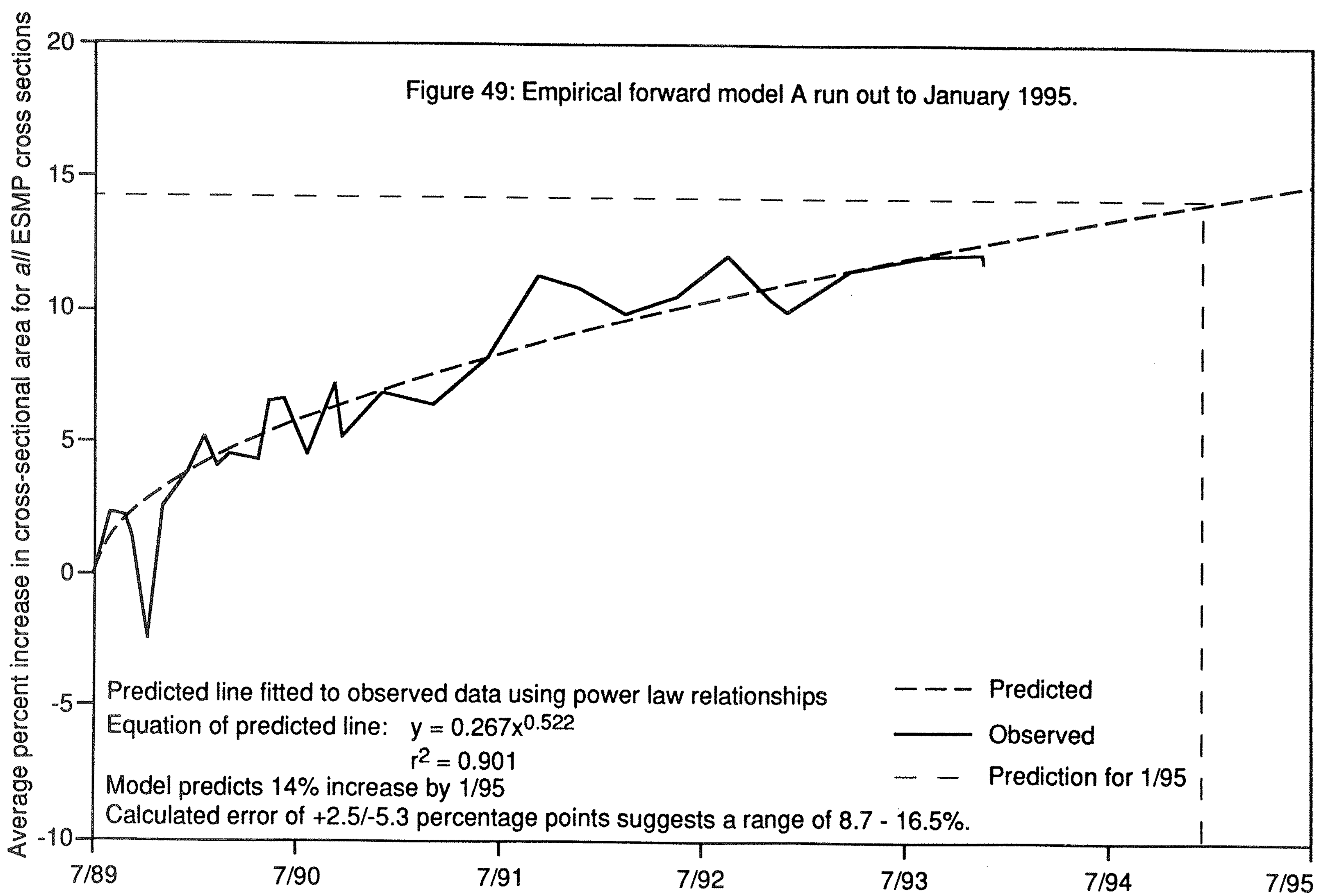
A weakness of both models is that they will never actually reach equilibrium or become asymptotic. Rather, they will continue to increase, but at smaller and smaller rates. This is not a significant problem however, since attempting to predict more than 10 years of change based on a maximum of 4.5 years of data is tentative, and nothing more than a best guess. The complete runs of the models may be found in Appendix VII.

Predictions

Figures 49 and 50 are runs of Model A and Model B, respectively, for the time period from the beginning of the data sets to January 1995. Both predict an approximately 13% increase in average bankfull cross-sectional area (from pre-diversion conditions) within the study area (Table 14). The calculated error in Model A suggests a range of 7.7-15.5%. The calculated error in Model B suggests a range of 12.2-15.1%. Both models come close to predicting measured amounts of change between the beginning of the data sets and January 1994 (Table 14).

When the models are run out to January 2000 (Figures 51 and 52), the difference in the amount of change predicted is greater (Table 14). Model B (Figure 52) predicts a more conservative amount of increase (15.36%; range is 14.6-17.5%) than Model A (19.6%; range is 14.3-22.1%). This is a function of the different exponents of the two equations (Table 14, Figures 51 and 52). The exponent of Model B is less than half of that of Model A, which causes the curve to flatten out earlier (approach equilibrium) in Figure 52 than in Figure 51. The idea of continuous adjustments clustering around a mean (dynamic equilibrium) is illustrated well in Figure 52.

Figure 49: Empirical forward model A run out to January 1995.



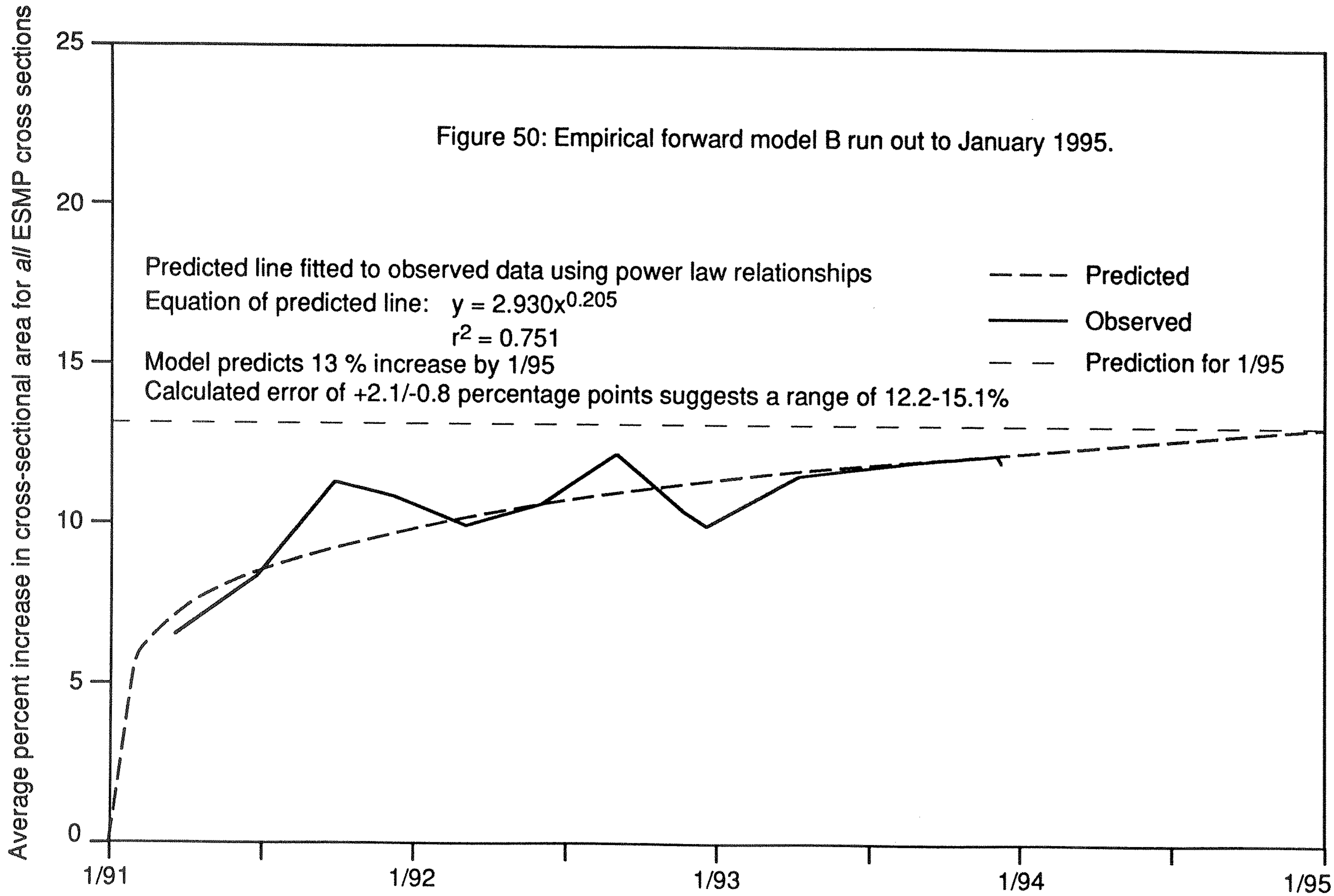


Figure 50: Empirical forward model B run out to January 1995.

Table 14: Forward model summary.

Model A (7/89) % Change = 0.267(# of days^0.522)
r^2 = .901

Year	Years	Months	(Days)	*Predicted avg total % increase*	*Measured avg total % increase*	
Jan-1992	2.42	29	870	*9.14*	*10.88*	
Jan-1993	3.42	41	1230	*10.95*	*9.95*	
Jan-1994	4.42	53	1590	*12.52*	*11.83*	Corrected = 13.29
Jan-1995	5.42	65	1950	*13.93*		
Jan-2000	10.42	125	3750	*19.60*		
Jan-2019	29.42	353	10590	*33.69*		

Model B (1/91) % Change = 2.930(# of days^0.205)
r^2 = .751

Year	Years	Months	(Days)	*Predicted avg total % increase*	*Measured avg total % increase*	
Jan-1992	1	12	360	*9.79*	*10.88*	Corrected = 13.29
Jan-1993	2	24	720	*11.29*	*9.95*	
Jan-1994	3	36	1080	*12.27*	*11.83*	
Jan-1995	4	48	1440	*13.01*		
Jan-2000	9	108	3240	*15.36*		
Jan-2019	28	336	10080	*19.39*		

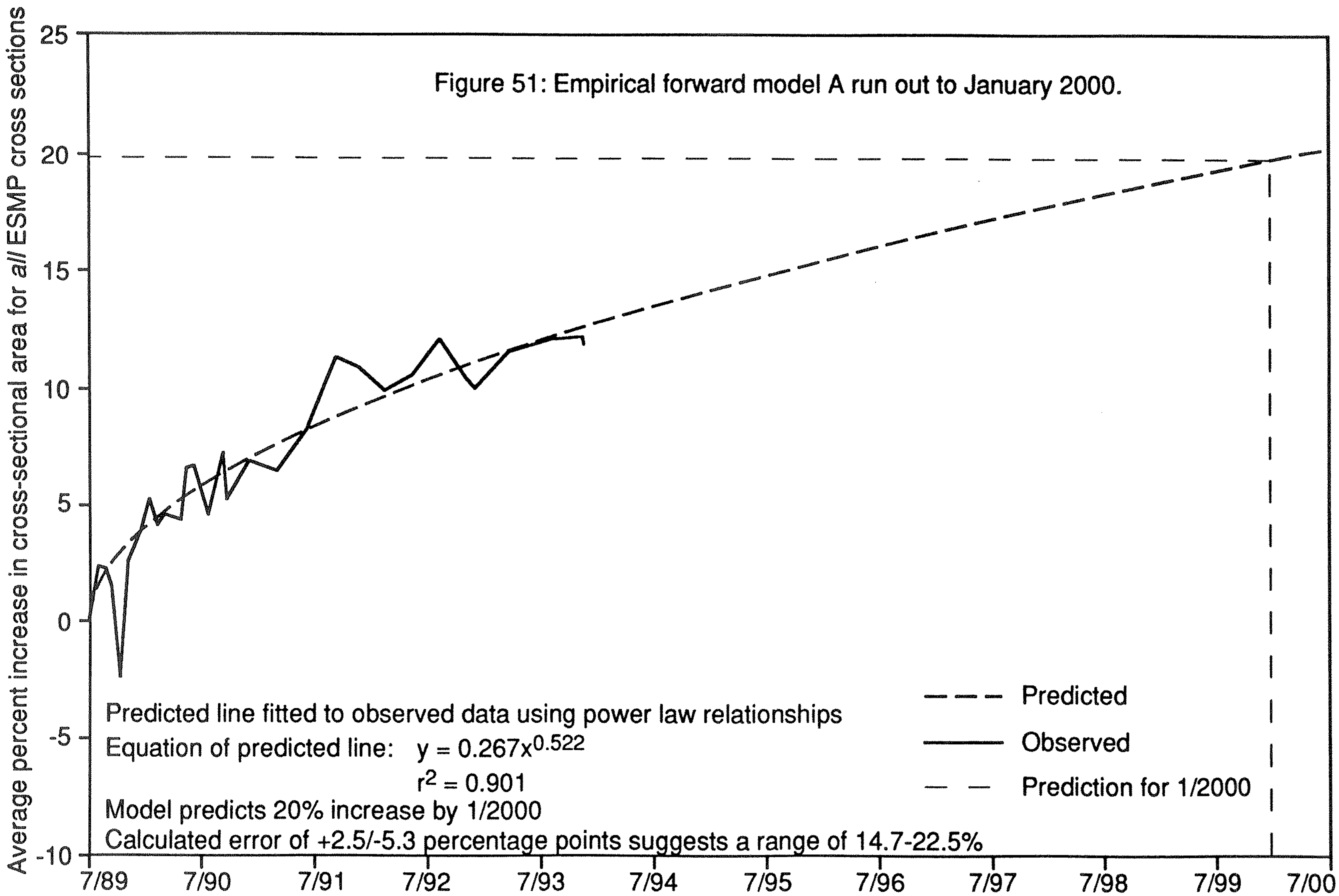


Figure 51: Empirical forward model A run out to January 2000.

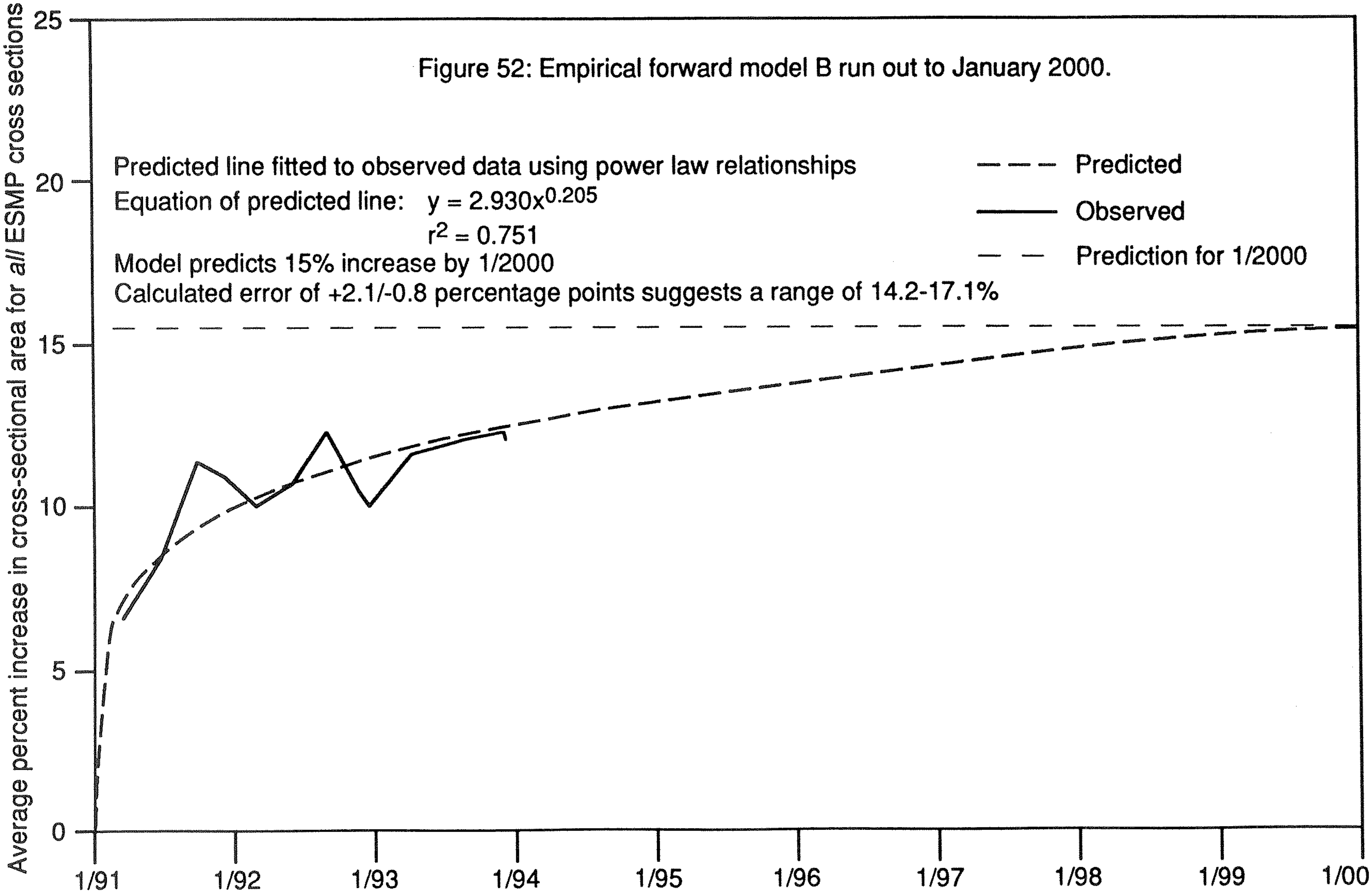


Figure 52: Empirical forward model B run out to January 2000.

The general amounts of change predicted by both models up to the year 2000 are acceptable (though Model A appears to be becoming unrealistic at that point). However, if the empirical relationship is extrapolated an additional 20 years to the year 2019, the predictions are less than sound. The dichotomy in the average amounts of total channel change predicted by the two models at this point (Figures 53 and 54, Table 14) is worth noting. In Figure 54, Model B can be seen to be leveling off with time, and predicts an average 19.5% increase (range is 18.7-21.6%) in channel area from pre-diversion conditions. Model A, however, becomes less realistic, predicting an average total increase of 35% (range is 29.7-37.5%), with the curve not appearing to level off.

In order for a best-guess model of future trends and magnitudes of channel change to be acceptable, it must be representative of the system (thus approaching some kind of dynamic equilibrium) and realistic. Model B fits these two criterion better than Model A, and thus is used to predict an average total increase in bankfull cross-sectional area of the channel in the study area to be ~20% in the year 2019. This value represents a mean about which continuous actual channel adjustments likely will cluster. Model A is also considered unrealistic in light of the bedrock and bed material controls that limit potential erosion, as well as the tendency of the ESMP transects to deepen thus far. The transects can only deepen so far until they are actually on bedrock, when down-cutting will be severely inhibited. Widening will continue to occur.

The data collected from cross-sections established for this study suggest an annual increase in channel cross-sectional area of ~ 4.6% for the reaches downstream of the outfall pipe, and similar changes (+4%) upstream. One year's worth of surveying data is insufficient to determine the amount of change over the long term, since a system in dynamic equilibrium is continually experiencing minor adjustments. However, it is in general agreement with the long term trend of the ESMP data (~ +4%/yr).

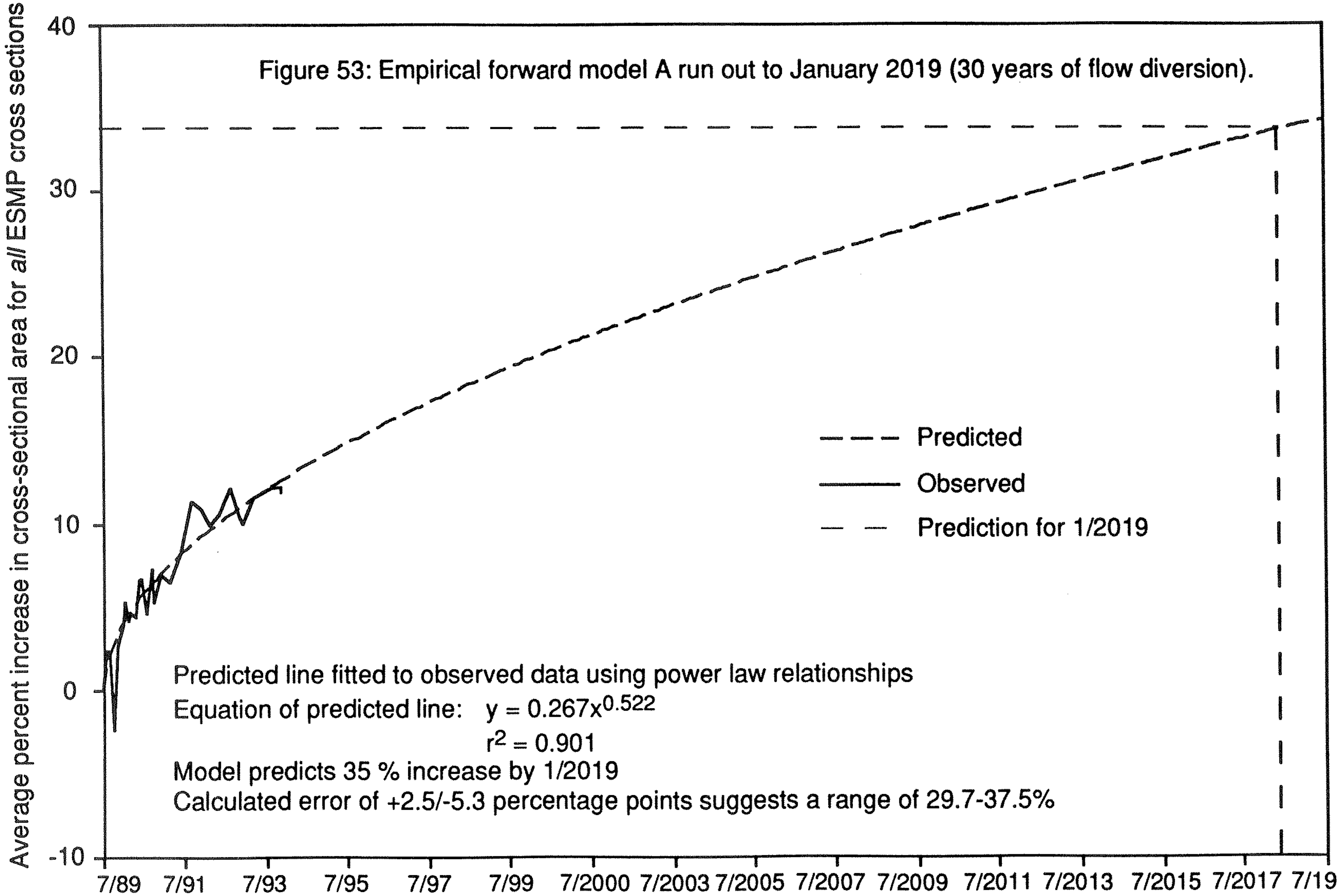


Figure 53: Empirical forward model A run out to January 2019 (30 years of flow diversion).

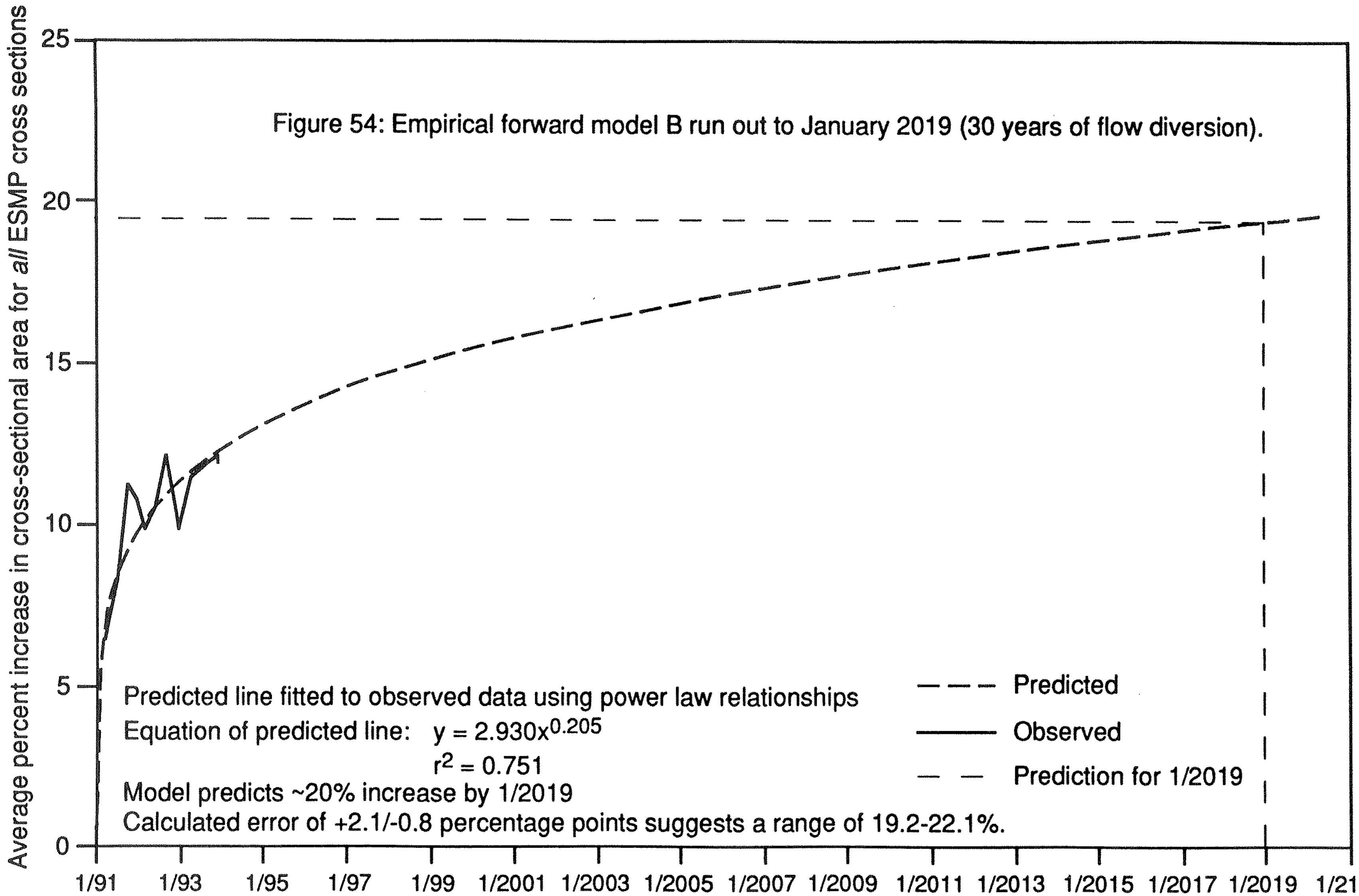


Figure 54: Empirical forward model B run out to January 2019 (30 years of flow diversion).

LITERATURE REVIEW

FLOW DIVERSIONS AND THEIR IMPACTS

Channel incision is a common response to external changes to the fluvial system, such as climate change, land-use changes, or tectonism (Miller, 1991). Leopold (1968, cited in Allen and Narramore (1985)) hypothesized that with new flow regimes brought on by urbanization, the channel should react to maintain a quasi-equilibrium under the new conditions, although possibly only after a lag time after the change in flow regime. In the case of the East Branch Perkiomen Creek, the external perturbation is a significant artificial sustained increase in discharge.

It seems that most of the transfer of water in the United States is via pipelines or artificial canals (Petsch 1985; Mooty and Jeffcoat, 1986). In Canada, many flow diversions are transported through existing river channels. The difference between such diversions and the East Branch Perkiomen diversion is that they appear to be a smaller percentage of the total flow.

Diversion of flow to rivers induces a complex set of geomorphic responses (Hirsch *et al.*, 1990). Kellerhals (1982) noted that after a threefold increase in mean annual discharge, the unstable braided channel of the lower Kemano River in British Columbia, Canada widened and straightened. There was no change in the magnitude or frequency of the largest floods or sediment input from upstream (Hirsch *et al.*, 1990). Discharge on the Cheslatta River (also in British Columbia) was increased by two orders of magnitude with dramatic effects. A new gravel-river was formed by degradation through glaciofluvial gravels, to the point where the new gravel-paved channel is controlled by bedrock sills (Kellerhals, 1982; Hirsch *et al.* 1990). The amount of channel incision was 15-30 ft (5-10 m).

Miller (1990) observed that aside from an increase in discharge, flows within Fountain Creek in Colorado became less charged with sediment, and more constant than intermittent (e.g. elevated baseflow) with interbasin transfer. After several decades of transfer, its channel has enlarged and the width to depth ratio decreased.

BEDROCK CHANNELS

Bedrock-influenced or controlled stream channel morphology has been found by several workers to be related to the structure of the rocks. Miller (1991) correlated channel gradient and bedding plane orientation (relative to flow) to knickpoints. Schumm *et al.* (1987) found that sinuosity increases when a stream flows up-the-dip of the underlying bedrock. Part of the Nelson River valley in Canada follows a topographic break or trough in the raised arc of the Precambrian shield surrounding Hudson Bay (Wolman *et al.*, 1990). The St. Lawrence reflects hydrologic control by the Great Lakes, but within a geologic path determined by the contact between crystalline and sedimentary rocks (Wolman *et al.*, 1990). Harden (1985) determined that bedrock structure was the only significant factor that discriminated between straight and meandering reaches in the central Colorado plateau.

Rock strength or resistance to erosion has been determined to govern flow patterns, channel morphology, knickpoint migration, and channel incision (e.g. Howard and Kerby, 1983; Baker, 1984; and Wohl *et al.*, 1994). Gordon *et al.* (1992) note that in bedrock channels, most of the stream power is expended as frictional resistance. Others, however, concluded that rock strength plays a minimal role in determining channel form (e.g. Harden, 1985; Miller, 1991; Seidl and Dietrich, 1992; Wohl, 1993).

Joints in bedrock are common to most all geologic settings, and seem to exert varying degrees of influence on bedrock-influenced and bedrock-controlled channels. Drainage patterns have been found to be joint-controlled by Baker (1984), Myrick *et al.* (1988), Nelson (1988), and Yelderman *et al.* (1988). Wohl (1990) and Miller (1991) concluded that joints can be conducive to plucking and quarrying by stream flows when oriented normal to flow.

Fractures in bedrock have been found to control stream channel and/or valley orientation by Fisher *et al.* (1988), Johnson (1988), Steele *et al.* (1988), and Canavan and Kochel (1990). Fracturing or faulting may be conducive to erosion and knickpoint formation (Wohl *et al.*, 1994). Pools and riffles are associated with areas where a river channel crosses local and regional fracture zones (Dolan *et al.*, 1978).

Other studies have concluded that bedrock structure plays a minimal, if any, role in bedrock-influenced or controlled channel morphology (e.g. Seidl and Dietrich, 1992; Wohl, 1993). In their flume experiments using simulated bedrock, Shepard and Schumm (1974) found that jointing of bedrock is not absolutely necessary for inner channel development.

Bedrock channels were determined to be associated with steep channel gradients, which influence flow hydraulics and erosional processes (e.g. Ashley and Renwick, 1983; Seidl and Dietrich, 1992; Wohl, 1993; Seidl *et al.*, 1994; Wohl *et al.*, 1994).

There are very few studies of channels that lie somewhere in the middle of the bedrock-alluvium continuum. Most bedrock channel studies have been carried out in arid (badlands), constructional or tectonically active regions, where channel gradients are steep (0.1-0.2 in some cases).

The East Branch Perkiomen Creek is located in a temperate, humid continental climate, on a passive margin. It flows over mudstones, has a gentle gradient (0.002), and is not really incised (~2 ft maximum). There are a few studies, however, that are relevant to the East Branch Perkiomen. Ashley *et al.* (1988) conducted a study of the Raritan River in New Jersey, which flows over mudstones of the Passaic Formation, which is the same formation (Brunswick/Passaic) that floors the East Branch Perkiomen. Braun (1983) attributed marked differences in the dimensions of meanders in the Appalachian Valley and Ridge to differences in the relative erodability of bedrock. Meanders in mechanically resistant, thick-bedded to massive lithologies (generally carbonates) are smaller than meanders in less resistant, thin-bedded shaley lithologies. He determined that, in effect, weaker rocks produced larger meanders. He also determined that weaker (shaley) rocks produced a more trapezoidal channel form than stronger rocks. Channels in shale were also found to be trapezoidal by Allen and Narramore (1985). The bedrock meander size differences are not related to bed material size or slope differences (Braun, 1983). In reply to Braun (1983), Abrahams (1985) argued that meander wavelength in channels with both bedrock and alluvial reaches is inversely related to rock strength, since the channel is being cut by flows with a higher recurrence interval.

There are clearly a variety of conclusions about the effects of geologic structure on bedrock channel form and erosional processes. However, because these studies were carried out in a variety of geologic, geomorphic, tectonic, and climatic settings, this is not surprising. Aside from Ashley *et al.* (1988) and Braun (1983) (though that study is only partially related), none of the studies are directly applicable to the study area in this thesis.

DISCUSSION

The East Branch Perkiomen Creek lies somewhere on a continuum between bedrock and alluvium channels. Both bedrock and alluvium control channel form and response to the radical hydrologic changes that flow diversion has imposed on the third-order stream. The bedrock that floors the channel exerts a strong influence on channel morphology at the regional scale as illustrated by the relations in Figure 6. Where the channel begins to flow in the up-dip direction, sinuosity increases.

Bedrock also appears to exert strong control on channel morphology in the headwaters region. The channel orientation correlates closely with the two sub-vertical dominant joint sets (Figure 19). Where the channel is not sub-parallel to these two sets, it is sub-parallel to the third subordinate, orthogonal set. Although the sub-vertical orientation of the joints makes them conducive to plucking (e.g. Wohl, 1990), their parallelism with stream flow most likely inhibits quarrying (e.g. Miller, 1991). The channel is also oriented

oriented parallel to the strike of bedding (Figure 19), flowing slightly up-dip along gently dipping bedding plane surfaces.

Bedrock lines the channel floor and outcrops at least 6 inches above the channel floor along 21% of the banks, especially in cutbank areas. The channel itself is by no means incised into bedrock, but rather is locally constrained by it. Erosion of the bedrock is limited primarily by the resistance of the rock to the boundary shear stress imposed by stream flows. The bedrock outcrops lining the banks are inhibiting meander migration, but not stopping it. Thus, the stream will tend to take the path of least resistance, which in this case is that sub-parallel to the two dominant joint sets and parallel to the strike of bedding.

The trapezoidal form of the channel (Figure 24) is typical of shaley lithologies (e.g. Braun, 1983; Allen and Narramore, 1985). The channel in plan view has a low sinuosity (1.2). The measured channel dimensions of bankfull width (42 ft) and broad and small hydraulic meander wavelength (L = 700 ft, λ = 175 ft, respectively) are not adjusted to each other, contrary to fluvial geomorphology theory. The measured broad hydraulic meander wavelength (L) is greater than that suggested (420-504 ft) by bankfull channel width, whereas the measured small hydraulic meander wavelength (λ) is smaller. Channel width is adjusted to bankfull discharges (~130 cfs, as calculated from discharge records for the last 10 years), whereas broad hydraulic meander wavelength (L) appears to be adjusted to drainage area (4.05 mi^2) and natural mean annual discharge (5.5 cfs). Small hydraulic meander wavelength (λ) cannot be correlated using standard equations. The correlation of channel orientation and form with the underlying bedrock and its structure point to the strong influence the bedrock is exerting on the channel, and may explain why the small hydraulic meander wavelength (λ) is so small. The slope of the channel is 0.00287.

The alluvium within the channel is an armor of highly imbricated angular to sub-angular tabular gravel chips ($d_{50} \approx$ 26 mm). This armor provides maximum stability, and prevents the winnowing and flushing of finer-grained materials it protects. In areas of bank-outcrop, the grain size of the alluvium has been demonstrated to be substantially higher (e.g. at TS12 d_{50} = 30 mm). The fine-grained, silty-clayey alluvium (Figure 22, Table 5) that makes up the majority of the channel banks also controls channel form and dimensions. When saturated, they are very coherent. When dry, they have brick-like hardness. These fine grained materials are cohesive, presenting a smooth surface to flow, making them less affected by boundary shear stress. This in turn makes them resistant to entrainment and erosion. On cutbanks of meander bends, the occasional absence of the erodible upper (Bt) horizon with the dense, compact lower (Bx) horizon forming coherent mud ledges indicates that their different compositions also exerts a control on bank erosion.

Catchment characteristics are governed by both bedrock and overburden. Bedrock lies close to the surface, making regolith thin. The regolith produced by the in-situ weathering of bedrock is silty and clayey, with low infiltration rates. Low infiltration rates and thin soils make runoff flashy, with dramatic overland flow during storm events. This characteristic of the stream is easily seen in Figure 4.

As a point on the bedrock-alluvium continuum, the bedrock-influenced East Branch Perkiomen sometimes adheres to alluvial channel regularities as suggested by Ashley *et al.* (1988) for the Raritan River, and sometimes it does not, as generally suggested by Richards (1982). What is interesting is that although bedrock is strongly influencing how straight the channel is, hydraulic geometry relationships are valid for the stream during both natural and diversion flows. Recall that hydraulic geometry theory was established using alluvial systems. Also interesting is that hydraulic geometry relationships are not valid at bankfull flows (using empirically derived bankfull discharge and empirically derived values for constants and exponents), which are considered to be the channel-forming flows. This is either the result of the channel being out of phase with bankfull discharge because of bedrock influence, or the fact that the derived values for the constants and exponents were determined at discharges much lower than bankfull.

As noted by Hirsch *et al.* (1990), diversion of flow to rivers induces a complex set of geomorphic responses. If Wolman and Miller's (1960) hypothesis is correct, flow diversion will have a significant impact on channel modification in that the magnitude of high-frequency events has been increased. The most readily apparent direct effect of flow diversion to the East Branch Perkiomen Creek is the overall change in hydrography of the creek. Mean annual discharge has increased almost sixfold (6.8 cfs to 37.7 cfs), as has the mean of the maximum month (five-fold, 12 cfs to 57 cfs); the time of year with the maximum discharge has changed from mid spring to late summer. With the distortion of the annual hydrograph (Figure 11) from its natural form, the relative magnitudes of summer and winter flows have been switched. Storm hydrographs (Figure 17) have also been altered from their natural form, with water levels remaining high after storm events, instead of falling down to some low baseflow. During flow diversion, water levels in the stream are continuously high, resulting in constant saturation of bank materials. Flow downstream of the outfall pipe is less charged with sediment than upstream (0.02 mg/l vs. 0.04 mg/l), consistent with other flow diversion projects (e.g., Miller 1990). Water backs up upstream of the outfall pipe during diversion periods, resulting in continuous wetting of the lower part of the banks.

Stream power (a surrogate for erosive power) has increased downstream of the outfall pipe as a result of the flow diversion (e.g. from 1.65 watts/m^2 to 5.63 watts/m^2 for $\omega 1$). In channels with bedrock, much of the stream power is spent on the frictional dissipation of energy (Gordon *et al.*, 1992), so this may not be as critical as it would be for a purely alluvial system. Another effect of the flow diversion is that the median grain size of bed materials downstream of the outfall pipe (d_{50} = 26 mm) is larger than upstream of the outfall pipe (d_{50} = 20 mm). This is the result of flushing of finer grained materials from the channel bed during diversion flows, when shear stresses exceed critical tractive forces required for such flushing. Only the armor over finer grained materials remains. Maximum bed shear stresses of ~11 N/m^2 during diversion flows are not capable of moving d_{16} material (15 mm) downstream of the outfall pipe. Downstream of the outfall pipe, d_{16} values are consistent (Table 4), reflecting the competence of diversion flows, whereas d_{84}

values are variable. This variability in d_{84} values reflects changes in bedrock outcrop within the channel banks, with larger d_{84} values being associated with areas of bedrock outcrop within the banks. Where bedrock does not outcrop in the banks, the erodible upper (Bt) soil horizon has been stripped away, leaving ledges of dense, compact, lower (Bt) soil horizon mud. When water levels are lower during the winter, these mud ledges are likely to be prone to erosion by frost action.

Over the period of flow diversion, average bankfull cross-sectional area downstream of the outfall point has increased from pre-diversion conditions by a total of 13%, and by as much as 44%. Between August 1993 and June 1994, the cross-sections surveyed for this study changed by ~+4.3%. Between August 1993 and December 1993, the average amount of change in the ESMP cross-sections was -0.14%. Although there is overlap of the survey periods, these numbers cannot be readily compared because the ESMP surveys do not include the effects of flows between December 1993 and June 1994. There have been several high flow events (Figure 11) during that time period which may have caused some of the cross-sections established for this study to adjust.

Both channel widening and deepening have occurred. The deepening seen in the East Branch Perkiomen is not channel incision into bedrock, but rather changes in the gravel armor over the bedrock. Channel widening is more likely than deepening because of the fine-grained banks and low critical tractive forces that are exceeded during diversion flows. However, the coherent nature of the banks, as well as hypothesized electro-chemical attractions between the silt and clay particles, are inhibiting widening to some degree. In addition, the areas of the banks that are exposed to maximum boundary shear stresses (1.08τ) (Figures 13 and 21) are frequently bedrock or the dense, resistant lower (Bx) soil horizon.

The changes seen in the ESMP control section indicate that flow diversion has an effect on reaches upstream of the outfall pipe. With the addition of discharge at the outfall pipe, the water surface slope decreases, causing water to back up within the channel upstream of the outfall pipe for about 600 ft. This is a result of streams being connected systems, where a change at one point will have an effect elsewhere. The placement of the control section for the ESMP was inappropriate because the diversion has a direct physical effect on that area, whereas areas farther upstream are less affected, and would serve as better controls.

The pattern of channel adjustment during the diversion period reflects the perturbation of this dynamic equilibrium system. The variable rate of the channel adjustment seen during the phased start-up of the diversion program is a result of the system responding to erratic (by natural standards) discharge patterns. It is the continuous shifting and rearranging of the armoring materials, as well as bank degradation that produced the changes seen after the start-up period (Figure 48), which appear to be clustering around a mean, suggesting dynamic equilibrium. As the amount of change leveled off, the stream became more adjusted to the new hydrologic regime imposed upon it. Throughout the flow diversion period, channel adjustments are often associated with bankfull or greater events. The stream will continue to adjust to the new regime into the future, since natural systems often take longer periods of time to come into equilibrium with some external change.

A question to be considered here is: Will the stream be able to adjust completely to the new flow regime during the life of the diversion? On the human time scale, the period of the diversion, about 40-50 years, is significant. The average total amount of bankfull channel cross-sectional area increase after of 30 years of diversion flows will be about 20%. Also on the human scale, the amount of change seems significant. On a geologic scale, however, an adjustment of only +13% over a four and a half year period seems minimal considering the radical change in hydrology, and the fact that there should be a lag-time (systems take time to adjust). Bedrock-influenced channels have been shown to provide sufficient resistance to erosion in that they are resistant to short term changes in flow hydraulics (e.g. Baker, 1984). It is clear that the diversion will only be in place for a geological instant. If this were a sand-bed stream, where resistance to channel modification is significantly less, we would surely have seen a greater amount of adjustment at this point.

The overall assessment of this altered system is that the fluvial response to a radically altered flow regime has been to flush fines from materials that armor the channel bed, rearrange the channel armor, widen and apparently deepen slightly. Widening in some areas has occurred as the result of stripping of weaker upper soil horizons. With the flushing of the loose materials and fines, a portion of the flow boundary is more resistant, which may inhibit the self-adjusting tendency of the stream. The average total amount of change to the channel itself (+13 %) has been limited by bedrock, which strongly influences, but does not dominate or control, channel changes. This strong influence places the East Branch Perkiomen just on the bedrock side of the middle of the bedrock-alluvium continuum.

From the literature, it can be broadly stated that in temperate, tectonically quiescent/passive areas (e.g. studies from the eastern coast, interior, and midwestern regions of North America), bedrock exerts control on channels primarily through joints, bedding dip, and rock strength. In constructional or tectonically active regions (e.g. the studies from Oregon, Israel, and Hawaii), as well as arid areas (Israel, Australia), channel gradient controls flow hydraulics, which govern channel morphology. In such areas, lithologic and structural variations, however, exert minimal control. The East Branch Perkiomen Creek falls into the former category, with bedrock geology strongly influencing channel response to the diversion flows that have been imposed upon it.

Several workers have noted bedrock controls on regional stream orientation such as those seen on the East Branch Perkiomen (e.g. Fisher *et al.*, 1988; Johnson, 1988; Steele, *et al.* 1988; and Canavan and Kochel, 1990). The general increase in sinuosity where the channel flows up-dip agrees with Schumm *et al.* (1987). Joint control of drainage patterns similar to those seen on the East Branch Perkiomen have been noted by Baker (1984), Nelson (1988), and Yelderman *et al.* (1988). The trapezoidal form is diagnostic of shaley rocks (e.g. Braun, 1983). The disagreement between measured hydraulic meander wavelength (700 ft) and that suggested (420 ft) using Ashley *et al.'s* coefficient of 10 for the Raritan river points to more bedrock control on the East Branch Perkiomen, perhaps because of its lower stream power ($\omega 3$, eq. 17) resulting from its smaller drainage area. The overall conclusion that the morphology of the East Branch Perkiomen is partially a function of the physical characteristics of the bedrock is consistent with Ashley and Renwick's (1983) and Ashley *et al.'s* (1988) findings for the Raritan River, which has the same slope as the East Branch Perkiomen (~0.002) and also flows over Brunswick/Passaic Formation rocks within the Newark basin.

The response of the East Branch Perkiomen to flow diversion thus far is similar to the response of the lower Kemano River in British Columbia, Canada after a threefold increase in mean annual discharge due to flow diversion (Kellerhals, 1982). Both channels have widened. The Cheslatta River in British Columbia, Canada, responded to a two orders of magnitude increase in discharge by cutting down 15 -30 ft through glaciofluvial gravels until a new gravel-paved channel controlled by bedrock sills was formed (Kellerhals, 1982; Hirsch *et al.* 1990). This response is much more radical than that of the East Branch Perkiomen because the Cheslatta River flowed over unconsolidated materials.

SUMMARY AND CONCLUSIONS

The East Branch Perkiomen Creek provides an example of a stream strongly influenced (but not dominated) by bedrock controls in a temperate, humid continental climate in a tectonically inactive region, flowing over mudstones with a low slope. Such an example is not readily available in the bedrock-channel literature, and provides an important example on a multi-sided continuum where tectonics, climate, geology and geomorphology govern how bedrock controls stream channels.

1. The regional drainage pattern of the East Branch Perkiomen Creek is hybrid dendritic-trellis. Within the study area, it is a third-order stream with a hybrid dendritic-trellis drainage pattern, and a trapezoidal form. It is generally cut into mudstone bedrock of the Triassic Brunswick/Passaic Formation about 4 in. (~10 cm). In cutbank areas it can be up against bedrock and cut in as much as 3 ft (~ 1 m). The sinuosity index is 1.2 (Table 15).

2. Bedding within the bedrock is indistinct and strikes 055°, dipping gently (10°) to the NW. The mudstones are highly jointed. There are three sub-vertical, bedding-plane normal joint sets. The two dominant sets strike 025° and 055°, whereas the subordinate orthogonal set strikes 300°.

3. Bedrock control of channel orientation in the East Branch Perkiomen is evident at the regional and local levels. Regionally, channel sinuosity increases from ~1.07 to ~1.27 where the channel flows up-dip. The hybrid dendritic-trellis drainage pattern is likely a result of bedrock influence. Over the length of the study area (~1 mile; 1.6 km), flow parallels (225°) the dominant joint sets (025°/205° and 055°/235°). Bedding strike (055°/235°) also parallels flow. Streamflow is slightly up-dip along gently dipping (10°) bedding planes.

Table 15: East Branch Perkiomen Creek geomorphic and hydrologic characteristics

	American	Metric
Drainage area	4.05 mi^2	10.49 km^2
Sinuosity Index		1.2
Meander wavelength		
Greater channel	700 ft	213 m
Thalweg	175 ft	53 m
Mean flow depth at bankfull	2.81 ft	0.85 m
Channel width at bankfull	42 ft	13 m
Bankfull discharge		
Calculated from USGS discharge records	150 cfs	4.24 m^3/s
Calculated from bankfull channel width	130 cfs	3.68 m^3/s
Slope (bankfull)		0.0033
Density of Passaic Fm. mudstone		2.45 g/cm^3
Density of bank materials		1.63 g/cm^3
Mean annual discharge		
Pre-diversion	6.8 cfs	0.2 m^3/s
With diversion	37.7 cfs	1.1 m^3/s
Pumping rate		
Summer	~ 58 cfs	~ 1.6 m^3/s
Winter	~ 10 cfs	~ 0.3 m^3/s

4. The catchment surrounding the study area is mantled with thin (3-7 ft; 1-2.1 m) silty/clayey loam soils with low infiltration rates, making drainage flashy. The parent materials of these soils are mudstones and shales of the Triassic Brunswick/Passaic Formation.

5. There are no obvious potholes present in the channel bed. It is armored with a discontinuous veneer of medium to coarse (median b-axis = 23 mm) angular to sub-angular tabular mudstone chips over a bedrock liner. The d_{84} values are variable from reach to reach, and are larger in areas where bedrock outcrops along the channel margin, reflecting a proximal source. Bedrock outcrop greater than 6 in. (15 cm) above the channel floor lines 21% of the channel banks. The remainder of the channel banks are comprised of a coherent silt-clay sediment that is derived from the in-place weathering of bedrock and deposition during waning flood flows. Two distinct soils horizons (upper = Bt, lower = Bx) are visible within much of the channel banks. Remnants of bedding from weathered bedrock can be seen in the Bx horizon. There are limited areas on the cutbanks of meander bends where the Bt horizon has been stripped away, leaving mud ledges of Bx soils. These mud ledges are likely to be prone to erosion by frost action during low flow periods (winter).

6. Broad hydraulic meander wavelength ($L \approx 700$ ft; 213 m) appears to be adjusted to pre-diversion hydraulic conditions using the measures of drainage area (4.05 mi^2; 10.49 km^2)and mean annual discharge (5.5 cfs; 0.16 m^3/s). Small ($\lambda \approx 175$ ft) and broad hydraulic meander wavelength and bankfull channel width (42 ft; 13 m) do not appear to be adjusted to one another. Bankfull channel width is adjusted to bankfull discharge. Small ($\lambda \approx 175$ ft) hydraulic meander wavelength cannot be correlated using established relations. Data indicate that the channel follows hydraulic geometry relationships at low to moderate discharges, but perhaps not at bankfull stage (130 cfs; 3.7 m^3/s). Bedrock may be inhibiting meander migration.

7. The intrabasin transfer of water to Limerick via the East Branch Perkiomen Creek has had a significant impact on the hydrology of the stream. Mean annual discharge has been increased by 454% from 6.8 cfs to 37.7 cfs (0.19 to 1.07 m^3/s). The hydrograph has been grossly altered from its natural form of low baseflow with dominant storm peaks to one of alternating summer (elevated diversion flows of 57 cfs; 1.6 m^3/s) and winter (lower diversion flows of 10 cfs; 0.28 m^3/s) plateaus. There is a regulated, seasonal switch in flow regimes, which has reversed the relative magnitude of summer and winter flows. The magnitude of the 2-3 year flood appears to have increased by ~ 75 cfs (~ 2 m^3/s). Storm hydrographs have been altered such that storm peaks are less prominent. Streamflow has become more regular than intermittent as a result of constant regulation. The discharge downstream of the outfall has half the suspended sediment concentration of that upstream (0.02 mg/l vs 0.04 mg/l).

8. Channel bed materials downstream of the outfall pipe are coarser (higher d_{16} and d_{50} values) downstream of the outfall pipe than upstream. d_{16} values are consistent downstream of the outfall pipe. This suggests that downstream of the outfall pipe fine-grained materials have been flushed by diversion flows, and that d_{16} values are governed by the competence of diversion flows.

9. Stream power is significantly greater during elevated discharge periods (diversion flows) than non-diversion flows in the same reaches, as well as downstream of the outfall pipe during diversion flows (e.g. from 1.4 watts/m^2 upstream to 4.77 watts/m^2 downstream for ωl). Because of bedrock in the channel and a higher proportion of resistant materials present due to flushing by diversion flows, this may not be as significant as it would be for a purely alluvial system.

10. Boundary shear stresses are also greater during diversion flows. This is due to an increase in hydraulic radius during higher discharges. Shear stresses produced during diversion flows (τ_d = 6-8 N/m^2) are not capable of moving the armor materials (mean d_{16} = 15 mm), but can flush associated surface fines. Bankfull flows (τ_{bkf} = 20.3 N/m^2) are

capable of rearranging the armoring materials, as well as deep flushing of materials trapped under the armor. Further calculations suggest that bankfull flows are not capable of complete entrainment of the armoring material. The relative position of the fine grained alluvium in the channel suggests that it is subjected to minimal boundary shear stresses due to variations in boundary shear stress distribution.

11. Channel adjustment was variable during the phased start-up of the transfer, but leveled off once normal pumping operations began. This may be the result of the 'flushing' of loose, fine to medium grained materials from the channel during the initial stages of the transfer as the channel adjusted to the external perturbation. Channel change is often associated with storm flows in excess of 130 cfs (3.7 m^3/s).

12. Over a four and a half year period, average total change in cross-sectional area of ESMP sections has been limited to ~+13% (maximum 44%) or ~ 3%/year from pre-operational conditions, with some areas widening, while others deepened. The control section changed by a total of ~+22%. This is a result of streams being connected hydraulic systems, where a major change at one point may affect upstream (e.g., water backing up upstream) or downstream reaches. The ESMP "control" section was placed too close to the outfall pipe to serve as a useful record of channel change unaffected by diversion flows.

13. Periodic surveys of cross-sections established for this study (in mid-1993, 4 years after flow diversion began) indicate an average overall change in bankfull cross-sectional area of +4.1% for upstream areas, and +4.6% for downstream areas over the period of one year. This change is probably simply a minor adjustment to dynamic equilibrium system, and is not a steady rate at which the channel will change into the future.

14. Approximately 72,995 ft^3 (2150 m^3) of material has been lost over the last 4.5 years, which is approximately 3,720 tons (3,780 metric tonnes). This translates to about 825 tons (838 metric tonnes) per year thus far. This averages out to 0.034 g/l of suspended load, which is consistent with measured suspended loads.

15. The behavior of the stream as demonstrated by channel change with time appears to follow power law relations.

16. A forward (predictive) model based on dynamic equilibrium and power law relations suggests that average channel cross-sectional area will increase by ~20% from pre-operational conditions by the year 2019 (30 years of flow diversion).

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Appendix I

East Branch Perkiomen Creek discharge at the Bucks Road USGS gage for Water Years 1984-1994

Flow diversion from Bradshaw Reservoir to the East Branch Perkiomen Creek for 1989-1994.

Appendix I

East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage

Water Year 1984 (10/1/83 - 9/30/84)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1		0.59	4.9	1.6	2.1	4	18	6.9	10	190	1	0.17
2		0.53	3.6	1.2	2	2.9	9.3	4.7	5.2	13	0.89	0.14
3		0.53	3.9	1	6.8	2.2	5.9	4.14	3.5	4.9	0.82	0.2
4		0.49	88	1	137	1.8	17	123	2.6	3.4	0.7	1.2
5		0.45	17	1	22	5.4	278	14	1.7	3.4	0.77	0.7
6		0.45	22	1.1	7.9	20	27	6.2	1.3	9.1	0.71	0.34
7		0.43	19	1	4	9.3	11	4.5	1	313	0.5	0.24
8		0.36	5.7	0.81	2.1	5.8	6.2	22	0.81	13	0.47	0.23
9		0.32	4.2	0.52	1.9	4.7	3.9	15	0.61	6.7	0.37	0.2
10		1.4	3.7	0.66	3.8	3.7	3.1	5.7	0.45	3.7	7.3	0.2
11		9.2	3	0.68	15	3.1	2.6	3.9	0.35	5.6	1.8	0.21
12	61	5.4	73	0.66	14	2.6	2.2	4.3	0.28	3	2.3	0.2
13	0.3	2.6	169	0.64	9.7	11	2	4.5	0.34	1.7	2.5	0.15
14	0.34	2	39	0.62	20	94	2	3.6	0.95	1.1	1.1	0.14
15	0.23	27	13	0.6	94	48	2.7	2.4	0.38	0.86	0.79	0.15
16	0.17	69	7.5	0.57	33	30	47	1.9	0.28	0.76	0.59	0.24
17	0.14	8	4.4	0.56	14	15	12	1.5	0.42	0.6	0.48	0.21
18	0.14	4	3.2	0.55	13	8.6	6.9	1.3	2.7	5.5	0.38	0.15
19	0.83	2.9	2.6	0.54	7.9	6.4	5.5	1.4	5.2	1.9	0.36	0.08
20	0.39	2.5	1.6	0.53	6.3	5	4.8	2.1	1.3	0.93	0.36	0.06
21	0.22	45	1	0.51	4.5	8.1	3.5	7.6	0.7	21	0.26	0.06
22	0.16	6.8	69	0.5	3.2	7.3	2.5	2.1	0.51	5	0.23	0.06
23	3.7	4.1	13	0.9	3.6	4.4	7.3	9.7	0.41	2.4	0.42	0.05
24	50	8.1	4.4	2	68	3.2	7.8	7.2	7.8	1.6	0.39	0.05
25	4.8	89	3.5	24	13	3.4	5	2.6	70	1.1	0.25	0.04
26	2.4	16	2.6	34	7	3.2	3.4	16	5.4	0.81	0.2	0.04
27	1.5	7.2	2.5	34	4.4	2.5	2.5	14	2.6	22	0.17	0.03
28	1.1	38	43	13	22	19	2.1	14	1.7	5.6	0.18	0.03
29	0.88	38	15	4.8	11	54	7.6	172	1.2	2.7	0.21	0.06
30	0.71	8.3	3.8	3.1		53	8.6	148	12	1.9	0.18	0.08
31	0.65		2.2	2.7		46		24		1.4	0.28	
Total	129.01	398.65	648.30	135.35	553.20	487.60	517.40	650.20	141.69	647.66	26.96	5.71
Mean	7.13	13.30	20.90	4.37	19.10	15.70	17.20	21.00	4.72	20.90	0.87	0.19
Max	61.00	89.00	169.00	34.00	137.00	94.00	278.00	172.00	70.00	313.00	7.30	1.20
Min	0.14	0.32	1.00	0.50	1.90	1.80	2.00	1.30	0.28	0.60	0.17	0.03

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1985 (10/1/84 - 9/30/85)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	0.2	1.3	1.8	5.6	0.46	3.2	4.6	0.49	5.5	0.17	0.49	0.06
2	0.59	1.2	1.3	20	0.44	3	2.3	0.83	0.87	0.16	0.19	0.06
3	0.26	0.88	6	9	0.43	2.2	1.8	56	0.56	0.11	0.11	0.05
4	0.17	0.83	4.9	5.4	0.42	2	1.7	11	0.43	0.09	0.08	0.05
5	0.17	20	2.7	5.6	0.4	4.1	1.4	4.3	5.3	0.07	0.06	0.04
6	0.14	4.7	39	4.5	0.39	2.4	1.4	2.9	2.2	0.07	0.06	0.03
7	0.14	2.5	9.1	5.3	0.38	1.8	1.1	2.5	0.99	0.14	0.06	0.01
8	0.14	1.8	4.3	4.5	0.37	2.5	1	1.7	3.1	0.1	0.17	0
9	0.18	1.6	3.2	2.3	0.36	2.3	0.9	1.2	2	0.11	0.13	0.03
10	0.2	1.5	3.2	1.5	0.35	1.8	0.77	1.1	1.1	0.09	0.08	0.06
11	0.18	1.5	3	1.6	0.34	1.6	0.75	0.94	0.78	0.08	0.07	0.05
12	0.15	1.5	2.5	1.5	177	9.2	0.73	0.76	0.7	0.06	0.06	0.03
13	0.13	1.1	2.2	1.3	37	4.6	0.62	0.68	0.53	0.07	0.05	0.01
14	0.11	0.9	1.9	1.2	17	2.9	0.59	0.55	0.46	0.06	0.05	0
15	0.11	0.83	3.1	1	8	2.2	0.68	0.43	0.4	0.06	0.05	0
16	0.09	0.8	2.6	0.92	5.8	1.7	0.66	0.42	5	0.09	0.04	0
17	0.09	0.75	2.7	0.88	5	1.7	0.51	2.6	1.9	0.05	0.03	0
18	0.09	0.69	2.4	0.84	3.8	1.3	0.45	7.2	1.1	0.04	0.01	0
19	0.09	0.9	3.1	0.8	4.6	1	0.45	1.8	0.86	0.02	0	0
20	0.11	0.74	3.8	0.76	4.5	1.1	0.44	1	0.63	0	0	0
21	0.09	0.61	5.5	0.73	4.3	0.94	0.42	0.85	0.46	0	0.02	0
22	1.4	0.53	24	0.7	5.5	0.87	0.41	1.3	0.33	0.01	0.01	0
23	4.1	0.53	6.2	0.66	13	2.6	0.38	0.93	0.3	0	0	0
24	0.91	0.56	4.1	0.64	12	2.5	0.36	0.88	0.29	0	0	0
25	0.67	0.52	4.2	0.61	10	2.2	0.39	0.68	0.27	0	0.13	0
26	0.56	0.46	2.6	0.58	6.8	1.4	0.36	0.58	0.25	0.11	0.42	0.26
27	0.48	0.45	2.7	0.56	7	1.2	0.48	0.39	0.25	1	0.18	372
28	1.7	0.48	7.8	0.54	4	1.1	0.59	0.36	0.2	0.67	0.12	9.8
29	14	5	11	0.52		1.1	0.52	0.35	0.26	0.09	0.08	3.6
30	2.5	2.5	5.2	0.49		0.97	0.49	0.28	0.22	0.07	0.07	2.5
31	1.6		4	0.47		1		0.25		0.38	0.08	
Total	31.35	57.66	180.10	81.00	329.64	68.48	27.25	105.25	37.24	3.97	2.90	388.64
Mean	1.01	1.92	5.81	2.61	11.80	2.21	0.91	3.40	1.24	0.13	0.09	13
Max	14.00	20.00	39.00	20.00	177.00	9.20	4.60	56.00	5.50	1.00	0.49	372
Min	0.09	0.45	1.30	0.47	0.34	0.87	0.36	0.25	0.20	0.00	0.00	0

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1986 (10/1/85 - 9/30/86)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	2	0.36	43	0.44	4.4	2	0.86	1.4	0	0	0.21	0.08
2	1.7	0.37	27	0.42	19	1.8	0.85	1.1	0	0.02	2.7	0.05
3	21	0.37	8.2	3.1	9	1.9	0.74	0.93	0	0.04	2.4	0.05
4	12	0.4	5.1	2.2	7.8	2.3	0.74	0.81	0	0.04	0.54	0.05
5	11	5.4	4.1	4.7	38	3.1	0.77	0.73	0	0.03	0.31	0.05
6	5.6	2.9	4.5	2.4	17	3.1	1.8	0.62	0	0.01	0.22	0.06
7	3	1.9	4.8	1.3	7.5	2.5	1.8	0.54	0.1	0	0.17	0.04
8	2.1	1.4	4.8	0.82	5.6	1.4	1.4	0.44	0.1	0	0.16	0.04
9	1.5	1.2	4	0.6	4.2	1.3	1.1	0.46	0.1	0	0.11	0.02
10	1.5	1.1	3.6	0.45	3.6	1.8	0.87	0.42	0	0	0.12	0
11	1.2	1	3.4	0.42	3.1	10	0.82	0.42	0	0	0.88	0
12	1	0.95	4.3	0.38	2.7	5.3	0.73	0.37	0.15	0	0.25	0
13	1.5	1.1	8.1	0.36	2.5	44	0.67	0.31	0.21	0	0.17	0
14	1.3	1.1	10	0.354	2.3	88	0.61	0.24	0.11	0	0.12	0
15	1.1	1.5	3.6	0.34	2.1	49	0.66	0.24	0.1	0	0.09	0
16	1.1	59	2.8	0.32	1.9	14	73	0.28	3.3	0	0.08	0
17	1.4	83	2.5	0.3	2.8	7.4	79	0.27	1.7	0	0.1	0
18	1.2	13	1.9	0.29	46	5	22	0.2	0.35	0	0.16	0
19	0.852	7.2	1.3	2.9	52	6.1	9.2	0.16	0.19	1.8	0.13	0
20	0.78	5.3	1	14	55	4.8	5.2	0.3	0.15	0.33	0.09	0
21	0.56	4	0.88	4.8	61	2.8	4.9	0.36	0.13	0.18	0.26	0
22	0.59	40	0.8	2.9	26	3.1	7.1	0.87	0.15	0.13	0.7	0
23	0.55	16	0.72	2.5	16	3.1	27	0.35	0.08	0.07	0.27	0
24	0.51	7.1	0.68	1.7	12	1.9	12	0.2	0.04	0.06	0.43	0
25	0.78	4.8	0.62	31	8.8	1.6	5.2	0.16	0.02	0.06	0.23	0
26	0.64	20	0.59	143	5.1	1.5	3.8	0.14	0	0.06	0.16	0
27	0.57	26	0.56	27	3.7	1.5	3.1	0.1	0	0.09	0.11	0.05
28	0.77	78	0.52	14	2.6	1.3	2.5	0.1	0	0.09	0.12	0.08
29	0.66	33	0.5	9		1.2	2.1	0.1	0	2.2	0.15	0.14
30	0.44	23	0.47	7		1.1	1.8	0	0	1.2	0.13	0.11
31	0.43		0.45	5		0.98		0		0.29	1	
Total	79.33	440.45	154.80	283.99	421.70	274.88	272.32	12.62	6.98	6.70	11.67	0.82
Mean	2.56	14.70	4.99	9.16	15.10	8.87	9.08	0.41	0.23	0.22	0.38	0.03
Max	21.00	83.00	43.00	143.00	61.00	88.00	79.00	1.40	3.30	2.20	2.70	0.14
Min	0.43	0.36	0.45	0.29	1.90	0.98	0.61	0.00	0.00	0.00	0.08	0

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1987 (10/1/86 - 9/30/87)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	0.09	0.11	2.6	2.4	2.8	118	6.6	2	0.09	0.03	0.03	0.04
2	0.1	0.12	21	9.7	4	46	3.4	1.6	0.12	0.04	0.05	0.02
3	0.09	0.1	58	10	13	22	2.6	1.8	0.1	0.12	0.04	0.01
4	0.17	0.11	9.2	6.6	18	12	142	10	0.14	0.04	0.03	0
5	0.24	0.2	5.2	4.2	10	8	22	8.3	0.25	0.05	0.03	0
6	0.21	1.6	3.7	3.2	7.3	7.3	56	5.6	0.13	0.05	0.05	0.01
7	0.15	0.75	3.2	3.1	6	7.9	18	3	0.09	0.06	0.04	0.04
8	0.13	2.3	2.9	3.2	5.4	6.8	8.9	2	0.08	0.09	0.04	0.07
9	0.1	1.9	34	2.9	4.7	5.3	5	1.5	0.13	4.1	0.04	0.13
10	0.08	1.4	19	5.7	4.2	3.3	3.6	1.1	0.06	0.97	0.04	0.1
11	0.08	7.5	7.8	14	3.7	2.5	2.8	0.87	0.04	0.27	0.04	0.05
12	0.08	5.1	11	7.5	3.2	2.3	2.6	0.71	0.04	0.16	0.03	0.04
13	0.09	1.9	6.7	9.3	2.7	2.1	4.1	0.56	0.04	0.14	0.02	0.36
14	0.2	1.2	3.5	11	2.4	1.9	2.6	0.49	0	0.23	0.02	0.24
15	0.17	0.91	3.1	0.18	2	1.8	2.1	0.78	0.01	0.39	0.03	0.08
16	0.14	0.84	3.1	8.3	1.8	1.6	1.9	0.55	0.01	0.13	0.02	0.08
17	0.15	0.71	3.5	4.3	1.8	1.4	8.7	0.4	0	0.13	0.02	0.19
18	0.15	4	62	12	1.8	1.3	7.2	0.32	0	0.11	0.01	1.3
19	0.13	30	21	33	1.8	1.2	4.3	0.32	0	0.07	0	0.52
20	0.11	35	7.8	17	1.8	1.3	3.1	0.64	0	0.03	0	0.32
21	0.1	60	5.4	9.9	1.9	1.4	2.5	0.62	0.01	0.01	0.01	0.21
22	0.08	7.5	3.6	6	2	1.1	1.9	0.4	0.33	0.03	0.03	0.18
23	0.08	4.2	2.9	5.5	3.1	0.92	1.6	0.38	0.59	0.03	0.01	0.15
24	0.07	9.1	9.7	4.8	2.8	0.86	11	0.36	0.15	0.04	0	0.13
25	0.06	5.7	128	4.5	2.8	0.82	30	0.25	0.09	0.03	0	0.1
26	0.15	100	14	4.2	2.8	0.82	6.2	0.23	0.06	0.04	0	0.09
27	0.32	24	7.2	3.9	2.8	0.76	3.7	0.21	0.05	0.03	0.03	0.09
28	0.24	8.1	5.3	3.6	2.8	0.97	3.9	0.21	0.07	0.02	0.04	0.09
29	0.18	5.1	3.9	3.4		0.92	5.4	0.17	0.01	0.03	0.04	0.09
30	0.15	3.5	3.5	3.2		1.1	3	0.14	0.02	0.03	0.03	0.09
31	0.13		3	3		15		0.11		0.04	0.01	
Total	4.22	322.95	474.80	237.40	119.40	278.67	376.70	45.62	2.71	7.54	0.78	4.82
Mean	0.14	10.80	15.30	7.66	4.26	8.99	12.60	1.47	0.09	0.24	0.03	0.16
Max	0.32	100.00	128.00	33.00	18.00	118.00	142.00	10.00	0.59	4.10	0.05	1.3
Min	0.06	0.10	2.60	2.40	1.80	0.76	1.60	0.11	0.00	0.01	0.00	0

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1988 (10/1/87 - 9/30/88)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	0.09	1.1	11	1.3	27	2.1	1.3	1.9	0.66	0	1.8	0.23
2	0.11	1	5	1.1	61	1.8	1.3	1.3	2.9	0	1.3	0.16
3	0.71	0.96	3.2	0.74	19	3.6	1.2	1.2	1.1	0	0.98	0.14
4	2.1	0.93	3.1	0.65	44	45	1.5	1.1	0.91	0	0.76	2.2
5	0.63	0.85	2.3	0.6	11	18	1.4	1.5	0.67	0	0.61	1.1
6	0.4	0.69	1.8	0.55	3.8	7	1.1	8	0.51	0	0.53	0.32
7	0.79	0.63	1.5	0.53	1.8	5.4	1.6	5.3	0.41	0	0.46	0.22
8	0.44	0.57	1.3	0.51	1.3	4.1	2	2.4	0.37	0	0.36	0.16
9	0.37	0.6	1.3	0.5	1.2	4	1.4	1.5	0.51	0	0.31	0.14
10	0.35	15	1.2	0.49	1.2	4.8	1	9.5	0.43	0	0.25	0.11
11	0.42	29	1.2	0.46	1	2.9	0.78	67	0.31	0	0.23	0.1
12	0.5	13	1.1	0.45	11	2.4	0.65	10	0.25	0	0.19	0.09
13	0.46	10	0.94	0.45	9.1	2.7	0.6	5.4	0.19	0	0.16	0.11
14	0.42	5	0.76	0.43	4	2.2	0.55	6.7	0.15	0	0.15	0.19
15	0.44	2.9	12	0.41	10	1.8	0.56	3.6	0.13	0	0.13	0.17
16	0.41	2.2	9.3	0.4	63	1.4	0.62	2.8	0.12	0	0.13	0.14
17	0.37	1.9	3.4	0.4	26	1.3	0.53	2.5	0.12	1	0.2	0.13
18	0.39	2	2.2	2.5	15	1.1	0.83	17	0.14	0.5	0.17	0.16
19	0.31	1.5	1.8	11	18	1.2	1.3	75	0.12	0.08	0.14	0.18
20	0.34	1.4	5.6	76	53	1.1	0.71	41	0.11	1.2	0.12	0.17
21	0.55	1.1	4.5	30	9	0.88	0.58	13	0.09	12	0.11	0.16
22	0.45	0.81	2.7	9.6	4.3	0.72	0.46	15	0.08	13	0.11	0.11
23	0.44	0.77	2.3	5.8	4.5	0.71	0.5	13	0.08	1.6	0.14	0.11
24	0.44	0.86	1.8	3.2	4.2	0.86	0.7	6.5	0.07	16	0.45	0.11
25	0.52	0.77	1.9	3.6	2.8	0.77	0.54	5	0.07	2	0.48	0.11
26	0.55	0.76	3.2	4.5	2.1	8.7	0.44	3.7	0.08	98	0.3	0.1
27	1	0.69	2.3	2.5	2.3	12	0.45	2.5	0.05	43	0.2	0.09
28	11	0.67	2.1	2.2	2.7	3.5	11	1.9	0.03	26	0.14	0.08
29	2.5	19	1.8	1.9	2.5	2.4	3.2	1.5	0.01	6.1	0.22	0.07
30	1.7	85	1.1	1.6		1.8	3.1	1.1	0	2.9	0.56	7
31	1.3		0.96	1.9		1.5		0.86		2.9	0.38	
Total	30.50	201.66	94.66	166.27	415.80	147.74	41.90	328.76	10.67	226.28	12.07	7.23
Mean	0.98	6.72	3.05	5.36	14.30	4.77	1.40	10.60	0.36	7.30	0.39	0.24
Max	11.00	85.00	12.00	76.00	63.00	45.00	11.00	75.00	2.90	98.00	1.80	2.2
Min	0.09	0.27	0.76	0.40	1.00	0.71	0.44	0.86	0.00	0.00	0.11	0.07

Appendix I

East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage

Water Year 1989 (10/1/88 - 9/30/89)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	0.12	0.28	3.7	1.4	3	1.3	14	0.99	1.1	1.5	0.95	0.42
2	0.09	0.31	2.6	1.5	2.4	1.2	5.2	31	0.98	1.2	2	0.5
3	0.11	0.31	2.2	1.5	3	1.2	5.5	4.8	0.85	1.1	12	0.41
4	0.11	0.31	1.8	1.3	2.2	1.2	4.7	2.3	1.3	1.1	11	0.35
5	0.11	4.2	1.6	0.99	1.6	1.4	3.6	17	0.98	24	9.9	0.31
6	0.09	6.6	1.4	1	1.5	3.6	23	102	1.2	9.1	13	4.8
7	0.08	2	1.3	1	1.4	3.1	8.4	24	18	4.4	10	9
8	0.06	1.3	1.3	6	1.1	1.9	4.6	7.3	8.6	3.6	9.6	9
9	0.06	1.2	1.2	5.4	0.97	1.9	3.2	4.4	45	1.6	9	9
10	0.06	1.1	1.1	2.6	0.85	2.8	2.3	92	30	1.2	8.2	9
11	0.04	1	1	2	0.85	7.1	1.7	39	4.7	1.1	8.7	9
12	0.03	0.94	0.81	13	0.8	11	1.4	12	2.4	0.89	15	8.8
13	0.03	5.2	0.76	9.3	0.7	5.7	1.3	6.9	22	9.3	92	9
14	0.03	4.4	0.7	3.5	1.8	4.7	1.2	4.5	5.8	2.8	23	9
15	0.03	1.9	0.67	40	6.8	5.2	11	3.7	12	1.3	152	9
16	0.03	1.4	0.62	9.4	11	3	21	89	23	2.3	35	9.1
17	0.03	36	0.6	4.6	3	1.9	5.6	65	10	2.4	25	9.1
18	0.03	6.8	0.58	3.1	1.9	8.2	2.6	11	4	1.4	14	9.9
19	0.03	3.5	0.58	2.8	1.5	6.2	2.4	5	2.3	1.6	8	22
20	0.01	179	0.65	2.4	1.4	2.8	1.6	3	1.6	2.9	3.4	418
21	0.01	24	0.94	1.6	61	24	1.4	2.2	21	1.6	4.4	37
22	0.24	7.7	0.93	1.2	37	5.7	1.3	1.6	30	1.3	9.4	9.9
23	0.39	4.2	1.1	1.1	11	3	1.1	3.2	46	1.1	1.7	9.3
24	0.4	3.1	8.5	1.1	3.9	39	1	11	38	0.89	1.1	16
25	0.45	2.4	7.2	1.2	1.9	21	0.99	4.1	8.6	0.79	0.76	23
26	0.43	2	2.6	1.4	1.7	6.3	0.99	2.4	4.1	0.82	0.63	34
27	0.4	3.4	1.7	2.4	2	3.6	0.92	3.8	17	0.66	0.55	24
28	0.38	82	4	1.5	1.7	2.7	0.84	2.5	4.6	0.59	0.55	20
29	0.35	10	4.3	1.4		2.3	0.81	1.5	6.4	0.52	0.6	20
30	0.33	5.1	2.4	7		11	1	1.2	2.3	0.48	0.61	22
31	0.31		1.8	4.6		36		1.2		1.1	0.5	
Total	4.87	401.65	60.64	137.29	167.97	230.00	134.65	559.59	373.81	84.64	482.55	770.89
Mean	0.16	13.39	1.96	4.43	6.00	7.42	4.49	18.10	12.50	2.73	15.60	25.70
Max	0.45	179.00	8.50	40.00	61.00	39.00	23.00	102.00	46.00	24.00	152.00	418.00
Min	0.01	0.28	0.58	0.99	0.70	1.20	0.81	0.99	0.85	0.48	0.50	0.31

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1990 (10/1/89 - 9/30/90)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	18	20	31	32	13	27	38	35	26	34	50	62
2	35	26	30	14	13	45	39	33	35	32	55	62
3	23	28	29	11	12	45	48	32	30	32	61	62
4	17	27	29	9.7	35	45	38	33	34	28	56	62
5	16	27	29	9.9	16	45	42	89	35	16	50	61
6	17	26	24	9.0	12	44	38	39	33	28	61	60
7	16	26	21	8.6	12	45	42	36	18	45	45	61
8	16	26	22	8.2	11	45	40	35	23	45	61	61
9	16	33	26	8.4	9.9	45	24	35	41	31	56	59
10	16	31	26	31	41	34	9.8	68	32	25	60	60
11	14	28	23	22	17	1.4	6.7	45	24	36	62	60
12	16	28	30	12	14	21	3.1	37	33	54	62	60
13	16	27	21	9.7	13	38	2.1	83	30	67	51	60
14	16	27	21	9.0	11	45	1.8	48	24	63	58	60
15	16	23	21	9.0	13	45	30	38	44	57	61	59
16	16	34	21	11	12	41	7.0	36	38	35	61	58
17	28	25	21	12	11	46	4.0	33	37	47	62	58
18	25	28	22	16	9.9	51	3.1	35	138	54	62	58
19	76	28	22	12	9.9	44	2.2	21	288	37	66	58
20	125	21	20	14	9.0	66	1.8	21	225	37	62	58
21	30	9.9	16	33	15	72	2.8	21	42	46	58	58
22	25	31	20	18	9.9	70	2.2	23	41	47	62	60
23	17	29	20	13	31	64	1.6	22	39	36	62	60
24	16	29	22	14	30	35	6.6	20	39	52	62	59
25	12	29	20	87	12	34	23	20	34	55	59	58
26	15	31	21	75	9.6	34	33	21	29	58	59	46
27	16	30	21	20	9.0	35	34	21	29	55	64	34
28	18	37	21	15	9.2	35	33	20	29	55	64	42
29	18	32	21	77		35	32	184	28	58	62	43
30	17	32	15	68		37	33	47	34	58	62	43
31	17		15	17		40		14		58	62	
Total	739.0	828.9	701.0	705.5	420.4	1309.4	621.8	1245.0	1532.0	1381.0	1838.0	1702.0
Mean	23.8	27.6	22.6	22.8	15.0	42.2	20.7	40.2	51.1	44.5	59.3	56.7
Max	125	37	31	87	41	72	48	184	288	67	66	62
Min	12	9.9	15	8.2	9.0	1.4	1.6	14	18	16	45	34

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1991 (10/1/90 - 9/30/91)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	43	9	10	17	11	10	12	41	42	56	60	60
2	43	9	10	14	10	10	11	39	33	60	61	61
3	43	9	18	13	10	23	11	40	25	51	61	61
4	43	9	153	12	10	37	10	41	25	60	61	60
5	43	9	19	11	10	16	10	42	24	60	61	52
6	43	9	14	12	16	22	11	63	25	60	61	60
7	43	9	12	13	27	28	13	53	25	51	61	55
8	45	9	12	11	17	14	13	44	25	59	61	61
9	95	10	11	48	13	12	17	43	34	61	62	62
10	44	84	11	25	12	11	24	43	54	60	62	61
11	43	18	10	17	11	11	27	43	59	60	62	62
12	43	12	10	70	10	11	28	42	61	60	62	62
13	43	11	10	28	10	11	25	40	60	50	61	62
14	43	11	10	16	17	12	25	42	59	60	59	55
15	43	10	15	16	13	20	26	44	59	60	60	62
16	33	10	23	79	10	14	26	43	53	60	60	62
17	42	10	13	39	10	12	26	42	56	60	60	62
18	55	11	31	17	10	39	29	43	59	58	60	61
19	110	10	20	14	12	19	26	43	60	44	47	23
20	146	10	13	13	20	14	25	42	60	41	48	54
21	42	9	23	15	13	12	82	42	60	41	49	60
22	43	9	21	12	12	11	42	33	60	42	57	60
23	107	11	30	11	11	30	32	39	60	36	60	60
24	80	12	60	11	10	22	45	40	60	47	60	61
25	144	11	16	10	10	16	37	40	60	50	60	58
26	115	10	13	10	10	14	29	40	60	40	58	60
27	43	10	12	10	10	23	28	42	60	56	53	50
28	43	10	12	10	10	16	27	44	58	61	53	58
29	43	10	13	10		13	25	42	45	60	54	58
30	22	10	49	11		17	37	40	49	60	53	55
31	10		68	16		13		39		61	52	
Total	1778	383	742	611	344	533	779	1314	1470	1685	1799	1738
Mean	57	13	24	20	12	17	26	42	49	54	58	58
Max	146	84	153	79	27	39	82	63	61	61	62	62
Min	10	9	10	10	10	10	10	33	24	36	47	23

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1992 (10/1/91 - 9/30/92)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	57	58	60	42	11	12	13	33	35	31	58	56
2	58	58	60	43	11	12	12	41	34	34	58	56
3	58	58	95	43	11	12	12	47	34	34	58	51
4	58	58	40	48	11	12	12	47	26	35	58	45
5	58	58	46	46	11	11	11	47	64	36	58	54
6	58	58	40	44	11	11	11	40	56	43	58	56
7	59	58	44	25	11	16	11	29	35	43	58	56
8	58	58	43	14	10	16	11	35	31	43	58	56
9	58	58	45	15	10	13	11	38	30	44	58	56
10	58	58	64	15	10	21	11	48	28	42	48	56
11	58	58	47	14	10	62	12	35	29	51	43	56
12	58	58	45	13	9	19	11	33	31	55	47	56
13	58	59	49	13	10	15	11	32	36	54	56	56
14	58	58	48	27	10	13	11	31	38	51	58	56
15	58	58	32	18	14	12	10	30	35	50	58	56
16	60	58	43	15	20	12	10	34	33	56	58	56
17	68	58	43	14	13	11	11	32	33	58	58	56
18	62	58	42	13	13	12	12	32	33	48	51	56
19	60	58	42	13	16	13	13	32	33	57	56	56
20	60	57	41	12	16	16	11	32	33	58	58	56
21	46	59	42	12	14	17	11	32	34	58	58	56
22	52	83	42	12	13	16	16	32	33	58	58	56
23	58	61	42	18	13	18	27	32	34	58	57	56
24	58	64	42	23	13	16	31	32	34	59	57	56
25	58	62	42	13	14	16	34	32	34	59	56	56
26	58	61	42	12	29	36	34	32	34	58	56	33
27	36	60	41	11	16	38	31	32	34	59	56	54
28	40	60	42	11	14	18	26	32	34	59	56	57
29	58	60	47	11	13	15	26	32	33	58	56	56
30	58	60	47	11		13	28	32	33	58	56	57
31	56		43	11		14		40		60	56	
Total	1758	1790	1441	632	377	538	491	1088	1044	1567	1735	1639
Mean	57	60	47	20	13	17	16	35	35	51	56	55
Max	68	83	95	48	29	62	34	48	64	60	58	57
Min	36	57	32	11	9	11	10	29	26	31	43	33

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1993 (10/1/92 - 9/30/93)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	58	44	13	14	13	22	105	15	50		58	55
2	58	44	13	13	15	25	43	14	62		60	56
3	58	55	12	12	14	31	33		62		56	56
4	56	32	12	13	12	116	28		62		56	55
5	57	32	13	79	14	43	26		62		58	56
6	58	37	12	20	14	31	25		61		58	43
7	57	31	12	16	18	24	24		57		58	43
8	53	30	12	15	18	35	24		60		58	36
9	58	29	12	14	20	32	22		51		58	25
10	52	29	12	13	21	28	80		48		58	32
11	63	29	231	13	21	28	27		59		58	38
12	62	29	41	16	21	25	22		47	38	58	49
13	60	80	22	46	27	15	17		60	43	57	56
14	55	32	17	22	26	5	15			46	57	58
15	28	30	15	16	25	10	14			42	57	60
16	42	29	14	15	42	10	94			58	57	62
17	57	29	74	14	54	71	37			58	194	62
18	31	29	24	13	31	61	21			59	45	62
19	29	28	18	12	26	40	16			68	59	60
20	29	28	19	12	24	35	13			59	62	53
21	29	28	16	12	23	54	13		40	58	61	27
22	35	28	14	23	24	62	43		59	58	57	54
23	44	121	14	16	24	61	17		53	58	54	60
24	44	40	14	16	23	147	14	55	53	58	54	60
25	44	35	13	17	22	64	13	51	60	47	50	60
26	44	22	13	14	22	47	50	57	60	57	51	70
27	44	20	12	13	22	37	20	60	58	58	55	92
28	44	15	12	13	22	44	16	53		56	59	66
29	44	14	13	13		65	15	60		49	58	42
30	43	14	16	13		37	15	61		45	54	46
31	44		16	13		30		58		52	54	
Total	1480	1043	751	551	638	1335	902	484	1124	1067	1889	1594
Mean	48	35	24	18	23	43	30	48	56	53	61	53
Max	58	121	231	79	54	147	105	61	62	62	59	194
Min	29	14	12	12	12	5	14	14	40	38	45	27

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I
East Branch Perkiomen Creek discharge (cfs) at the Bucks Road USGS Gage
Water Year 1994 (10/1/93 - 9/30/94)

Day	October	November	December	January	February	March	April	May	June	July	August	September
1	49	70	10	13	14	11	23	12				
2	51	63	9	11	17	11	21	12				
3	60	51	8	11	14	11	19	13				
4	58	37	41	10	14	11	21	14				
5	56	45	299	11	12	13	17	12				
6	58	44	22	10	13	17	17	31				
7	59	43	13	10	13	17	27	61				
8	58	42	11	11	14	36	16	54				
9	58	42	11	11	13	27	16	34				
10	58	42	13	13	13	125	17	32				
11	58	42	22	2	25	47	18	31				
12	63	41	12	6	19	25	17	30				
13	47	41	10	21	14	34	83	30				
14	38	41	10	20	14	62	35	36				
15	38	41	11	20	13	56	19	41				
16	38	40	11	20	13	34	31	65				
17	38	40	10	20	13	20	23	63				
18	49	45	11	26	12	12	17	62				
19	58	43	15	80	11	20	16	62				
20	59	34	12	0	18	39	15	62				
21	58	31	65	0	64	35	12	62				
22	65	32	21	0	45	136	12	62				
23	58	32	25	0	17	87	12	54				
24	56	13	20	0	23	54	11	56				
25	56	12	17	25	25	50	11	65				
26	57	12	16	26	14	36	11	36				
27	59	12	16	27	12	71	17	54				
28	60	199	15	93	11	77	14	58				
29	60	15	14	72		90	12	62				
30	60	12	14	37		28	12					
31	85		13	23		23						
Total	1725	1257	797	629	500	1315	592	1266	0	0	0	0
Mean	55.6	41.9	25.7	20.3	17.9	42.4	19.7	43.7	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Max	85	199	299	93	64	136	83	65				
Min	38	12	8	0	11	11	11	12				

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I

Flow diversion from Bradshaw Reservoir (MGD) to the East Branch Perkiomen Creek
1989 (1/1/89 - 1/31/89)

MGD x 1.55 = average cfs

Date	January	February	March	April	May	June	July	August	September	October	November	December
1										13.00	13.60	17.50
2										11.25	17.50	17.50
3										12.14	17.45	17.50
4									.00	11.21	17.33	17.50
5									.00	11.62	17.33	17.50
6									4.30	12.56	17.25	16.70
7									6.50	12.97	17.34	16.12
8									6.50	12.97	17.34	15.04
9									6.50	12.82	13.70	17.50
10									6.50	12.89	17.34	17.50
11									6.50	11.29	17.34	17.50
12									6.50	12.46	17.34	22.62
13									6.50	12.61	17.34	16.86
14									6.50	13.00	17.33	16.07
15									6.50	13.00	15.60	16.08
16									6.50	12.90	16.26	16.00
17									6.50	7.80	14.36	16.04
18									7.58	10.14	17.50	16.70
19									10.11	3.88	17.50	14.71
20									.55	.00	12.93	13.51
21									.00	10.23	5.71	12.74
22									.00	12.64	16.19	14.97
23									.00	11.18	17.34	15.98
24									7.33	10.13	17.33	16.12
25									12.93	7.71	17.34	16.16
26									6.74	10.31	17.33	16.22
27									11.33	11.46	17.33	12.39
28									11.85	13.00	17.33	6.48
29									11.01	13.00	17.24	6.46
30									13.00	12.40	17.50	6.46
31										12.38		6.46

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I

Flow diversion from Bradshaw Reservoir (MGD) to the East Branch Perkiomen Creek
1990 (1/1/90 - 1/31/90)

MGD x 1.55 = average cfs

Date	January	February	March	April	May	June	July	August	September	October	November	December
1	6.46	6.39	18.43	23.84	22.41	18.16	23.84	34.11	40.24	29.26	6.25	6.26
2	6.46	6.86	29.41	23.83	22.26	26.66	23.84	37.41	40.24	29.27	6.00	6.26
3	6.46	6.46	29.40	3.52	22.40	22.67	23.84	40.95	40.33	29.30	6.25	6.26
4	6.03	6.46	29.41	17.24	22.40	25.85	20.64	36.76	40.35	29.26	6.26	3.59
5	6.57	6.46	29.33	23.12	15.93	26.01	10.31	35.77	40.15	29.30	6.25	6.26
6	6.46	6.32	29.22	23.11	22.39	25.04	20.30	40.24	40.23	29.29	6.25	6.26
7	6.47	6.46	29.42	23.12	22.40	13.53	30.36	27.89	40.15	29.29	6.25	6.26
8	6.59	6.45	29.35	23.12	22.40	18.77	30.36	40.84	40.21	12.41	6.25	6.26
9	6.46	6.45	29.40	14.77	22.40	24.53	22.30	37.90	39.79	27.72	7.20	6.26
10	6.46	5.17	22.40	6.99	14.72	24.47	19.09	40.91	39.78	28.55	4.40	6.26
11	6.46	6.46	.00	.00	19.39	19.61	26.86	41.05	39.63	28.58	6.25	6.26
12	6.45	6.32	13.20	.00	22.40	26.02	38.74	41.02	40.03	28.67	6.25	6.26
13	6.46	6.46	25.20	.00	18.62	23.42	41.95	32.49	39.97	28.77	6.25	6.26
14	6.45	6.45	29.42	.00	22.41	19.01	41.95	38.60	40.05	28.77	6.25	6.14
15	6.46	6.46	29.42	.00	22.40	21.20	35.00	40.93	39.97	25.59	6.25	6.26
16	6.46	5.47	27.51	.00	22.26	27.37	24.61	40.96	39.90	28.77	6.25	6.26
17	6.19	6.46	29.42	.00	20.42	27.58	31.07	40.93	40.01	28.62	6.25	6.25
18	6.45	6.45	29.42	.00	22.40	21.93	36.10	40.90	39.90	25.19	6.25	6.25
19	6.45	6.46	28.58	.00	14.94	23.82	25.33	38.63	39.76	24.59	6.25	6.25
20	6.46	6.46	36.81	.00	15.19	23.44	25.88	40.58	39.76	28.40	6.25	6.25
21	6.46	6.46	43.77	.00	15.13	27.05	31.39	39.11	39.81	28.26	6.25	6.25
22	6.46	6.46	43.75	.00	17.24	27.09	31.50	40.31	39.75	27.60	6.25	6.25
23	6.42	6.46	41.27	.00	15.04	27.09	24.62	40.24	39.81	20.42	6.25	6.25
24	6.46	6.46	22.41	5.90	15.76	27.10	34.33	40.27	39.74	16.29	6.25	3.90
25	3.97	6.46	22.41	16.53	15.46	25.37	36.67	37.79	39.72	27.33	6.25	6.25
26	1.85	6.45	23.60	21.95	15.46	22.40	38.57	40.13	31.77	27.44	6.25	6.25
27	6.46	6.45	23.83	22.41	15.46	22.87	36.18	38.98	24.55	27.51	6.25	6.25
28	6.46	6.45	23.84	22.36	15.45	22.40	37.65	40.19	29.11	27.39	6.25	6.25
29	5.34		23.84	21.55	10.56	19.87	38.95	40.31	29.26	27.42	6.26	6.25
30	3.92		23.84	22.42	5.95	23.85	38.88	40.31	29.35	13.55	6.26	5.68
31	6.46		23.84		8.45		39.06	40.38		6.25		3.55

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I
Flow diversion from Bradshaw Reservior (MGD) to the East Branch Perkiomen Creek
1991 (1/1/91 - 1/31/91)

MGD x 1.55 = average cfs

Date	January	February	March	April	May	June	July	August	September	October	November	December
1	6.43	6.26	6.26	6.20	26.70	27.59	35.95		38.21	36.02	36.24	36.64
2	6.44	6.26	6.26	6.25	26.08	22.02	37.93		38.30	36.79	36.40	36.62
3	6.43	6.26	5.97	6.25	25.89	16.99	32.45		38.56	36.80	36.33	.00
4	6.43	6.26	4.95	6.25	26.72	16.99	37.51		38.31	36.78	36.28	13.92
5	6.44	6.27	6.22	6.25	26.95	16.16	37.46		32.66	36.80	36.33	26.46
6	6.44	6.29	6.26	6.83	26.95	16.99	37.42		37.08	36.80	36.40	23.65
7	6.44	6.20	5.54	8.40	26.89	16.98	28.31		34.37		36.51	27.27
8	6.43	6.26	6.26	8.39	26.80	16.98	37.29		38.21	36.89	36.36	27.38
9	6.43	6.26	6.26	11.71	26.76	22.20	38.18		38.46	36.84	36.32	27.69
10	6.43	6.25	6.26	16.63	26.96	34.79	38.19		38.37	36.73	36.34	
11	6.33	6.24	6.26	18.85	27.05	36.67	38.18		38.34	36.64	36.35	27.60
12	1.77	6.23	6.26	19.23	26.89	36.75	38.21		38.42		36.35	27.54
13	6.44	6.26	6.26	17.00	25.89	36.84	32.01		13.71	36.71	36.43	27.62
14	6.48	6.26	6.26	17.00	27.93	36.82	37.73		33.63	36.76		18.63
15	6.48	6.25	6.26	17.00	28.69	36.82	38.22		38.13	36.84	36.54	18.52
16	6.48	6.26	6.26	17.00	28.43	34.08	38.20		38.17	38.82	36.58	27.35
17	6.08	6.26	6.26	18.95	28.30	35.61	38.20		38.08	36.74	36.55	27.23
18	6.22	6.26	6.19	16.99	26.63	37.85	36.98	37.86	37.98	36.78	36.51	27.05
19	6.26	6.26	6.25	16.99	28.45	38.25	29.32	29.12	12.71	36.82	36.53	26.99
20	6.26	6.26	6.26	17.00	28.45	37.91	27.63	22.01	34.65	36.76	35.76	27.16
21	5.47	6.26	6.26	8.79	28.51	38.00	27.71	30.85	37.91	30.29	36.70	27.21
22	6.26	6.26	6.20	11.36	21.85	37.98	25.06	36.01	37.94	33.41	33.30	27.05
23	6.26	6.26	6.26	17.09	26.43	38.12	21.85	37.45	37.91	36.85	30.05	27.35
24	6.26	6.23	6.26	16.04	27.09	38.08	30.93	37.50	38.27	36.81	36.67	27.10
25	6.26	6.26	6.26	17.09	26.81	38.13	31.20		33.57	36.85	36.69	27.19
26	6.24	6.26	6.26	16.57	27.38	37.92	27.91		36.13	36.83	36.67	
27	6.22	6.26	6.26	17.00	27.21	37.97	28.74		36.80	23.77	36.54	27.10
28	6.22	6.26	6.20	17.00	26.84	36.83		33.19	36.48	27.56	36.52	27.35
29	6.25		6.26	16.50	27.69	29.22		34.27	36.75	36.24	36.63	27.15
30	6.26		6.26	24.80	26.60	31.59		34.09	35.28	36.31	36.64	
31	6.26		6.26		24.87			33.10		35.25		27.10

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I
Flow diversion from Bradshaw Reservior (MGD) to the East Branch Perkiomen Creek
1992 (1/1/92 - 1/31/92)

MGD x 1.55 = average cfs

Date	January	February	March	April	May	June	July	August	September	October	November	December
1	27.10	6.35	6.36	6.36	21.30	21.79	20.21	36.52	36.45	37.09	29.53	6.50
2	27.30	6.36	6.36	6.36	26.50	21.79	22.50	36.68	36.50	36.96	29.52	6.50
3	27.10	6.35	6.53	6.36	30.95	20.81	22.50	36.58	31.90	36.87	21.10	6.50
4	27.30	6.35	6.36	6.36	30.95	17.04	22.49	35.59	30.89	36.92	17.75	6.50
5	27.10	6.35	6.35	6.36	30.95	9.80	22.15	36.64	35.43	37.11	17.75	6.50
6	27.10	6.36	6.36	6.36	26.16	10.96	28.11	36.79	35.43	37.15	17.74	6.50
7	13.34	6.36	6.36	6.36	19.70		28.11	36.75	35.97	37.08	17.74	6.51
8	7.88	6.35	6.36	6.36	19.70	17.04	28.12	36.82	35.85	34.45	17.74	6.50
9	7.88	6.36	6.36	6.36	19.70	17.04	28.11	36.51	35.72	36.40	17.74	6.50
10	7.88	6.36	6.36	6.36	19.70	17.04	27.90	29.72	35.95	30.49	17.74	6.50
11	7.88	6.36	2.75	6.36	19.70	17.04	32.57	27.92	36.16	36.72	17.74	5.50
12	7.88	6.22	6.36	6.36	19.70	17.04	34.08	31.36	36.33	36.83	17.55	.00
13	7.88	6.36	6.37	6.36	19.45	20.20	33.85	35.90	36.47	37.00	13.97	3.18
14	7.88	6.36	6.37	6.36	19.45	21.10	31.68	36.44	36.49	34.20	17.57	4.93
15	7.81	6.36	6.37	6.36	19.96	21.09	31.09	36.35	36.40	16.60	17.57	5.81
16	7.87	6.36	6.36	6.36	21.18	21.07	35.03	36.25	36.35	27.83	17.57	6.32
17	7.88	6.36	6.36	6.36		21.07	35.17	36.29	36.18	36.30	17.57	4.03
18	7.88	6.36	6.36	6.36		21.08	29.68	32.90	36.11	.08	17.57	4.74
19	7.88	6.36	6.36	6.36		20.90	35.79	35.69	36.35	.11	17.57	7.05
20	7.88	6.36	6.36	6.36		21.30	35.99	36.40	36.43	.00	17.57	7.05
21	7.88	6.36	6.36	6.36		21.90	36.14	36.50	36.29	.00	17.57	7.05
22	7.88	6.36	6.36	8.48		21.70	36.40	36.60	36.86	.00	17.57	7.05
23	7.88	6.36	6.35	16.90		20.00	36.25	36.50	36.32	.00	3.94	7.05
24	7.24	6.36	6.36	19.28	21.08	22.04	36.30	36.50	36.54	.00	17.57	7.05
25	6.36	6.36	6.36	21.41	21.08	22.04	36.35	36.20	36.53	.00	14.16	7.05
26	6.36	6.36	6.36	21.41	21.08	22.04	36.57	36.08	14.39	.00	6.51	7.05
27	6.36	6.19	3.77	19.69	21.09	22.04	36.30	36.13	34.92	.28	6.5	7.05
28	6.36	6.36	6.36	17.04	21.09	22.03	36.34	35.92	36.26	.99	6.50	7.05
29	6.36	6.36	6.36	17.00	21.09	22.03	36.45	36.19	36.75	2.08	6.50	7.05
30	6.36		6.36	17.90	21.65	22.04	36.52	36.42	36.93	.79	6.50	6.40
31	6.36		6.35		21.79		36.60	36.29		1.21		6.58

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I
Flow diversion from Bradshaw Reservior (MGD) to the East Branch Perkiomen Creek
1993 (1/1/93 - 1/31/93)

MGD x 1.55 = average cfs

Date	January	February	March	April	May	June	July	August	September	October	November	December
1	6.57	6.71	11.20	2.20	7.87	32.71		40.14	38.50	30.92	34.67	7.72
2	6.57	6.61	11.20	7.40		39.32		39.60	37.17	34.19	36.53	7.72
3	6.57	6.62	11.20	11.20		39.30		35.99	36.95	35.95	30.42	7.72
4	7.15	6.74	7.00	11.20		39.30		36.71	36.87	35.95	23.18	7.62
5	4.38	6.46	.00	11.20		39.33		37.35	36.97	35.95	23.18	7.68
6	6.68	6.62	10.90	11.20		38.90		37.35	36.99	37.67	25.51	7.72
7	6.70	6.61	3.50	11.20		36.61		37.36	37.81	37.76	26.71	7.72
8	6.50	11.20	11.20	11.20		38.26		37.34	26.63	37.75	26.72	7.72
9	6.57	11.20	11.20	10.80		32.69		37.35	21.10	37.74	26.71	8.92
10	6.57	11.20	11.20	6.30		29.91		37.35	26.72	37.76	26.72	9.15
11	6.57	11.20	11.20	8.21		37.37	27.76	37.38	26.72	37.75	26.71	9.15
12	6.57	11.20	11.20	10.57		29.97	27.76	37.23	33.02	37.75	26.70	9.15
13	6.57	11.20	5.90	9.37			31.03	37.21	32.54	25.28	26.72	9.15
14	6.57	11.20	.00	7.91			31.53	37.25	39.33	25.29	26.72	9.15
15	6.57	11.20	7.40	7.48			31.90	37.54	39.32	25.28	26.72	9.15
16	6.57	9.50	3.70	7.50			39.31	37.50	39.32	25.29	26.72	9.15
17	6.57	6.20	7.10	10.83			39.31	14.10	39.32	25.30	26.72	9.46
18	6.57	11.20	.10	9.23			39.31	28.94	39.32	32.87	27.66	9.85
19	6.35	11.20	11.20	8.96			39.31	37.49	39.20	36.53	26.70	9.85
20	6.57	11.20	11.20	6.91		34.44	39.31	39.60	34.82	36.53	22.81	9.85
21	6.58	11.20	11.20	6.90		29.58	39.30	38.52	25.09	34.15	21.21	7.09
22	6.57	11.20	7.90	6.91		36.85	39.32	36.71	36.19	37.76	21.76	12.79
23	6.57	11.20	9.60	7.08	38.17	35.30	39.31	35.75	39.32	35.15	21.77	13.77
24	6.58	11.20	.00	6.86	36.10	37.90	39.31	35.87	39.32	35.15	10.05	11.63
25	6.57	11.20	6.60	6.86	33.11	37.74	33.42	32.91	39.32	35.14	9.83	10.01
26	6.57	11.20	9.60	4.53	37.28	37.82	39.32	34.66	36.10	36.18	9.63	10.01
27	6.57	11.20	11.20	5.08	38.35		39.32	37.03	36.10	37.22	9.60	10.01
28	6.57	11.20	11.20	7.86	33.81		38.35	39.37	23.90	37.23	7.02	10.01
29	6.57		4.50	7.53	39.02		35.07	38.58	24.80	37.22	7.73	10.01
30	6.53		11.20	7.88	38.70		31.83	37.05	30.90	37.22	7.72	10.01
31	6.62		11.20		36.14		37.18	36.96		37.76		7.96

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix I

Flow diversion from Bradshaw Reservior (MGD) to the East Branch Perkiomen Creek
1994 (1/1/94 - 1/31/94)

MGD x 1.55 = average cfs

Date	January	February	March	April	May	June	July	August	September	October	November	December
1	7.86	7.05	6.62	7.87	6.69							
2	7.86	7.05	6.62	7.86	6.69							
3	7.86	7.05	5.46	7.86	8.24							
4	7.98	7.05	6.76	7.68	9.11							
5	8.06	7.05	6.75	7.75	8.44							
6	7.76	7.05	6.75	7.87	23.26							
7	8.45	7.05	6.75	7.87	39.64							
8	5.00	7.05	4.61	7.22	15.08							
9	13.24	7.05	6.76	7.21	19.67							
10	6.67	7.05	2.25	7.22	19.67							
11	.00	5.78	.00	7.22	19.68							
12	4.25	7.86	.00	7.22	19.67							
13	15.16	7.86	.00	4.04	19.67							
14	14.50	7.86	.00	6.63	23.14							
15	14.69	7.86	.00	7.50	27.67							
16	14.68	7.86	.00	5.21	39.89							
17	14.50	7.86	.00	7.86	39.32							
18	14.37	7.30	.00	7.86	39.32							
19	6.27	7.05	7.46	7.86	39.32							
20	.00	7.05	7.13	7.52	39.32							
21	.00	3.54	5.71	6.69	39.32							
22	3.62	.00	.36	6.69	32.86							
23	13.30	.00	1.89	6.69	37.60							
24	15.56	3.52	2.77	6.69	36.80							
25	11.24	6.62	6.88	6.56	27.84							
26	10.24	6.06	7.87	6.69	16.40							
27	6.38	6.62	4.56	6.12	31.87							
28	3.94	6.62	6.02	6.69	35.39							
29	1.29		21.60	6.69								
30	7.86		6.22	6.69								
31	11.24		7.17									

Data gaps are the result of incomplete data available from the Delaware River Basin Commission

Appendix II: Surveying Methods

The self-leveling level was used to determine the elevation of a series of points situated along a traverse line in order to construct a topographic profile. Traverse lines were established perpendicular to the channel so as to achieve a true cross section. A stake was placed in the ground at each end of the traverse line. The distance to and bearing from some known control point or points to the stakes was noted so that the traverse could be re-established if one of the stakes were removed from the ground. The cross sections were placed as follows (refer to Figure 15):

The stream gage cross section at Spruce Road was utilized since it was necessary for the Rutgers stream gaging station and is located at the Spruce Road bridge.

RA+25B is located on the western channel about 25 ft above the confluence where the stream becomes third order.

RA+25A is located about 40 ft downstream of the same confluence.

RA+14 is located about 500 ft stream distance upstream of the outfall point on the first tight meander bend whose cutbank is the west bank.

RA12, RA18, and RA33 are located 600 ft, 900 ft, and 1650 ft (respectively) stream distance downstream of the Elephant Road bridge.

At each cross section, a bench mark had to be established by transferring the elevation of a known point to the benchmark. At most cross sections, the benchmark was established by driving a large nail into the base of a large tree that would not be growing much more. Elevation of the benchmark on the Elephant Road bridge was transferred to all of the cross sections using the following procedure:

1. Find a benchmark or some point at which the elevation is known.

2. Set up the tripod and level so that the level is higher than the benchmark and is situated somewhere between the benchmark and the first unknown point.
3. Place the stadia rod on the benchmark (making sure that the rod is vertical).
4. Shoot a back-sight to the rod, and record this value.
5. Add the value of the back-sight to the elevation of the benchmark to determine the height of the instrument (H.I.), and record this value.
6. If the first unknown point can be sighted directly from the level:
    a. Place the stadia rod on the unknown point.
    b. Shoot a foresight to the rod, and record this value.
    c. Subtract the foresight from H.I., giving the elevation of the unknown point, and record this value.
    d. Place the stadia rod back on the benchmark, shoot a foresight, subtract it from H.I.; the calculated value should be virtually identical to the known elevation of the benchmark.
7. If the first unknown point cannot be sighted directly from the level:
    a. Find a location between the level and the first unknown point that will serve as an intermediate control point; this is known as a turning point.
    b. Hammer a metal stake into the ground at the turning point, and tie a ribbon on the stake so that it can be easily found.
    c. Place the stadia rod on top of the stake, shoot a foresight, and record this value.
    d. Subtract the foresight from H.I. to determine the elevation of the turning point, and record this value.
    e. Carefully move the tripod to a location between the first turning point and the first unknown. Again make sure that the level is higher than the turning point.

f. **Re-level the level.**

g. Shoot a back-sight to the stadia rod still situated on top of the first turning point.

h. Add the back-sight to the elevation of the first turning point to determine the new height of the instrument at its new location; record this value.

i. If the first unknown point can now be seen from the new position of the level, place the stadia rod at this point, shoot a foresight, and subtract the foresight from the new H.I. to determine the elevation of the unknown point.

j. If the first unknown point still cannot be seen from the new location of the instrument, locate a second turning point, and repeat steps 7b-7h.

k. Repeat step 7j as many times as necessary until the level is situated so that it can clearly sight on the stadia rod placed on an unknown point; it may be necessary to remove shrubs or small tree limbs that obstruct the line of sight.

8. Repeat the above procedures for any other unknown points.

9. After the elevation of the last unknown point is determined, one needs to backtrack along the surveyed route in order to close the loop and determine the error (±0.010 - ±0.015 is acceptable).

   a. Through a combination of re-shooting front-sight and back-sights of turning points and the unknown points, gradually return the level to a point so that one can sight on the stadia rod placed on the original benchmark.

   b. Shoot a foresight, subtract this from the last determination of H.I., and calculate the elevation of the benchmark. This determination should agree reasonably well with its known elevation.

c. In closing the loop, the elevations of all unknown points except that located farthest from the benchmark are redetermined. Again, the second determinations should agree reasonably well with the first determinations.

d. Under some circumstances, it may be more desirable to loop back to the original starting part, rather than backtrack. In any event, the survey must return to the original benchmark. This is known as closing the loop.

e. Remove all stakes placed at turning points.

The elevations of the benchmarks used for this study are as follows:

Cross section and benchmark	Elevation (ft) above MSL
Elephant Road Bridge - NW abutment	358.67
RU Gage - SW bridge abutment	370.52
RA+25B - tree nail	362.30
RA+25A - tree nail	362.30
RA+14 - ESMP concrete pylon	358.33
RA12 - ESMP concrete pylon	352.31
RA33 - tree nail	349.32
RA18 - tree nail	352.06

When surveying the cross sections, a flexible tape was strung between the two stakes; the tape was taut and level. The distance between the two stakes was recorded. Distance along this tape from one bank or the other constitutes the X-axis of all of the diagrams of the cross sections established from this study. The following procedure was used for surveying the profile:

1. Set up the level so that there is an unobstructed view to both the benchmark and all the points along the cross section.
2. Shoot the back-sight on the control point (benchmark)
3. Add the back-sight to the benchmark to get the elevation of the instrument.
4. Position the stadia rod at the first stake and determine the first foresight.
5. Subtracting the foresight from the elevation of the instrument gives the elevation of the surveyed point.
6. Move the stadia rod to the next station, record its position along the tape measure, and record the foresight. Repeat for all stations along the traverse. Station spacing should be closer in areas of rapid change in topography.
7. The last station is at the second stake.
8. Re-shoot the back-sight on the control point and determine the error. The errors in this study were always less than ±0.003 ft.

Appendix III: Modified sieving and pipetting method

This method is based on the lab manual used in the Rutgers University sedimentology class.

Samples were wet sieved with water through a #230 (4ϕ) sieve, which allows material smaller than very fine sand (.0625 mm) to pass. The material coarse fraction was allowed to dry, and then was sieved using -1 ϕ (gravel), 0 ϕ (very coarse sand), 1 ϕ (coarse sand), 2 ϕ (medium sand), and 3 ϕ (fine sand) sieves in order to separate the different sand sizes, as well as to determine the amount of sand and gravel in the original aliquot.

The slurry that passed through the #230 sieve was treated with 6g/l sodium oxalate (an anti-flocculent), the total volume of which was recorded so that it could be subtracted later. The slurry was then decanted into a 1000 ml graduated cylinder. Water was added to bring the total volume of the suspension to 1000 ml.

The suspension was stirred well. After 20 seconds, 25 ml was withdrawn from a depth of 20 cm with a pipette and placed into a pre-weighed beaker. The beaker was dried in an oven at 110° C and allowed to re-equilibrate with ambient room humidity, and then weighed. Subtracting 1/50 of the total amount of sodium oxalate added and then multiplying by 50 gives the amount of silt and clay in the original aliquot.

After 2 hours, 3 minutes, another 25 ml was withdrawn from a depth of 10 cm with a pipette and placed into a second pre-weigher beaker. The sample was then treated in the same way as the first one. Taking the final weight of the sample, subtracting 1/50 of the total amount of sodium oxalate added and then multiplying by 50 gives the amount of clay in the original aliquot. This is subtracted from the silt and clay value to get silt. The silt and clay values were then added to the sand and gravel values to determine the original amount of material. Sand-silt-clay and sand-gravel-mud ratios were then calculated.

Appendix IV - ESMP cross-sectional area determination and vertical exaggeration correction method.

Image transfer

1. Scan the plotted cross section using an AppleScanner and AppleScan software. Use the Line *Art* setting. A threshold value of 4 was best for these cross sections given their specific level of contrast.
2. Save the file in TIFF format. Open the file using Canvas 3.5.1.
3. Use the create polygon tool in Canvas to trace the image of the cross sections and scales. Do not close the cross section polygons.

Vertical exaggeration correction and bank-full cross-sectional area determination

Vertical exaggeration correction involves re-scaling the Y axis so that it is the same as the X axis.

1. Close the polygon of the given cross section by bringing the top of the lower bank over to the other bank. Make the connecting line perfectly horizontal by holding the shift key down. Delete the points on the higher bank that do not fall within the closed polygon. This is now the bank-full cross section. One needs to always close the polygon from the same point for consistency and accuracy.
2. Select the RULERS dialog box, and set the scale to 1 point = 1 point.
3. Determine the X and Y scales in terms of points per foot for both the x and y axes. Select the RULERS dialog box, and set the scale to that of the x axis in terms of point/foot.
4. Vertical exaggeration (V.E.) = 1/(y points/x points). The correction factor = V.E. x 100. The list of the correction factors for each survey of each cross section is given Appendix V.
5. Select the cross section of interest and open the SCALES dialog box. Set the display to percent, and select Y scale, setting the value to the number obtained in step 5. The Y axis scale is now that of the X axis.
6. Select the cross section of interest and open the OBJECT SPECIFICATIONS dialog box. Click on the CALCULATE button. The bank-full cross-sectional area will be displayed.

Appendix V - Bankfull cross sectional areas for each survey of each ESMP cross section.

Survey set	TS14 (control)	TS13B	TS13A	TS12A	TS12	TS9	TS7A	TS4	TS3
19-Jul-89	48.01	85.24	103.83	122.99	174.05	130.84	147.67	98.30	89.20
16-Aug-89	50.42	87.30	104.89	122.23	174.02	130.00	149.45	105.25	94.21
12-Sep-89	49.67	88.30	102.91	125.45	174.08	131.27	146.71	106.47	92.64
27-Sep-89	47.60	87.28	107.25	127.42	171.04	127.91	153.18	103.58	89.08
25-Oct-89	48.43	66.87	108.58	121.15	171.21	125.94	147.97	101.04	87.85
20-Nov-89	54.72	77.65	114.15	126.52	168.44	129.40	151.87	103.92	90.38
3-Jan-90	47.43	72.99	110.99	161.96	181.59	132.64	150.01	100.78	91.33
1-Feb-91	51.96	72.99	114.26	160.62	184.39	126.81	152.07	102.43	91.50
26-Feb-90	54.33	69.92	108.86	158.83	182.44	123.82	149.54	102.39	91.39
19-Mar-90	53.69	73.53	104.33	159.37	187.36	129.29	152.64	101.21	89.06
11-May-90	54.53	70.57	109.98	158.07	182.51	129.35	148.98	101.56	89.77
30-May-90	54.41	74.56	111.92	159.67	187.94	135.20	146.79	-	91.85
25-Jun-90	52.93	78.27	110.96	163.31	185.06	132.46	152.42	103.94	91.05
9-Aug-90	53.08	68.77	111.40	164.29	184.23	129.18	151.63	98.88	90.28
26-Sep-90	55.97	74.40	113.30	166.91	187.44	125.93	154.89	102.54	91.61
10-Oct-90	53.91	76.07	107.50	163.95	181.57	126.09	150.24	100.25	92.62
20-Dec-90	54.71	73.59	108.47	163.04	183.35	134.27	153.76	102.53	96.68
20-Mar-91	54.53	74.73	106.86	161.32	185.05	128.07	155.10	104.52	95.12
26-Jun-91	54.61	74.17	110.26	166.55	186.36	133.36	155.49	108.00	95.65
27-Sep-91	55.32	79.37	114.68	177.59	191.64	138.52	156.86	105.36	97.32
9-Dec-91	55.89	79.92	111.41	171.48	190.58	136.13	156.92	108.68	98.72
2-Mar-92	57.11	79.63	110.15	168.37	191.30	133.18	154.97	106.54	97.00
2-Jun-92	57.19	81.12	111.22	169.05	193.76	132.97	155.86	106.66	97.12
31-Aug-92	57.81	79.22	113.69	175.98	196.22	138.36	155.65	106.80	98.25
20-Nov-92	56.65	80.15	113.37	169.90	192.67	135.49	155.13	104.66	97.16
18-Dec-92	56.40	79.03	110.68	169.27	195.73	129.81	156.40	105.55	98.24
7-Apr-93	59.53	78.18	114.96	171.10	194.35	131.19	154.24	105.64	102.32
25-Aug-93	58.27	80.86	115.00	170.84	197.35	132.33	150.87	107.75	103.59
2-Dec-93	56.64	84.96	115.57	170.90	193.57	128.67	158.61	106.77	103.63
7-Dec-93	56.61	83.07	115.51	173.84	192.58	129.00	156.41	107.29	101.91
Final absolute corrected value	98.16	101.77	149.40	144.34	192.58	177.40	115.51	90.30	58.79

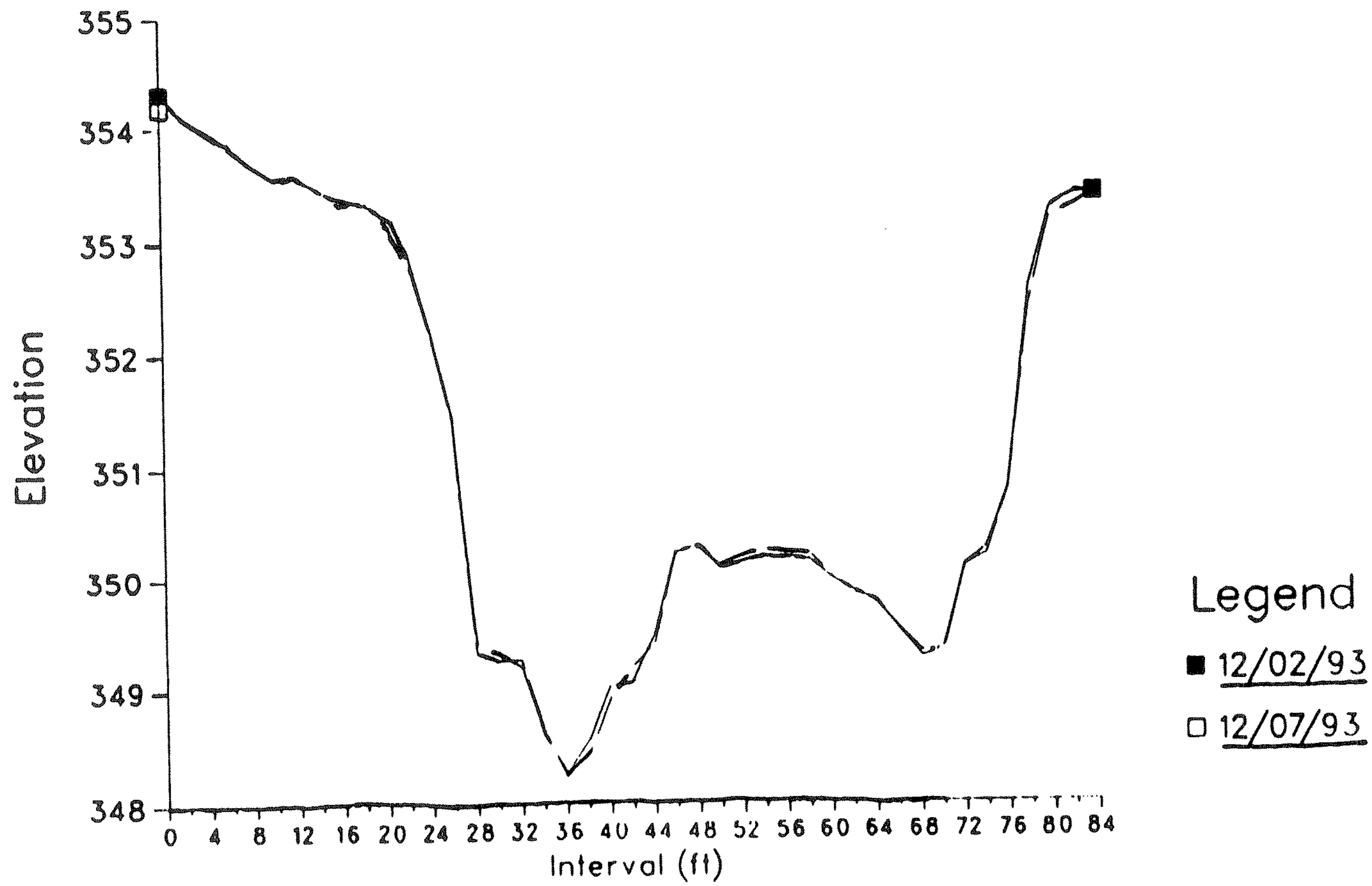
All values are in square feet

Appendix V - Table of vertical exaggeration correction factors for ESMP Cross sections

Survey set	TS14 (control)	TS13B	TS13A	TS12A	TS12	TS9	TS7A	TS4	TS3
19-Jul-89	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
16-Aug-89	41.99	25.37	22.68	5.70	11.29	10.54	10.50	20.24	14.36
12-Sep-89	41.99	25.37	22.68	5.70	11.29	10.54	10.50	20.24	14.36
27-Sep-89	41.99	25.37	22.68	5.70	11.29	10.54	10.50	20.24	14.36
25-Oct-89	41.99	25.18	22.68	5.70	11.29	10.54	10.50	20.24	14.36
20-Nov-89	41.99	25.18	22.68	5.70	11.29	10.54	10.50	20.24	14.36
3-Jan-90	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
1-Feb-91	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
26-Feb-90	20.83	19.37	15.64	5.10	9.68	7.24	8.06	10.80	10.30
19-Mar-90	20.83	19.37	15.64	5.10	9.68	7.24	8.06	10.80	10.30
11-May-90	20.83	19.37	15.64	5.10	9.68	7.24	8.06	10.80	10.30
30-May-90	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
25-Jun-90	20.83	21.72	15.64	5.10	9.68	7.24	8.06	-	10.30
9-Aug-90	20.83	19.37	15.64	5.10	9.68	7.24	8.06	10.80	10.30
26-Sep-90	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
10-Oct-90	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
20-Dec-90	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
20-Mar-91	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
26-Jun-91	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
27-Sep-91	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
9-Dec-91	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
2-Mar-92	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
2-Jun-92	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
31-Aug-92	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
20-Nov-92	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
18-Dec-92	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
7-Apr-93	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
25-Aug-93	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
2-Dec-93	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30
7-Dec-93	20.83	21.72	15.64	5.10	9.68	7.24	8.06	10.80	10.30

These are the values input into the Y-scale box in the SCALE dialog box of Canvas 3.5.1
These values represent the inverse of the percent vertical exaggeration on the original plotted cross sections

East Branch Perkiomen Creek
Stream Cross-Section Measurements at Station TS#12



Appendix VI: Hydraulic Claculations.

Date	Cross Sect.	Qg	Qp	Qm	U	h	A	P	w	R	Re #	Fr#	τ	"n"	ω1	ω2	ω3
8/10/93	RA12	1.64	1.64	2.05	1.04	.17	1.96	12.39	11.41	.16	17896.46	.80	4.12	.01	4.30	42.76	56.45
8/10/93	RA33	1.64	1.64	1.93	.89	.17	2.16	13.06	12.65	.17	15190.15	.69	4.30	.02	3.84	42.76	56.45
	Average										**16543.31**	**.75**	**4.21**	**.02**	**4.07**	**42.76**	**56.45**
8/19/93	RU Gage	.01		.01	.03	.07	.21	3.09	3.02	.07	208.25	.04	1.81	.31	.05	.16	56.45
8/19/93	RA+25B	.02		.02	.04	.19	.59	3.32	3.12	.18	724.47	.03	4.59	.42	.18	.59	56.45
	Average	**.01**									**466.36**	**.03**	**3.20**	**.36**	**.12**	**.38**	**56.45**
9/7/93	RU Gage	.00		.00	.02	.00	.00	1.75	1.75	.00	.00		.00		.00	.00	56.45
9/7/93	RA+14	.02		.02	.01	.24	1.31	5.46	5.38	.24	322.96	.01	6.26	1.53	.08	.45	56.45
9/7/93	TS14A	.00		.00	.02	.07	.26	3.87	3.78	.07	108.24	.02	1.72	.53	.03	.11	56.45
	Average	**.01**									**143.73**	**.01**	**2.66**	**1.03**	**.04**	**.19**	**56.45**
9/7/93	TS13B	1.22	1.66	.35	.53	.17	.66	4.15	3.96	.16	8898.06	.42	4.15	.03	2.22	31.70	56.45
9/7/93	TS13A	1.22	1.66	1.70	.86	.29	1.99	7.01	6.88	.28	24688.15	.51	7.38	.03	6.32	31.70	56.45
9/7/93	TS12A	1.22	1.66	.58	.55	.15	1.05	7.57	6.81	.14	8543.54	.45	3.62	.03	2.00	31.70	56.45
9/7/93	TS12	1.22	1.66	1.93	1.11	.25	1.75	6.66	6.88	.26	28029.86	.70	6.84	.02	7.55	31.70	56.45
9/7/93	RA12	1.22	1.66	1.15	.62	.24	1.86	8.54	7.81	.22	14664.59	.40	5.66	.03	3.50	31.70	56.45
9/7/93	RA18	1.22	1.66	2.95	.40	.69	7.39	11.80	10.74	.63	27393.05	.15	16.31	.10	6.51	31.70	56.45
9/7/93	RA33	1.22	1.66	1.62	.77	.16	2.11	13.55	13.03	.16	12429.17	.61	4.06	.02	3.12	31.70	56.45
	Average										**17806.63**	**.46**	**6.86**	**.03**	**4.46**	**31.70**	**56.45**
9/14/93	RU Gage	.00			.02	.05	.14	3.00	2.82	.05	89.27	.03	1.20	.37	.02	.00	56.45
9/14/93	RA12	1.64	1.72	1.85	.88	.21	2.09	10.45	9.88	.20	18692.66	.61	5.21	.02	4.61	42.76	56.45
9/14/93	RA18	1.64	1.72	3.63	.51	.66	7.06	11.75	10.72	.60	33842.63	.20	15.65	.07	8.05	42.76	56.45
9/14/93	RA33	1.64	1.72	1.74	.82	.16	2.12	13.57	13.08	.16	13259.21	.65	4.07	.02	3.34	42.76	56.45
	Average										**21931.50**	**.49**	**8.31**	**.04**	**5.33**	**42.76**	**56.45**
Rain 9/26/93	RU Gage	.26		.26	.30	.22	.89	4.26	3.98	.21	6617.03	.20	6.41	.06	1.91	8.12	56.45
9/26/93	RA+25B	.25		.25	.25	.28	.98	3.84	3.51	.26	7073.68	.15	7.88	.08	1.99	7.65	56.45
9/26/93	RA+25A	.01		.01	.00	.30	1.95	6.86	6.45	.28	129.05	.00	8.75	5.57	.04	.26	56.45
9/26/93	RA+14	.56		.56	.44	.20	1.28	6.46	6.25	.20	8940.82	.31	6.10	.04	2.67	17.25	56.45
	Average	**.27**									**5690.14**	**.17**	**7.29**	**1.44**	**1.65**	**8.32**	**56.45**
9/26/93	RA12	1.98	1.58	1.46	.70	.21	2.09	10.45	9.88	.20	14733.63	.48	6.17	.03	4.30	61.07	56.45
9/26/93	RA18	1.98	1.58	2.78	.39	.66	7.06	11.75	10.77	.60	25737.42	.16	18.52	.09	7.28	61.07	56.45
9/26/93	RA33	1.98	1.58	2.34	.87	.20	2.68	13.58	13.18	.20	17737.90	.62	6.08	.02	5.32	61.07	56.45
	Average										**19402.99**	**.42**	**10.26**	**.05**	**5.63**	**61.07**	**56.45**
10/8/93	RA12	1.64	1.65	1.15	.54	.21	2.13	10.80	10.36	.20	11108.51	.38	5.14	.03	2.78	42.76	56.45
10/8/93	RA18	1.64	1.65	1.54	.38	.41	4.06	10.38	9.83	.39	15618.62	.19	10.18	.07	3.86	42.76	56.45
10/8/93	RA33	1.64	1.65	1.71	.81	.16	2.11	13.17	12.97	.16	13171.39	.64	4.17	.02	3.38	42.76	56.45
	Average										**13299.51**	**.40**	**6.50**	**.04**	**3.34**	**42.76**	**56.45**
4/8/94	RU Gage	.01		.01	.11	.04	.10	2.82	2.74	.04	392.83	.18	.94	.02	.10	.28	56.45
4/8/94	RA+25B	.07		.07	.07	.31	.98	3.09	3.21	.32	2175.08	.04	8.29	.02	.59	1.82	56.45
	Average										**1283.96**	**.11**	**4.61**	**.02**	**.35**	**1.05**	**56.45**
4/8/94	RA12	.45	.32	.23	.30	.14	.75	5.63	5.48	.13	4113.82	.26	3.46	.02	1.04	11.72	56.45
4/8/94	RA18	.45	.32	.45	.19	.25	2.33	9.66	9.20	.24	4897.00	.12	6.27	.02	1.22	11.72	56.45
4/8/94	RA33	.45	.32	.87	.47	.23	1.86	8.97	8.12	.21	10745.58	.31	5.39	.02	2.54	11.72	56.45
	Average										**6585.47**	**.23**	**5.04**	**.02**	**1.60**	**11.72**	**56.45**
Bankfull 130 cfs 3.68 m^3/s (Calc'd U)	Average	3.68			.43	.63	8.64		13.72	.63	**26775.51**	**.17**	**20.28**	**.04**	**8.64**	**118.45**	**56.45**

List of symbols and constants

- Qg discharge at the USGS Gage (m^3/s) if downstream of outfall; Qm if upstream
- Qp pumping Rate (m^3/s)
- Qm measured discharge (m^3/s)
- U average flow velocity (m/s, measured)
- h mean flow depth (m)
- A cross sectinal area (m^2)
- P wetted perimeter (m)
- w top width (m)
- R hydraulic radius(m)
- Re# Reynold's number
- Fr# Froude number
- τ observed shear stress (N.m^2)
- "n" Manning's "n" (back-calculated)
- ω stream power
  - ω1 Shear stress*velocity
  - ω2 Density*Gravity*Q*Slope
  - ω3 D.A. * Slope
- D.A. drainage area above USGS Gage — 11.29 km^2
- ρ density of water at 21.1°C — 997.97 kg/m^3
- g acceleration due to gravity — 9.8 m/s
- μ molecular viscosity of water — .01
- Sc slope of the channel (thalweg) — .00287
- Sw slope of the water surface — .00260
- slope of the water surface at bnkfl — .00329

Appendix VII: Complete run of Empirical Model A

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
0.00	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.08	1	30	1.17	3.28	0.85	0.63	0.26	4.07	2.14	2.59	3.34	1.58
0.17	2	60	1.70	3.73	1.19	0.80	0.55	6.50	2.78	2.83	4.65	2.26
0.25	3	90	2.11	4.02	1.45	0.92	0.86	8.53	3.24	2.98	5.64	2.80
0.33	4	120	2.46	4.24	1.66	1.02	1.18	10.36	3.61	3.09	6.48	3.25
0.42	5	150	2.77	4.41	1.85	1.11	1.52	12.04	3.93	3.18	7.21	3.65
0.50	6	180	3.06	4.57	2.02	1.18	1.85	13.61	4.21	3.26	7.87	4.02
0.58	7	210	3.32	4.70	2.17	1.25	2.20	15.09	4.46	3.32	8.47	4.35
0.67	8	240	3.57	4.82	2.32	1.31	2.55	16.51	4.69	3.38	9.03	4.67
0.75	9	270	3.80	4.92	2.45	1.36	2.90	17.88	4.90	3.43	9.55	4.96
0.83	10	300	4.02	5.02	2.58	1.42	3.26	19.19	5.10	3.48	10.05	5.24
0.92	11	330	4.23	5.11	2.70	1.47	3.62	20.46	5.29	3.52	10.52	5.51
1.00	12	360	4.43	5.19	2.82	1.51	3.98	21.69	5.46	3.56	10.97	5.77
1.08	13	390	4.62	5.27	2.93	1.55	4.35	22.89	5.63	3.59	11.39	6.01
1.17	14	420	4.81	5.34	3.03	1.60	4.72	24.07	5.79	3.63	11.81	6.25
1.25	15	450	4.99	5.41	3.14	1.64	5.10	25.21	5.94	3.66	12.20	6.48
1.33	16	480	5.17	5.47	3.23	1.67	5.47	26.33	6.09	3.69	12.59	6.70
1.42	17	510	5.34	5.54	3.33	1.71	5.85	27.42	6.23	3.72	12.96	6.92
1.50	18	540	5.50	5.59	3.42	1.75	6.23	28.50	6.37	3.75	13.32	7.13
1.58	19	570	5.66	5.65	3.51	1.78	6.62	29.56	6.50	3.77	13.67	7.33
1.67	20	600	5.82	5.70	3.60	1.81	7.00	30.59	6.62	3.80	14.01	7.53
1.75	21	630	5.98	5.76	3.69	1.84	7.39	31.62	6.75	3.82	14.34	7.72
1.83	22	660	6.13	5.81	3.77	1.87	7.78	32.62	6.87	3.85	14.66	7.91
1.92	23	690	6.27	5.85	3.85	1.90	8.17	33.61	6.98	3.87	14.98	8.10
2.00	24	720	6.42	5.90	3.93	1.93	8.56	34.59	7.10	3.89	15.28	8.28
2.08	25	750	6.56	5.95	4.01	1.96	8.96	35.55	7.21	3.91	15.59	8.46
2.17	26	780	6.70	5.99	4.09	1.99	9.35	36.50	7.31	3.93	15.88	8.63
2.25	27	810	6.84	6.03	4.16	2.02	9.75	37.44	7.42	3.95	16.17	8.81
2.33	28	840	6.97	6.07	4.23	2.04	10.15	38.37	7.52	3.97	16.46	8.97
2.42	29	870	7.10	6.11	4.31	2.07	10.55	39.29	7.62	3.98	16.73	9.14
2.50	30	900	7.23	6.15	4.38	2.09	10.96	40.19	7.72	4.00	17.01	9.30
2.58	31	930	7.36	6.19	4.45	2.12	11.36	41.09	7.81	4.02	17.28	9.46
2.67	32	960	7.49	6.22	4.51	2.14	11.76	41.98	7.91	4.03	17.54	9.62
2.75	33	990	7.61	6.26	4.58	2.16	12.17	42.86	8.00	4.05	17.80	9.78
2.83	34	1020	7.73	6.29	4.65	2.19	12.58	43.73	8.09	4.07	18.06	9.93
2.92	35	1050	7.85	6.33	4.71	2.21	12.99	44.59	8.18	4.08	18.31	10.08
3.00	36	1080	7.97	6.36	4.78	2.23	13.40	45.44	8.27	4.10	18.56	10.23
3.08	37	1110	8.09	6.39	4.84	2.25	13.81	46.29	8.35	4.11	18.81	10.38
3.17	38	1140	8.21	6.42	4.90	2.28	14.22	47.12	8.44	4.12	19.05	10.52
3.25	39	1170	8.32	6.46	4.96	2.30	14.64	47.96	8.52	4.14	19.29	10.67
3.33	40	1200	8.44	6.49	5.03	2.32	15.05	48.78	8.60	4.15	19.52	10.81
3.42	41	1230	8.55	6.52	5.09	2.34	15.47	49.60	8.68	4.16	19.75	10.95
3.50	42	1260	8.66	6.54	5.15	2.36	15.88	50.41	8.76	4.18	19.98	11.09
3.58	43	1290	8.77	6.57	5.20	2.38	16.30	51.21	8.84	4.19	20.21	11.23
3.67	44	1320	8.88	6.60	5.26	2.40	16.72	52.01	8.92	4.20	20.43	11.36
3.75	45	1350	8.98	6.63	5.32	2.42	17.14	52.80	8.99	4.21	20.65	11.50
3.83	46	1380	9.09	6.66	5.38	2.43	17.56	53.59	9.07	4.23	20.87	11.63
3.92	47	1410	9.20	6.68	5.43	2.45	17.98	54.37	9.14	4.24	21.09	11.76
4.00	48	1440	9.30	6.71	5.49	2.47	18.41	55.15	9.21	4.25	21.30	11.89
4.08	49	1470	9.40	6.73	5.54	2.49	18.83	55.92	9.29	4.26	21.51	12.02
4.17	50	1500	9.51	6.76	5.60	2.51	19.26	56.68	9.36	4.27	21.72	12.15
4.25	51	1530	9.61	6.78	5.65	2.53	19.68	57.44	9.43	4.28	21.93	12.27
4.33	52	1560	9.71	6.81	5.70	2.54	20.11	58.20	9.50	4.29	22.14	12.40
4.42	53	1590	9.81	6.83	5.75	2.56	20.53	58.95	9.57	4.30	22.34	12.52
4.50	54	1620	9.90	6.86	5.81	2.58	20.96	59.70	9.63	4.31	22.54	12.64
4.58	55	1650	10.00	6.88	5.86	2.59	21.39	60.44	9.70	4.32	22.74	12.77
4.67	56	1680	10.10	6.90	5.91	2.61	21.82	61.18	9.77	4.33	22.94	12.89
4.75	57	1710	10.20	6.92	5.96	2.63	22.25	61.91	9.83	4.34	23.13	13.01
4.83	58	1740	10.29	6.95	6.01	2.64	22.68	62.64	9.90	4.35	23.32	13.12
4.92	59	1770	10.39	6.97	6.06	2.66	23.12	63.36	9.96	4.36	23.52	13.24
5.00	60	1800	10.48	6.99	6.11	2.68	23.55	64.08	10.02	4.37	23.71	13.36
5.08	61	1830	10.57	7.01	6.16	2.69	23.98	64.80	10.09	4.38	23.89	13.47
5.17	62	1860	10.66	7.03	6.21	2.71	24.42	65.51	10.15	4.39	24.08	13.59
5.25	63	1890	10.76	7.05	6.25	2.72	24.85	66.22	10.21	4.40	24.27	13.70
5.33	64	1920	10.85	7.07	6.30	2.74	25.29	66.93	10.27	4.41	24.45	13.82

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
5.42	65	1950	10.94	7.09	6.35	2.75	25.72	67.63	10.33	4.42	24.63	13.93
5.50	66	1980	11.03	7.12	6.39	2.77	26.16	68.33	10.39	4.43	24.81	14.04
5.58	67	2010	11.12	7.13	6.44	2.78	26.60	69.02	10.45	4.43	24.99	14.15
5.67	68	2040	11.20	7.15	6.49	2.80	27.04	69.72	10.51	4.44	25.17	14.26
5.75	69	2070	11.29	7.17	6.53	2.81	27.48	70.40	10.57	4.45	25.35	14.37
5.83	70	2100	11.38	7.19	6.58	2.83	27.92	71.09	10.62	4.46	25.52	14.48
5.92	71	2130	11.47	7.21	6.62	2.84	28.36	71.77	10.68	4.47	25.70	14.59
6.00	72	2160	11.55	7.23	6.67	2.85	28.80	72.45	10.74	4.48	25.87	14.69
6.08	73	2190	11.64	7.25	6.71	2.87	29.24	73.13	10.79	4.48	26.04	14.80
6.17	74	2220	11.72	7.27	6.76	2.88	29.68	73.80	10.85	4.49	26.21	14.90
6.25	75	2250	11.81	7.29	6.80	2.90	30.13	74.47	10.90	4.50	26.38	15.01
6.33	76	2280	11.89	7.30	6.84	2.91	30.57	75.13	10.96	4.51	26.55	15.11
6.42	77	2310	11.98	7.32	6.89	2.92	31.02	75.80	11.01	4.51	26.71	15.22
6.50	78	2340	12.06	7.34	6.93	2.94	31.46	76.46	11.07	4.52	26.88	15.32
6.58	79	2370	12.14	7.36	6.97	2.95	31.91	77.12	11.12	4.53	27.04	15.42
6.67	80	2400	12.22	7.37	7.01	2.96	32.35	77.77	11.17	4.54	27.21	15.52
6.75	81	2430	12.30	7.39	7.06	2.98	32.80	78.43	11.22	4.54	27.37	15.62
6.83	82	2460	12.39	7.41	7.10	2.99	33.25	79.08	11.28	4.55	27.53	15.72
6.92	83	2490	12.47	7.42	7.14	3.00	33.69	79.72	11.33	4.56	27.69	15.82
7.00	84	2520	12.55	7.44	7.18	3.02	34.14	80.37	11.38	4.56	27.85	15.92
7.08	85	2550	12.63	7.46	7.22	3.03	34.59	81.01	11.43	4.57	28.01	16.02
7.17	86	2580	12.70	7.47	7.26	3.04	35.04	81.65	11.48	4.58	28.17	16.12
7.25	87	2610	12.78	7.49	7.30	3.05	35.49	82.29	11.53	4.59	28.32	16.22
7.33	88	2640	12.86	7.50	7.34	3.07	35.94	82.93	11.58	4.59	28.48	16.32
7.42	89	2670	12.94	7.52	7.38	3.08	36.39	83.56	11.63	4.60	28.63	16.41
7.50	90	2700	13.02	7.54	7.42	3.09	36.84	84.19	11.68	4.60	28.79	16.51
7.58	91	2730	13.09	7.55	7.46	3.10	37.30	84.82	11.73	4.61	28.94	16.60
7.67	92	2760	13.17	7.57	7.50	3.11	37.75	85.44	11.78	4.62	29.09	16.70
7.75	93	2790	13.25	7.58	7.54	3.13	38.20	86.07	11.82	4.62	29.24	16.79
7.83	94	2820	13.32	7.60	7.58	3.14	38.66	86.69	11.87	4.63	29.39	16.89
7.92	95	2850	13.40	7.61	7.62	3.15	39.11	87.31	11.92	4.64	29.54	16.98
8.00	96	2880	13.47	7.63	7.66	3.16	39.57	87.93	11.97	4.64	29.69	17.07
8.08	97	2910	13.55	7.64	7.70	3.17	40.02	88.54	12.01	4.65	29.84	17.17
8.17	98	2940	13.62	7.65	7.73	3.18	40.48	89.16	12.06	4.66	29.99	17.26
8.25	99	2970	13.70	7.67	7.77	3.20	40.93	89.77	12.11	4.66	30.13	17.35
8.33	100	3000	13.77	7.68	7.81	3.21	41.39	90.38	12.15	4.67	30.28	17.44
8.42	101	3030	13.85	7.70	7.85	3.22	41.85	90.98	12.20	4.67	30.42	17.53
8.50	102	3060	13.92	7.71	7.88	3.23	42.30	91.59	12.24	4.68	30.57	17.62
8.58	103	3090	13.99	7.73	7.92	3.24	42.76	92.19	12.29	4.69	30.71	17.71
8.67	104	3120	14.06	7.74	7.96	3.25	43.22	92.79	12.33	4.69	30.85	17.80
8.75	105	3150	14.14	7.75	7.99	3.26	43.68	93.39	12.38	4.70	30.99	17.89
8.83	106	3180	14.21	7.77	8.03	3.27	44.14	93.99	12.42	4.70	31.13	17.98
8.92	107	3210	14.28	7.78	8.07	3.29	44.60	94.59	12.47	4.71	31.27	18.07
9.00	108	3240	14.35	7.79	8.10	3.30	45.06	95.18	12.51	4.71	31.41	18.16
9.08	109	3270	14.42	7.81	8.14	3.31	45.52	95.77	12.55	4.72	31.55	18.24
9.17	110	3300	14.49	7.82	8.18	3.32	45.98	96.36	12.60	4.72	31.69	18.33
9.25	111	3330	14.56	7.83	8.21	3.33	46.44	96.95	12.64	4.73	31.83	18.42
9.33	112	3360	14.63	7.85	8.25	3.34	46.91	97.54	12.68	4.74	31.97	18.50
9.42	113	3390	14.70	7.86	8.28	3.35	47.37	98.12	12.73	4.74	32.10	18.59
9.50	114	3420	14.77	7.87	8.32	3.36	47.83	98.71	12.77	4.75	32.24	18.68
9.58	115	3450	14.84	7.88	8.35	3.37	48.30	99.29	12.81	4.75	32.37	18.76
9.67	116	3480	14.91	7.90	8.39	3.38	48.76	99.87	12.85	4.76	32.51	18.85
9.75	117	3510	14.98	7.91	8.42	3.39	49.22	100.45	12.89	4.76	32.64	18.93
9.83	118	3540	15.05	7.92	8.46	3.40	49.69	101.03	12.93	4.77	32.78	19.01
9.92	119	3570	15.12	7.93	8.49	3.41	50.15	101.60	12.98	4.77	32.91	19.10
10.00	120	3600	15.18	7.95	8.52	3.42	50.62	102.17	13.02	4.78	33.04	19.18
10.08	121	3630	15.25	7.96	8.56	3.43	51.08	102.75	13.06	4.78	33.17	19.27
10.17	122	3660	15.32	7.97	8.59	3.44	51.55	103.32	13.10	4.79	33.30	19.35
10.25	123	3690	15.39	7.98	8.63	3.45	52.02	103.89	13.14	4.79	33.43	19.43
10.33	124	3720	15.45	8.00	8.66	3.46	52.48	104.45	13.18	4.80	33.56	19.51
10.42	125	3750	15.52	8.01	8.69	3.47	52.95	105.02	13.22	4.80	33.69	19.60
10.50	126	3780	15.59	8.02	8.73	3.48	53.42	105.58	13.26	4.81	33.82	19.68
10.58	127	3810	15.65	8.03	8.76	3.49	53.89	106.15	13.30	4.81	33.95	19.76
10.67	128	3840	15.72	8.04	8.79	3.50	54.36	106.71	13.34	4.82	34.08	19.84
10.75	129	3870	15.78	8.05	8.83	3.51	54.83	107.27	13.38	4.82	34.21	19.92
10.83	130	3900	15.85	8.07	8.86	3.52	55.30	107.83	13.42	4.83	34.33	20.00
10.92	131	3930	15.91	8.08	8.89	3.53	55.76	108.39	13.45	4.83	34.46	20.08

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
11.00	132	3960	15.98	8.09	8.92	3.54	56.24	108.94	13.49	4.84	34.58	20.16
11.08	133	3990	16.04	8.10	8.96	3.55	56.71	109.50	13.53	4.84	34.71	20.24
11.17	134	4020	16.11	8.11	8.99	3.56	57.18	110.05	13.57	4.85	34.83	20.32
11.25	135	4050	16.17	8.12	9.02	3.57	57.65	110.60	13.61	4.85	34.96	20.40
11.33	136	4080	16.24	8.13	9.05	3.58	58.12	111.15	13.65	4.85	35.08	20.48
11.42	137	4110	16.30	8.14	9.09	3.59	58.59	111.70	13.68	4.86	35.21	20.56
11.50	138	4140	16.36	8.16	9.12	3.60	59.06	112.25	13.72	4.86	35.33	20.63
11.58	139	4170	16.43	8.17	9.15	3.61	59.54	112.80	13.76	4.87	35.45	20.71
11.67	140	4200	16.49	8.18	9.18	3.61	60.01	113.34	13.80	4.87	35.57	20.79
11.75	141	4230	16.55	8.19	9.21	3.62	60.48	113.89	13.83	4.88	35.69	20.87
11.83	142	4260	16.61	8.20	9.24	3.63	60.96	114.43	13.87	4.88	35.81	20.94
11.92	143	4290	16.68	8.21	9.28	3.64	61.43	114.97	13.91	4.89	35.94	21.02
12.00	144	4320	16.74	8.22	9.31	3.65	61.90	115.51	13.94	4.89	36.06	21.10
12.08	145	4350	16.80	8.23	9.34	3.66	62.38	116.05	13.98	4.89	36.18	21.17
12.17	146	4380	16.86	8.24	9.37	3.67	62.85	116.59	14.02	4.90	36.29	21.25
12.25	147	4410	16.92	8.25	9.40	3.68	63.33	117.13	14.05	4.90	36.41	21.33
12.33	148	4440	16.99	8.26	9.43	3.69	63.81	117.66	14.09	4.91	36.53	21.40
12.42	149	4470	17.05	8.27	9.46	3.70	64.28	118.20	14.12	4.91	36.65	21.48
12.50	150	4500	17.11	8.28	9.49	3.70	64.76	118.73	14.16	4.92	36.77	21.55
12.58	151	4530	17.17	8.29	9.52	3.71	65.24	119.26	14.20	4.92	36.88	21.63
12.67	152	4560	17.23	8.30	9.55	3.72	65.71	119.79	14.23	4.92	37.00	21.70
12.75	153	4590	17.29	8.31	9.58	3.73	66.19	120.32	14.27	4.93	37.12	21.78
12.83	154	4620	17.35	8.32	9.61	3.74	66.67	120.85	14.30	4.93	37.23	21.85
12.92	155	4650	17.41	8.33	9.64	3.75	67.15	121.38	14.34	4.94	37.35	21.92
13.00	156	4680	17.47	8.34	9.67	3.76	67.62	121.91	14.37	4.94	37.46	22.00
13.08	157	4710	17.53	8.35	9.70	3.76	68.10	122.43	14.41	4.94	37.58	22.07
13.17	158	4740	17.59	8.36	9.73	3.77	68.58	122.96	14.44	4.95	37.69	22.14
13.25	159	4770	17.65	8.37	9.76	3.78	69.06	123.48	14.47	4.95	37.81	22.22
13.33	160	4800	17.71	8.38	9.79	3.79	69.54	124.00	14.51	4.96	37.92	22.29
13.42	161	4830	17.77	8.39	9.82	3.80	70.02	124.52	14.54	4.96	38.04	22.36
13.50	162	4860	17.83	8.40	9.85	3.81	70.50	125.04	14.58	4.96	38.15	22.44
13.58	163	4890	17.89	8.41	9.88	3.82	70.98	125.56	14.61	4.97	38.26	22.51
13.67	164	4920	17.95	8.42	9.91	3.82	71.46	126.08	14.64	4.97	38.37	22.58
13.75	165	4950	18.00	8.43	9.94	3.83	71.94	126.60	14.68	4.98	38.49	22.65
13.83	166	4980	18.06	8.44	9.96	3.84	72.43	127.11	14.71	4.98	38.60	22.72
13.92	167	5010	18.12	8.45	9.99	3.85	72.91	127.63	14.74	4.98	38.71	22.79
14.00	168	5040	18.18	8.46	10.02	3.86	73.39	128.14	14.78	4.99	38.82	22.87
14.08	169	5070	18.24	8.47	10.05	3.86	73.87	128.65	14.81	4.99	38.93	22.94
14.17	170	5100	18.29	8.48	10.08	3.87	74.35	129.16	14.84	5.00	39.04	23.01
14.25	171	5130	18.35	8.49	10.11	3.88	74.84	129.68	14.88	5.00	39.15	23.08
14.33	172	5160	18.41	8.49	10.14	3.89	75.32	130.19	14.91	5.00	39.26	23.15
14.42	173	5190	18.47	8.50	10.16	3.90	75.80	130.69	14.94	5.01	39.37	23.22
14.50	174	5220	18.52	8.51	10.19	3.90	76.29	131.20	14.97	5.01	39.48	23.29
14.58	175	5250	18.58	8.52	10.22	3.91	76.77	131.71	15.01	5.01	39.59	23.36
14.67	176	5280	18.64	8.53	10.25	3.92	77.26	132.22	15.04	5.02	39.69	23.43
14.75	177	5310	18.69	8.54	10.28	3.93	77.74	132.72	15.07	5.02	39.80	23.50
14.83	178	5340	18.75	8.55	10.31	3.94	78.23	133.22	15.10	5.03	39.91	23.57
14.92	179	5370	18.81	8.56	10.33	3.94	78.71	133.73	15.14	5.03	40.02	23.64
15.00	180	5400	18.86	8.57	10.36	3.95	79.20	134.23	15.17	5.03	40.12	23.70
15.08	181	5430	18.92	8.57	10.39	3.96	79.68	134.73	15.20	5.04	40.23	23.77
15.17	182	5460	18.97	8.58	10.42	3.97	80.17	135.23	15.23	5.04	40.34	23.84
15.25	183	5490	19.03	8.59	10.44	3.98	80.66	135.73	15.26	5.04	40.44	23.91
15.33	184	5520	19.08	8.60	10.47	3.98	81.14	136.23	15.29	5.05	40.55	23.98
15.42	185	5550	19.14	8.61	10.50	3.99	81.63	136.73	15.32	5.05	40.65	24.05
15.50	186	5580	19.20	8.62	10.53	4.00	82.12	137.23	15.36	5.05	40.76	24.11
15.58	187	5610	19.25	8.63	10.55	4.01	82.60	137.72	15.39	5.06	40.86	24.18
15.67	188	5640	19.31	8.64	10.58	4.01	83.09	138.22	15.42	5.06	40.97	24.25
15.75	189	5670	19.36	8.64	10.61	4.02	83.58	138.71	15.45	5.06	41.07	24.32
15.83	190	5700	19.42	8.65	10.63	4.03	84.07	139.20	15.48	5.07	41.18	24.38
15.92	191	5730	19.47	8.66	10.66	4.04	84.56	139.70	15.51	5.07	41.28	24.45
16.00	192	5760	19.52	8.67	10.69	4.04	85.05	140.19	15.54	5.07	41.38	24.52
16.08	193	5790	19.58	8.68	10.71	4.05	85.54	140.68	15.57	5.08	41.49	24.58
16.17	194	5820	19.63	8.69	10.74	4.06	86.03	141.17	15.60	5.08	41.59	24.65
16.25	195	5850	19.69	8.69	10.77	4.07	86.51	141.66	15.63	5.08	41.69	24.72
16.33	196	5880	19.74	8.70	10.79	4.07	87.00	142.15	15.66	5.09	41.79	24.78
16.42	197	5910	19.79	8.71	10.82	4.08	87.50	142.64	15.69	5.09	41.90	24.85
16.50	198	5940	19.85	8.72	10.85	4.09	87.99	143.12	15.72	5.09	42.00	24.91

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
16.58	199	5970	19.90	8.73	10.87	4.10	88.48	143.61	15.75	5.10	42.10	24.98
16.67	200	6000	19.96	8.73	10.90	4.10	88.97	144.09	15.78	5.10	42.20	25.04
16.75	201	6030	20.01	8.74	10.93	4.11	89.46	144.58	15.81	5.10	42.30	25.11
16.83	202	6060	20.06	8.75	10.95	4.12	89.95	145.06	15.84	5.11	42.40	25.17
16.92	203	6090	20.12	8.76	10.98	4.12	90.44	145.55	15.87	5.11	42.50	25.24
17.00	204	6120	20.17	8.77	11.00	4.13	90.93	146.03	15.90	5.11	42.60	25.30
17.08	205	6150	20.22	8.77	11.03	4.14	91.43	146.51	15.93	5.12	42.70	25.37
17.17	206	6180	20.27	8.78	11.06	4.15	91.92	146.99	15.96	5.12	42.80	25.43
17.25	207	6210	20.33	8.79	11.08	4.15	92.41	147.47	15.99	5.12	42.90	25.50
17.33	208	6240	20.38	8.80	11.11	4.16	92.90	147.95	16.02	5.13	43.00	25.56
17.42	209	6270	20.43	8.81	11.13	4.17	93.40	148.43	16.05	5.13	43.10	25.63
17.50	210	6300	20.48	8.81	11.16	4.17	93.89	148.90	16.07	5.13	43.20	25.69
17.58	211	6330	20.54	8.82	11.18	4.18	94.38	149.38	16.10	5.14	43.30	25.75
17.67	212	6360	20.59	8.83	11.21	4.19	94.88	149.86	16.13	5.14	43.39	25.82
17.75	213	6390	20.64	8.84	11.23	4.20	95.37	150.33	16.16	5.14	43.49	25.88
17.83	214	6420	20.69	8.84	11.26	4.20	95.87	150.81	16.19	5.14	43.59	25.94
17.92	215	6450	20.74	8.85	11.29	4.21	96.36	151.28	16.22	5.15	43.69	26.01
18.00	216	6480	20.79	8.86	11.31	4.22	96.86	151.75	16.25	5.15	43.78	26.07
18.08	217	6510	20.85	8.87	11.34	4.22	97.35	152.23	16.27	5.15	43.88	26.13
18.17	218	6540	20.90	8.88	11.36	4.23	97.85	152.70	16.30	5.16	43.98	26.20
18.25	219	6570	20.95	8.88	11.39	4.24	98.34	153.17	16.33	5.16	44.07	26.26
18.33	220	6600	21.00	8.89	11.41	4.24	98.84	153.64	16.36	5.16	44.17	26.32
18.42	221	6630	21.05	8.90	11.44	4.25	99.33	154.11	16.39	5.17	44.27	26.38
18.50	222	6660	21.10	8.91	11.46	4.26	99.83	154.58	16.41	5.17	44.36	26.45
18.58	223	6690	21.15	8.91	11.49	4.26	100.33	155.05	16.44	5.17	44.46	26.51
18.67	224	6720	21.20	8.92	11.51	4.27	100.82	155.51	16.47	5.18	44.55	26.57
18.75	225	6750	21.25	8.93	11.53	4.28	101.32	155.98	16.50	5.18	44.65	26.63
18.83	226	6780	21.30	8.93	11.56	4.28	101.82	156.45	16.53	5.18	44.74	26.69
18.92	227	6810	21.35	8.94	11.58	4.29	102.32	156.91	16.55	5.18	44.84	26.76
19.00	228	6840	21.40	8.95	11.61	4.30	102.81	157.38	16.58	5.19	44.93	26.82
19.08	229	6870	21.45	8.96	11.63	4.30	103.31	157.84	16.61	5.19	45.03	26.88
19.17	230	6900	21.50	8.96	11.66	4.31	103.81	158.31	16.64	5.19	45.12	26.94
19.25	231	6930	21.55	8.97	11.68	4.32	104.31	158.77	16.66	5.20	45.22	27.00
19.33	232	6960	21.60	8.98	11.71	4.32	104.81	159.23	16.69	5.20	45.31	27.06
19.42	233	6990	21.65	8.99	11.73	4.33	105.31	159.69	16.72	5.20	45.40	27.12
19.50	234	7020	21.70	8.99	11.75	4.34	105.81	160.15	16.74	5.20	45.50	27.18
19.58	235	7050	21.75	9.00	11.78	4.34	106.30	160.61	16.77	5.21	45.59	27.24
19.67	236	7080	21.80	9.01	11.80	4.35	106.80	161.07	16.80	5.21	45.68	27.30
19.75	237	7110	21.85	9.01	11.83	4.36	107.30	161.53	16.82	5.21	45.77	27.36
19.83	238	7140	21.90	9.02	11.85	4.36	107.80	161.99	16.85	5.22	45.87	27.42
19.92	239	7170	21.95	9.03	11.87	4.37	108.30	162.45	16.88	5.22	45.96	27.48
20.00	240	7200	22.00	9.03	11.90	4.38	108.80	162.91	16.90	5.22	46.05	27.54
20.08	241	7230	22.05	9.04	11.92	4.38	109.30	163.36	16.93	5.22	46.14	27.60
20.17	242	7260	22.10	9.05	11.95	4.39	109.81	163.82	16.96	5.23	46.23	27.66
20.25	243	7290	22.15	9.06	11.97	4.40	110.31	164.27	16.98	5.23	46.33	27.72
20.33	244	7320	22.20	9.06	11.99	4.40	110.81	164.73	17.01	5.23	46.42	27.78
20.42	245	7350	22.24	9.07	12.02	4.41	111.31	165.18	17.04	5.23	46.51	27.84
20.50	246	7380	22.29	9.08	12.04	4.42	111.81	165.63	17.06	5.24	46.60	27.90
20.58	247	7410	22.34	9.08	12.06	4.42	112.31	166.09	17.09	5.24	46.69	27.96
20.67	248	7440	22.39	9.09	12.09	4.43	112.82	166.54	17.11	5.24	46.78	28.02
20.75	249	7470	22.44	9.10	12.11	4.43	113.32	166.99	17.14	5.25	46.87	28.08
20.83	250	7500	22.49	9.10	12.13	4.44	113.82	167.44	17.17	5.25	46.96	28.14
20.92	251	7530	22.53	9.11	12.16	4.45	114.32	167.89	17.19	5.25	47.05	28.20
21.00	252	7560	22.58	9.12	12.18	4.45	114.83	168.34	17.22	5.25	47.14	28.26
21.08	253	7590	22.63	9.12	12.20	4.46	115.33	168.79	17.24	5.26	47.23	28.31
21.17	254	7620	22.68	9.13	12.23	4.47	115.83	169.24	17.27	5.26	47.32	28.37
21.25	255	7650	22.73	9.14	12.25	4.47	116.34	169.69	17.30	5.26	47.41	28.43
21.33	256	7680	22.77	9.14	12.27	4.48	116.84	170.14	17.32	5.26	47.50	28.49
21.42	257	7710	22.82	9.15	12.30	4.48	117.34	170.58	17.35	5.27	47.59	28.55
21.50	258	7740	22.87	9.16	12.32	4.49	117.85	171.03	17.37	5.27	47.67	28.60
21.58	259	7770	22.92	9.16	12.34	4.50	118.35	171.48	17.40	5.27	47.76	28.66
21.67	260	7800	22.96	9.17	12.37	4.50	118.86	171.92	17.42	5.27	47.85	28.72
21.75	261	7830	23.01	9.18	12.39	4.51	119.36	172.37	17.45	5.28	47.94	28.78
21.83	262	7860	23.06	9.18	12.41	4.52	119.87	172.81	17.47	5.28	48.03	28.84
21.92	263	7890	23.10	9.19	12.43	4.52	120.37	173.25	17.50	5.28	48.11	28.89
22.00	264	7920	23.15	9.20	12.46	4.53	120.88	173.70	17.52	5.29	48.20	28.95
22.08	265	7950	23.20	9.20	12.48	4.53	121.38	174.14	17.55	5.29	48.29	29.01

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
22.17	266	7980	23.24	9.21	12.50	4.54	121.89	174.58	17.57	5.29	48.38	29.06
22.25	267	8010	23.29	9.21	12.52	4.55	122.39	175.02	17.60	5.29	48.46	29.12
22.33	268	8040	23.34	9.22	12.55	4.55	122.90	175.46	17.62	5.30	48.55	29.18
22.42	269	8070	23.38	9.23	12.57	4.56	123.41	175.90	17.65	5.30	48.64	29.23
22.50	270	8100	23.43	9.23	12.59	4.56	123.91	176.34	17.67	5.30	48.72	29.29
22.58	271	8130	23.48	9.24	12.61	4.57	124.42	176.78	17.70	5.30	48.81	29.35
22.67	272	8160	23.52	9.25	12.64	4.58	124.93	177.22	17.72	5.31	48.90	29.40
22.75	273	8190	23.57	9.25	12.66	4.58	125.43	177.66	17.75	5.31	48.98	29.46
22.83	274	8220	23.62	9.26	12.68	4.59	125.94	178.10	17.77	5.31	49.07	29.52
22.92	275	8250	23.66	9.26	12.70	4.59	126.45	178.54	17.79	5.31	49.15	29.57
23.00	276	8280	23.71	9.27	12.73	4.60	126.96	178.97	17.82	5.32	49.24	29.63
23.08	277	8310	23.75	9.28	12.75	4.61	127.46	179.41	17.84	5.32	49.32	29.69
23.17	278	8340	23.80	9.28	12.77	4.61	127.97	179.84	17.87	5.32	49.41	29.74
23.25	279	8370	23.85	9.29	12.79	4.62	128.48	180.28	17.89	5.32	49.50	29.80
23.33	280	8400	23.89	9.30	12.81	4.62	128.99	180.71	17.92	5.33	49.58	29.85
23.42	281	8430	23.94	9.30	12.84	4.63	129.50	181.15	17.94	5.33	49.66	29.91
23.50	282	8460	23.98	9.31	12.86	4.64	130.01	181.58	17.96	5.33	49.75	29.96
23.58	283	8490	24.03	9.31	12.88	4.64	130.52	182.01	17.99	5.33	49.83	30.02
23.67	284	8520	24.07	9.32	12.90	4.65	131.03	182.45	18.01	5.33	49.92	30.07
23.75	285	8550	24.12	9.33	12.92	4.65	131.54	182.88	18.04	5.34	50.00	30.13
23.83	286	8580	24.16	9.33	12.95	4.66	132.04	183.31	18.06	5.34	50.09	30.19
23.92	287	8610	24.21	9.34	12.97	4.66	132.55	183.74	18.08	5.34	50.17	30.24
24.00	288	8640	24.25	9.34	12.99	4.67	133.06	184.17	18.11	5.34	50.25	30.30
24.08	289	8670	24.30	9.35	13.01	4.68	133.57	184.60	18.13	5.35	50.34	30.35
24.17	290	8700	24.34	9.36	13.03	4.68	134.09	185.03	18.15	5.35	50.42	30.40
24.25	291	8730	24.39	9.36	13.05	4.69	134.60	185.46	18.18	5.35	50.50	30.46
24.33	292	8760	24.43	9.37	13.08	4.69	135.11	185.89	18.20	5.35	50.59	30.51
24.42	293	8790	24.48	9.37	13.10	4.70	135.62	186.32	18.23	5.36	50.67	30.57
24.50	294	8820	24.52	9.38	13.12	4.70	136.13	186.75	18.25	5.36	50.75	30.62
24.58	295	8850	24.57	9.39	13.14	4.71	136.64	187.17	18.27	5.36	50.84	30.68
24.67	296	8880	24.61	9.39	13.16	4.72	137.15	187.60	18.30	5.36	50.92	30.73
24.75	297	8910	24.66	9.40	13.18	4.72	137.66	188.03	18.32	5.37	51.00	30.79
24.83	298	8940	24.70	9.40	13.20	4.73	138.17	188.45	18.34	5.37	51.08	30.84
24.92	299	8970	24.75	9.41	13.23	4.73	138.69	188.88	18.36	5.37	51.16	30.89
25.00	300	9000	24.79	9.42	13.25	4.74	139.20	189.30	18.39	5.37	51.25	30.95
25.08	301	9030	24.83	9.42	13.27	4.74	139.71	189.73	18.41	5.37	51.33	31.00
25.17	302	9060	24.88	9.43	13.29	4.75	140.22	190.15	18.43	5.38	51.41	31.06
25.25	303	9090	24.92	9.43	13.31	4.75	140.74	190.57	18.46	5.38	51.49	31.11
25.33	304	9120	24.97	9.44	13.33	4.76	141.25	191.00	18.48	5.38	51.57	31.16
25.42	305	9150	25.01	9.44	13.35	4.77	141.76	191.42	18.50	5.38	51.65	31.22
25.50	306	9180	25.05	9.45	13.37	4.77	142.28	191.84	18.53	5.39	51.73	31.27
25.58	307	9210	25.10	9.46	13.39	4.78	142.79	192.26	18.55	5.39	51.82	31.32
25.67	308	9240	25.14	9.46	13.42	4.78	143.30	192.68	18.57	5.39	51.90	31.38
25.75	309	9270	25.18	9.47	13.44	4.79	143.82	193.11	18.59	5.39	51.98	31.43
25.83	310	9300	25.23	9.47	13.46	4.79	144.33	193.53	18.62	5.39	52.06	31.48
25.92	311	9330	25.27	9.48	13.48	4.80	144.84	193.95	18.64	5.40	52.14	31.53
26.00	312	9360	25.32	9.48	13.50	4.80	145.36	194.37	18.66	5.40	52.22	31.59
26.08	313	9390	25.36	9.49	13.52	4.81	145.87	194.78	18.68	5.40	52.30	31.64
26.17	314	9420	25.40	9.49	13.54	4.82	146.39	195.20	18.71	5.40	52.38	31.69
26.25	315	9450	25.45	9.50	13.56	4.82	146.90	195.62	18.73	5.41	52.46	31.75
26.33	316	9480	25.49	9.51	13.58	4.83	147.42	196.04	18.75	5.41	52.54	31.80
26.42	317	9510	25.53	9.51	13.60	4.83	147.93	196.46	18.77	5.41	52.62	31.85
26.50	318	9540	25.57	9.52	13.62	4.84	148.45	196.87	18.80	5.41	52.70	31.90
26.58	319	9570	25.62	9.52	13.64	4.84	148.96	197.29	18.82	5.41	52.78	31.96
26.67	320	9600	25.66	9.53	13.66	4.85	149.48	197.71	18.84	5.42	52.85	32.01
26.75	321	9630	25.70	9.53	13.68	4.85	149.99	198.12	18.86	5.42	52.93	32.06
26.83	322	9660	25.75	9.54	13.71	4.86	150.51	198.54	18.89	5.42	53.01	32.11
26.92	323	9690	25.79	9.54	13.73	4.86	151.03	198.95	18.91	5.42	53.09	32.16
27.00	324	9720	25.83	9.55	13.75	4.87	151.54	199.37	18.93	5.43	53.17	32.22
27.08	325	9750	25.87	9.56	13.77	4.87	152.06	199.78	18.95	5.43	53.25	32.27
27.17	326	9780	25.92	9.56	13.79	4.88	152.58	200.19	18.97	5.43	53.33	32.32
27.25	327	9810	25.96	9.57	13.81	4.89	153.09	200.61	19.00	5.43	53.41	32.37
27.33	328	9840	26.00	9.57	13.83	4.89	153.61	201.02	19.02	5.43	53.48	32.42
27.42	329	9870	26.04	9.58	13.85	4.90	154.13	201.43	19.04	5.44	53.56	32.47
27.50	330	9900	26.09	9.58	13.87	4.90	154.64	201.84	19.06	5.44	53.64	32.53
27.58	331	9930	26.13	9.59	13.89	4.91	155.16	202.25	19.08	5.44	53.72	32.58
27.67	332	9960	26.17	9.59	13.91	4.91	155.68	202.66	19.10	5.44	53.80	32.63

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
27.75	333	9990	26.21	9.60	13.93	4.92	156.20	203.08	19.13	5.44	53.87	32.68
27.83	334	10020	26.26	9.60	13.95	4.92	156.71	203.49	19.15	5.45	53.95	32.73
27.92	335	10050	26.30	9.61	13.97	4.93	157.23	203.90	19.17	5.45	54.03	32.78
28.00	336	10080	26.34	9.61	13.99	4.93	157.75	204.30	19.19	5.45	54.10	32.83
28.08	337	10110	26.38	9.62	14.01	4.94	158.27	204.71	19.21	5.45	54.18	32.88
28.17	338	10140	26.42	9.63	14.03	4.94	158.79	205.12	19.23	5.45	54.26	32.94
28.25	339	10170	26.46	9.63	14.05	4.95	159.31	205.53	19.26	5.46	54.34	32.99
28.33	340	10200	26.51	9.64	14.07	4.95	159.83	205.94	19.28	5.46	54.41	33.04
28.42	341	10230	26.55	9.64	14.09	4.96	160.34	206.35	19.30	5.46	54.49	33.09
28.50	342	10260	26.59	9.65	14.11	4.96	160.86	206.75	19.32	5.46	54.57	33.14
28.58	343	10290	26.63	9.65	14.13	4.97	161.38	207.16	19.34	5.47	54.64	33.19
28.67	344	10320	26.67	9.66	14.15	4.97	161.90	207.57	19.36	5.47	54.72	33.24
28.75	345	10350	26.71	9.66	14.17	4.98	162.42	207.97	19.38	5.47	54.79	33.29
28.83	346	10380	26.76	9.67	14.19	4.98	162.94	208.38	19.40	5.47	54.87	33.34
28.92	347	10410	26.80	9.67	14.21	4.99	163.46	208.78	19.43	5.47	54.95	33.39
29.00	348	10440	26.84	9.68	14.23	4.99	163.98	209.19	19.45	5.48	55.02	33.44
29.08	349	10470	26.88	9.68	14.25	5.00	164.50	209.59	19.47	5.48	55.10	33.49
29.17	350	10500	26.92	9.69	14.27	5.00	165.02	210.00	19.49	5.48	55.17	33.54
29.25	351	10530	26.96	9.69	14.29	5.01	165.54	210.40	19.51	5.48	55.25	33.59
29.33	352	10560	27.00	9.70	14.31	5.01	166.06	210.80	19.53	5.48	55.32	33.64
29.42	353	10590	27.04	9.70	14.32	5.02	166.59	211.21	19.55	5.49	55.40	33.69
29.50	354	10620	27.09	9.71	14.34	5.02	167.11	211.61	19.57	5.49	55.47	33.74
29.58	355	10650	27.13	9.71	14.36	5.03	167.63	212.01	19.59	5.49	55.55	33.79
29.67	356	10680	27.17	9.72	14.38	5.03	168.15	212.41	19.61	5.49	55.62	33.84
29.75	357	10710	27.21	9.72	14.40	5.04	168.67	212.81	19.63	5.49	55.70	33.89
29.83	358	10740	27.25	9.73	14.42	5.04	169.19	213.21	19.66	5.50	55.77	33.94
29.92	359	10770	27.29	9.73	14.44	5.05	169.71	213.61	19.68	5.50	55.85	33.99
30.00	360	10800	27.33	9.74	14.46	5.05	170.24	214.02	19.70	5.50	55.92	34.04

Appendix VII: Complete run of Empirical Model B

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
0.00	0	0	0.00	0.00	#DIV/0!	#DIV/0!	0.00	0.00	0.00	-11.18	0.00	0.00
0.08	1	30	4.33	7.18	6.00	17.00	5.14	31.99	2.58	-10.94	11.21	5.88
0.17	2	60	5.40	7.42	5.78	10.07	6.12	33.48	3.42	-10.70	12.58	6.78
0.25	3	90	6.14	7.57	5.66	7.41	6.77	34.39	4.03	-10.46	13.46	7.37
0.33	4	120	6.73	7.68	5.58	5.96	7.27	35.05	4.53	-10.22	14.13	7.82
0.42	5	150	7.22	7.76	5.52	5.04	7.69	35.57	4.96	-9.98	14.66	8.18
0.50	6	180	7.65	7.83	5.46	4.39	8.05	36.00	5.34	-9.74	15.11	8.50
0.58	7	210	8.04	7.88	5.42	3.91	8.37	36.37	5.68	-9.50	15.51	8.77
0.67	8	240	8.39	7.94	5.38	3.53	8.65	36.69	6.00	-9.26	15.86	9.01
0.75	9	270	8.71	7.98	5.35	3.23	8.91	36.98	6.29	-9.02	16.17	9.23
0.83	10	300	9.00	8.02	5.32	2.98	9.15	37.23	6.57	-8.78	16.46	9.43
0.92	11	330	9.28	8.06	5.29	2.78	9.37	37.47	6.82	-8.54	16.72	9.62
1.00	12	360	9.54	8.09	5.27	2.60	9.57	37.69	7.07	-8.30	16.97	9.79
1.08	13	390	9.79	8.12	5.25	2.45	9.77	37.89	7.30	-8.06	17.20	9.95
1.17	14	420	10.02	8.15	5.23	2.31	9.95	38.07	7.53	-7.82	17.41	10.11
1.25	15	450	10.24	8.18	5.21	2.20	10.12	38.24	7.74	-7.58	17.61	10.25
1.33	16	480	10.46	8.20	5.19	2.09	10.29	38.41	7.95	-7.34	17.80	10.39
1.42	17	510	10.66	8.23	5.18	2.00	10.45	38.56	8.14	-7.10	17.99	10.52
1.50	18	540	10.85	8.25	5.16	1.91	10.60	38.71	8.34	-6.86	18.16	10.64
1.58	19	570	11.04	8.27	5.15	1.84	10.74	38.85	8.52	-6.62	18.32	10.76
1.67	20	600	11.22	8.29	5.13	1.77	10.88	38.98	8.70	-6.38	18.48	10.87
1.75	21	630	11.40	8.31	5.12	1.70	11.01	39.10	8.87	-6.14	18.63	10.98
1.83	22	660	11.57	8.33	5.11	1.64	11.14	39.22	9.04	-5.90	18.78	11.09
1.92	23	690	11.73	8.35	5.09	1.59	11.27	39.34	9.21	-5.66	18.92	11.19
2.00	24	720	11.89	8.37	5.08	1.54	11.39	39.45	9.37	-5.42	19.05	11.29
2.08	25	750	12.05	8.38	5.07	1.49	11.50	39.56	9.52	-5.18	19.18	11.38
2.17	26	780	12.20	8.40	5.06	1.45	11.62	39.66	9.68	-4.94	19.31	11.47
2.25	27	810	12.35	8.41	5.05	1.41	11.73	39.76	9.83	-4.70	19.43	11.56
2.33	28	840	12.49	8.43	5.04	1.37	11.83	39.85	9.97	-4.46	19.55	11.65
2.42	29	870	12.63	8.44	5.03	1.33	11.94	39.95	10.12	-4.22	19.66	11.73
2.50	30	900	12.77	8.46	5.02	1.30	12.04	40.03	10.26	-3.98	19.78	11.82
2.58	31	930	12.90	8.47	5.02	1.27	12.14	40.12	10.39	-3.74	19.88	11.90
2.67	32	960	13.03	8.48	5.01	1.24	12.23	40.21	10.53	-3.50	19.99	11.97
2.75	33	990	13.16	8.49	5.00	1.21	12.33	40.29	10.66	-3.26	20.09	12.05
2.83	34	1020	13.29	8.51	4.99	1.18	12.42	40.37	10.79	-3.02	20.19	12.12
2.92	35	1050	13.41	8.52	4.98	1.16	12.51	40.44	10.92	-2.78	20.29	12.20
3.00	36	1080	13.53	8.53	4.98	1.13	12.60	40.52	11.04	-2.54	20.39	12.27
3.08	37	1110	13.65	8.54	4.97	1.11	12.69	40.59	11.17	-2.30	20.48	12.34
3.17	38	1140	13.77	8.55	4.96	1.09	12.77	40.66	11.29	-2.06	20.57	12.40
3.25	39	1170	13.88	8.56	4.96	1.07	12.86	40.73	11.41	-1.82	20.66	12.47
3.33	40	1200	13.99	8.57	4.95	1.05	12.94	40.80	11.53	-1.58	20.75	12.53
3.42	41	1230	14.10	8.58	4.94	1.03	13.02	40.87	11.64	-1.34	20.83	12.60
3.50	42	1260	14.21	8.59	4.94	1.01	13.10	40.93	11.76	-1.10	20.92	12.66
3.58	43	1290	14.32	8.60	4.93	0.99	13.17	41.00	11.87	-0.86	21.00	12.72
3.67	44	1320	14.42	8.61	4.93	0.97	13.25	41.06	11.98	-0.62	21.08	12.78
3.75	45	1350	14.53	8.62	4.92	0.96	13.32	41.12	12.09	-0.38	21.16	12.84
3.83	46	1380	14.63	8.63	4.91	0.94	13.40	41.18	12.20	-0.14	21.24	12.90
3.92	47	1410	14.73	8.64	4.91	0.93	13.47	41.24	12.31	0.10	21.32	12.96
4.00	48	1440	14.83	8.65	4.90	0.91	13.54	41.30	12.41	0.34	21.39	13.01
4.08	49	1470	14.93	8.66	4.90	0.90	13.61	41.35	12.52	0.58	21.46	13.07
4.17	50	1500	15.02	8.67	4.89	0.88	13.68	41.41	12.62	0.82	21.54	13.12
4.25	51	1530	15.12	8.67	4.89	0.87	13.75	41.46	12.72	1.06	21.61	13.17
4.33	52	1560	15.21	8.68	4.88	0.86	13.81	41.52	12.82	1.30	21.68	13.23
4.42	53	1590	15.30	8.69	4.88	0.85	13.88	41.57	12.92	1.54	21.75	13.28
4.50	54	1620	15.39	8.70	4.87	0.83	13.94	41.62	13.02	1.78	21.82	13.33
4.58	55	1650	15.48	8.71	4.87	0.82	14.01	41.67	13.12	2.02	21.88	13.38
4.67	56	1680	15.57	8.71	4.86	0.81	14.07	41.72	13.21	2.26	21.95	13.43
4.75	57	1710	15.66	8.72	4.86	0.80	14.13	41.77	13.31	2.50	22.01	13.48
4.83	58	1740	15.75	8.73	4.86	0.79	14.20	41.82	13.40	2.74	22.08	13.53
4.92	59	1770	15.83	8.73	4.85	0.78	14.26	41.86	13.50	2.98	22.14	13.57
5.00	60	1800	15.92	8.74	4.85	0.77	14.32	41.91	13.59	3.22	22.20	13.62
5.08	61	1830	16.00	8.75	4.84	0.76	14.38	41.95	13.68	3.46	22.26	13.67
5.17	62	1860	16.09	8.76	4.84	0.75	14.43	42.00	13.77	3.70	22.32	13.71
5.25	63	1890	16.17	8.76	4.83	0.74	14.49	42.04	13.86	3.94	22.38	13.76
5.33	64	1920	16.25	8.77	4.83	0.73	14.55	42.09	13.95	4.18	22.44	13.80

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
5.42	65	1950	16.33	8.78	4.83	0.72	14.61	42.13	14.04	4.42	22.50	13.85
5.50	66	1980	16.41	8.78	4.82	0.72	14.66	42.17	14.13	4.66	22.56	13.89
5.58	67	2010	16.49	8.79	4.82	0.71	14.72	42.22	14.21	4.90	22.62	13.93
5.67	68	2040	16.56	8.79	4.82	0.70	14.77	42.26	14.30	5.14	22.67	13.97
5.75	69	2070	16.64	8.80	4.81	0.69	14.83	42.30	14.38	5.38	22.73	14.02
5.83	70	2100	16.72	8.81	4.81	0.68	14.88	42.34	14.47	5.62	22.78	14.06
5.92	71	2130	16.79	8.81	4.80	0.68	14.93	42.38	14.55	5.86	22.84	14.10
6.00	72	2160	16.87	8.82	4.80	0.67	14.98	42.42	14.63	6.10	22.89	14.14
6.08	73	2190	16.94	8.82	4.80	0.66	15.04	42.45	14.72	6.34	22.94	14.18
6.17	74	2220	17.02	8.83	4.79	0.66	15.09	42.49	14.80	6.58	22.99	14.22
6.25	75	2250	17.09	8.84	4.79	0.65	15.14	42.53	14.88	6.82	23.05	14.26
6.33	76	2280	17.16	8.84	4.79	0.64	15.19	42.57	14.96	7.06	23.10	14.30
6.42	77	2310	17.23	8.85	4.78	0.64	15.24	42.60	15.04	7.30	23.15	14.34
6.50	78	2340	17.30	8.85	4.78	0.63	15.29	42.64	15.12	7.54	23.20	14.37
6.58	79	2370	17.37	8.86	4.78	0.63	15.34	42.68	15.20	7.78	23.25	14.41
6.67	80	2400	17.44	8.86	4.77	0.62	15.38	42.71	15.27	8.02	23.30	14.45
6.75	81	2430	17.51	8.87	4.77	0.61	15.43	42.75	15.35	8.26	23.34	14.48
6.83	82	2460	17.58	8.87	4.77	0.61	15.48	42.78	15.43	8.50	23.39	14.52
6.92	83	2490	17.65	8.88	4.77	0.60	15.53	42.82	15.50	8.74	23.44	14.56
7.00	84	2520	17.72	8.88	4.76	0.60	15.57	42.85	15.58	8.98	23.49	14.59
7.08	85	2550	17.78	8.89	4.76	0.59	15.62	42.88	15.65	9.22	23.53	14.63
7.17	86	2580	17.85	8.89	4.76	0.59	15.67	42.92	15.73	9.46	23.58	14.66
7.25	87	2610	17.92	8.90	4.75	0.58	15.71	42.95	15.80	9.70	23.62	14.70
7.33	88	2640	17.98	8.90	4.75	0.58	15.76	42.98	15.88	9.94	23.67	14.73
7.42	89	2670	18.04	8.91	4.75	0.57	15.80	43.01	15.95	10.18	23.71	14.77
7.50	90	2700	18.11	8.91	4.75	0.57	15.84	43.05	16.02	10.42	23.76	14.80
7.58	91	2730	18.17	8.92	4.74	0.56	15.89	43.08	16.09	10.66	23.80	14.83
7.67	92	2760	18.24	8.92	4.74	0.56	15.93	43.11	16.17	10.90	23.85	14.87
7.75	93	2790	18.30	8.93	4.74	0.55	15.97	43.14	16.24	11.14	23.89	14.90
7.83	94	2820	18.36	8.93	4.73	0.55	16.02	43.17	16.31	11.38	23.93	14.93
7.92	95	2850	18.42	8.94	4.73	0.54	16.06	43.20	16.38	11.62	23.97	14.97
8.00	96	2880	18.48	8.94	4.73	0.54	16.10	43.23	16.45	11.86	24.02	15.00
8.08	97	2910	18.55	8.95	4.73	0.54	16.14	43.26	16.52	12.10	24.06	15.03
8.17	98	2940	18.61	8.95	4.72	0.53	16.19	43.29	16.59	12.34	24.10	15.06
8.25	99	2970	18.67	8.95	4.72	0.53	16.23	43.32	16.65	12.58	24.14	15.09
8.33	100	3000	18.73	8.96	4.72	0.52	16.27	43.35	16.72	12.82	24.18	15.12
8.42	101	3030	18.79	8.96	4.72	0.52	16.31	43.37	16.79	13.06	24.22	15.16
8.50	102	3060	18.84	8.97	4.71	0.52	16.35	43.40	16.86	13.30	24.26	15.19
8.58	103	3090	18.90	8.97	4.71	0.51	16.39	43.43	16.92	13.54	24.30	15.22
8.67	104	3120	18.96	8.98	4.71	0.51	16.43	43.46	16.99	13.78	24.34	15.25
8.75	105	3150	19.02	8.98	4.71	0.50	16.47	43.49	17.06	14.02	24.38	15.28
8.83	106	3180	19.08	8.98	4.71	0.50	16.51	43.51	17.12	14.26	24.42	15.31
8.92	107	3210	19.13	8.99	4.70	0.50	16.54	43.54	17.19	14.50	24.45	15.34
9.00	108	3240	19.19	8.99	4.70	0.49	16.58	43.57	17.25	14.74	24.49	15.36
9.08	109	3270	19.25	9.00	4.70	0.49	16.62	43.59	17.32	14.98	24.53	15.39
9.17	110	3300	19.30	9.00	4.70	0.49	16.66	43.62	17.38	15.22	24.57	15.42
9.25	111	3330	19.36	9.00	4.69	0.48	16.70	43.65	17.45	15.46	24.60	15.45
9.33	112	3360	19.41	9.01	4.69	0.48	16.73	43.67	17.51	15.70	24.64	15.48
9.42	113	3390	19.47	9.01	4.69	0.48	16.77	43.70	17.57	15.94	24.68	15.51
9.50	114	3420	19.52	9.01	4,69	0.47	16.81	43.72	17.64	16.18	24.71	15.54
9.58	115	3450	19.58	9.02	4.69	0.47	16.85	43.75	17.70	16.42	24.75	15.56
9.67	116	3480	19.63	9.02	4.68	0.47	16.88	43.77	17.76	16.66	24.79	15.59
9.75	117	3510	19.68	9.03	4.68	0.46	16.92	43.80	17.82	16.90	24.82	15.62
9.83	118	3540	19.74	9.03	4.68	0.46	16.95	43.82	17.88	17.14	24.86	15.65
9.92	119	3570	19.79	9.03	4.68	0.46	16.99	43.85	17.95	17.38	24.89	15.67
10.00	120	3600	19.84	9.04	4.68	0.46	17.03	43.87	18.01	17.62	24.93	15.70
10.08	121	3630	19.90	9.04	4.67	0.45	17.06	43.89	18.07	17.86	24.96	15.73
10.17	122	3660	19.95	9.04	4.67	0.45	17.10	43.92	18.13	18.10	25.00	15.75
10.25	123	3690	20.00	9.05	4.67	0.45	17.13	43.94	18.19	18.34	25.03	15.78
10.33	124	3720	20.05	9.05	4.67	0.44	17.17	43.97	18.25	18.58	25.06	15.81
10.42	125	3750	20.10	9.05	4.67	0.44	17.20	43.99	18.31	18.82	25.10	15.83
10.50	126	3780	20.15	9.06	4.66	0.44	17.23	44.01	18.37	19.06	25.13	15.86
10.58	127	3810	20.21	9.06	4.66	0.44	17.27	44.04	18.43	19.30	25.16	15.88
10.67	128	3840	20.26	9.07	4.66	0.43	17.30	44.06	18.48	19.54	25.20	15.91
10.75	129	3870	20.31	9.07	4.66	0.43	17.34	44.08	18.54	19.78	25.23	15.93
10.83	130	3900	20.36	9.07	4.66	0.43	17.37	44.10	18.60	20.02	25.26	15.96
10.92	131	3930	20.41	9.08	4.65	0.43	17.40	44.13	18.66	20.26	25.30	15.99

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
11.00	132	3960	20.45	9.08	4.65	0.42	17.44	44.15	18.72	20.50	25.33	16.01
11.08	133	3990	20.50	9.08	4.65	0.42	17.47	44.17	18.77	20.74	25.36	16.03
11.17	134	4020	20.55	9.09	4.65	0.42	17.50	44.19	18.83	20.98	25.39	16.06
11.25	135	4050	20.60	9.09	4.65	0.42	17.53	44.21	18.89	21.22	25.42	16.08
11.33	136	4080	20.65	9.09	4.64	0.41	17.57	44.23	18.95	21.46	25.45	16.11
11.42	137	4110	20.70	9.09	4.64	0.41	17.60	44.26	19.00	21.70	25.49	16.13
11.50	138	4140	20.75	9.10	4.64	0.41	17.63	44.28	19.06	21.94	25.52	16.16
11.58	139	4170	20.79	9.10	4.64	0.41	17.66	44.30	19.11	22.18	25.55	16.18
11.67	140	4200	20.84	9.10	4.64	0.41	17.69	44.32	19.17	22.42	25.58	16.20
11.75	141	4230	20.89	9.11	4.64	0.40	17.73	44.34	19.23	22.66	25.61	16.23
11.83	142	4260	20.94	9.11	4.63	0.40	17.76	44.36	19.28	22.90	25.64	16.25
11.92	143	4290	20.98	9.11	4.63	0.40	17.79	44.38	19.34	23.14	25.67	16.28
12.00	144	4320	21.03	9.12	4.63	0.40	17.82	44.40	19.39	23.38	25.70	16.30
12.08	145	4350	21.07	9.12	4.63	0.39	17.85	44.42	19.44	23.62	25.73	16.32
12.17	146	4380	21.12	9.12	4.63	0.39	17.88	44.44	19.50	23.86	25.76	16.34
12.25	147	4410	21.17	9.13	4.63	0.39	17.91	44.46	19.55	24.10	25.79	16.37
12.33	148	4440	21.21	9.13	4.62	0.39	17.94	44.48	19.61	24.34	25.82	16.39
12.42	149	4470	21.26	9.13	4.62	0.39	17.97	44.50	19.66	24.58	25.84	16.41
12.50	150	4500	21.30	9.13	4.62	0.38	18.00	44.52	19.71	24.82	25.87	16.44
12.58	151	4530	21.35	9.14	4.62	0.38	18.03	44.54	19.77	25.06	25.90	16.46
12.67	152	4560	21.39	9.14	4.62	0.38	18.06	44.56	19.82	25.30	25.93	16.48
12.75	153	4590	21.44	9.14	4.62	0.38	18.09	44.58	19.87	25.54	25.96	16.50
12.83	154	4620	21.48	9.15	4.61	0.38	18.12	44.60	19.93	25.78	25.99	16.52
12.92	155	4650	21.53	9.15	4.61	0.38	18.15	44.62	19.98	26.02	26.02	16.55
13.00	156	4680	21.57	9.15	4.61	0.37	18.18	44.64	20.03	26.26	26.04	16.57
13.08	157	4710	21.61	9.15	4.61	0.37	18.21	44.66	20.08	26.50	26.07	16.59
13.17	158	4740	21.66	9.16	4.61	0.37	18.24	44.67	20.13	26.74	26.10	16.61
13.25	159	4770	21.70	9.16	4.61	0.37	18.27	44.69	20.19	26.98	26.13	16.63
13.33	160	4800	21.75	9.16	4.61	0.37	18.30	44.71	20.24	27.22	26.15	16.65
13.42	161	4830	21.79	9.17	4.60	0.36	18.32	44.73	20.29	27.46	26.18	16.68
13.50	162	4860	21.83	9.17	4.60	0.36	18.35	44.75	20.34	27.70	26.21	16.70
13.58	163	4890	21.87	9.17	4.60	0.36	18.38	44.77	20.39	27.94	26.24	16.72
13.67	164	4920	21.92	9.17	4.60	0.36	18.41	44.78	20.44	28.18	26.26	16.74
13.75	165	4950	21.96	9.18	4.60	0.36	18.44	44.80	20.49	28.42	26.29	16.76
13.83	166	4980	22.00	9.18	4.60	0.36	18.46	44.82	20.54	28.66	26.32	16.78
13.92	167	5010	22.04	9.18	4.60	0.35	18.49	44.84	20.59	28.90	26.34	16.80
14.00	168	5040	22.09	9.18	4.59	0.35	18.52	44.86	20.64	29.14	26.37	16.82
14.08	169	5070	22.13	9.19	4.59	0.35	18.55	44.87	20.69	29.38	26.39	16.84
14.17	170	5100	22.17	9.19	4.59	0.35	18.57	44.89	20.74	29.62	26.42	16.86
14.25	171	5130	22.21	9.19	4.59	0.35	18.60	44.91	20.79	29.86	26.45	16.88
14.33	172	5160	22.25	9.19	4.59	0.35	18.63	44.93	20.84	30.10	26.47	16.90
14.42	173	5190	22.29	9.20	4.59	0.35	18.66	44.94	20.89	30.34	26.50	16.92
14.50	174	5220	22.33	9.20	4.59	0.34	18.68	44.96	20.94	30.58	26.52	16.94
14.58	175	5250	22.37	9.20	4.58	0.34	18.71	44.98	20.99	30.82	26.55	16.96
14.67	176	5280	22.41	9.20	4.58	0.34	18.74	44.99	21.04	31.06	26.57	16.98
14.75	177	5310	22.45	9.21	4.58	0.34	18.76	45.01	21.08	31.30	26.60	17.00
14.83	178	5340	22.49	9.21	4.58	0.34	18.79	45.03	21.13	31.54	26.62	17.02
14.92	179	5370	22.54	9.21	4.58	0.34	18.82	45.04	21.18	31.78	26.65	17.04
15.00	180	5400	22.57	9.21	4.58	0.34	18.84	45.06	21.23	32.02	26.67	17.06
15.08	181	5430	22.61	9.22	4.58	0.33	18.87	45.08	21.28	32.26	26.70	17.08
15.17	182	5460	22.65	9.22	4.58	0.33	18.89	45.09	21.32	32.50	26.72	17.10
15.25	183	5490	22.69	9.22	4.57	0.33	18.92	45.11	21.37	32.74	26.75	17.12
15.33	184	5520	22.73	9.22	4.57	0.33	18.95	45.13	21.42	32.98	26.77	17.14
15.42	185	5550	22.77	9.23	4.57	0.33	18.97	45.14	21.47	33.22	26.80	17.16
15.50	186	5580	22.81	9.23	4.57	0.33	19.00	45.16	21.51	33.46	26.82	17.18
15.58	187	5610	22.85	9.23	4.57	0.33	19.02	45.17	21.56	33.70	26.84	17.20
15.67	188	5640	22.89	9.23	4.57	0.32	19.05	45.19	21.61	33.94	26.87	17.21
15.75	189	5670	22.93	9.24	4.57	0.32	19.07	45.21	21.65	34.18	26.89	17.23
15.83	190	5700	22.97	9.24	4.56	0.32	19.10	45.22	21.70	34.42	26.92	17.25
15.92	191	5730	23.00	9.24	4.56	0.32	19.12	45.24	21.75	34.66	26.94	17.27
16.00	192	5760	23.04	9.24	4.56	0.32	19.15	45.25	21.79	34.90	26.96	17.29
16.08	193	5790	23.08	9.25	4.56	0.32	19.17	45.27	21.84	35.14	26.99	17.31
16.17	194	5820	23.12	9.25	4.56	0.32	19.20	45.28	21.88	35.38	27.01	17.33
16.25	195	5850	23.16	9.25	4.56	0.32	19.22	45.30	21.93	35.62	27.03	17.34
16.33	196	5880	23.19	9.25	4.56	0.31	19.25	45.31	21.98	35.86	27.06	17.36
16.42	197	5910	23.23	9.25	4.56	0.31	19.27	45.33	22.02	36.10	27.08	17.38
16.50	198	5940	23.27	9.26	4.56	0.31	19.30	45.34	22.07	36.34	27.10	17.40

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
16.58	199	5970	23.31	9.26	4.55	0.31	19.32	45.36	22.11	36.58	27.12	17.42
16.67	200	6000	23.34	9.26	4.55	0.31	19.34	45.38	22.16	36.82	27.15	17.43
16.75	201	6030	23.38	9.26	4.55	0.31	19.37	45.39	22.20	37.06	27.17	17.45
16.83	202	6060	23.42	9.27	4.55	0.31	19.39	45.40	22.25	37.30	27.19	17.47
16.92	203	6090	23.45	9.27	4.55	0.31	19.42	45.42	22.29	37.54	27.21	17.49
17.00	204	6120	23.49	9.27	4.55	0.31	19.44	45.43	22.34	37.78	27.24	17.50
17.08	205	6150	23.53	9.27	4.55	0.30	19.46	45.45	22.38	38.02	27.26	17.52
17.17	206	6180	23.56	9.27	4.55	0.30	19.49	45.46	22.42	38.26	27.28	17.54
17.25	207	6210	23.60	9.28	4.54	0.30	19.51	45.48	22.47	38.50	27.30	17.56
17.33	208	6240	23.64	9.28	4.54	0.30	19.54	45.49	22.51	38.74	27.33	17.57
17.42	209	6270	23.67	9.28	4.54	0.30	19.56	45.51	22.56	38.98	27.35	17.59
17.50	210	6300	23.71	9.28	4.54	0.30	19.58	45.52	22.60	39.22	27.37	17.61
17.58	211	6330	23.75	9.29	4.54	0.30	19.61	45.54	22.64	39.46	27.39	17.63
17.67	212	6360	23.78	9.29	4.54	0.30	19.63	45.55	22.69	39.70	27.41	17.64
17.75	213	6390	23.82	9.29	4.54	0.30	19.65	45.56	22.73	39.94	27.43	17.66
17.83	214	6420	23.85	9.29	4.54	0.29	19.67	45.58	22.77	40.18	27.46	17.68
17.92	215	6450	23.89	9.29	4.54	0.29	19.70	45.59	22.82	40.42	27.48	17.69
18.00	216	6480	23.92	9.30	4.53	0.29	19.72	45.61	22.86	40.66	27.50	17.71
18.08	217	6510	23.96	9.30	4.53	0.29	19.74	45.62	22.90	40.90	27.52	17.73
18.17	218	6540	23.99	9.30	4.53	0.29	19.77	45.63	22.95	41.14	27.54	17.74
18.25	219	6570	24.03	9.30	4.53	0.29	19.79	45.65	22.99	41.38	27.56	17.76
18.33	220	6600	24.06	9.30	4.53	0.29	19.81	45.66	23.03	41.62	27.58	17.78
18.42	221	6630	24.10	9.31	4.53	0.29	19.83	45.68	23.07	41.86	27.60	17.79
18.50	222	6660	24.13	9.31	4.53	0.29	19.86	45.69	23.12	42.10	27.62	17.81
18.58	223	6690	24.17	9.31	4.53	0.29	19.88	45.70	23.16	42.34	27.65	17.83
18.67	224	6720	24.20	9.31	4.53	0.28	19.90	45.72	23.20	42.58	27.67	17.84
18.75	225	6750	24.24	9.31	4.52	0.28	19.92	45.73	23.24	42.82	27.69	17.86
18.83	226	6780	24.27	9.32	4.52	0.28	19.95	45.74	23.28	43.06	27.71	17.88
18.92	227	6810	24.30	9.32	4.52	0.28	19.97	45.76	23.33	43.30	27.73	17.89
19.00	228	6840	24.34	9.32	4.52	0.28	19.99	45.77	23.37	43.54	27.75	17.91
19.08	229	6870	24.37	9.32	4.52	0.28	20.01	45.78	23.41	43.78	27.77	17.92
19.17	230	6900	24.41	9.32	4.52	0.28	20.03	45.80	23.45	44.02	27.79	17.94
19.25	231	6930	24.44	9.33	4.52	0.28	20.05	45.81	23.49	44.26	27.81	17.96
19.33	232	6960	24.47	9.33	4.52	0.28	20.08	45.82	23.53	44.50	27.83	17.97
19.42	233	6990	24.51	9.33	4.52	0.28	20.10	45.83	23.57	44.74	27.85	17.99
19.50	234	7020	24.54	9.33	4.52	0.28	20.12	45.85	23.61	44.98	27.87	18.00
19.58	235	7050	24.57	9.33	4.51	0.27	20.14	45.86	23.66	45.22	27.89	18.02
19.67	236	7080	24.61	9.34	4.51	0.27	20.16	45.87	23.70	45.46	27.91	18.04
19.75	237	7110	24.64	9.34	4.51	0.27	20.18	45.89	23.74	45.70	27.93	18.05
19.83	238	7140	24.67	9.34	4.51	0.27	20.20	45.90	23.78	45.94	27.95	18.07
19.92	239	7170	24.70	9.34	4.51	0.27	20.23	45.91	23.82	46.18	27.97	18.08
20.00	240	7200	24.74	9.34	4.51	0.27	20.25	45.92	23.86	46.42	27.99	18.10
20.08	241	7230	24.77	9.34	4.51	0.27	20.27	45.94	23.90	46.66	28.01	18.11
20.17	242	7260	24.80	9.35	4.51	0.27	20.29	45.95	23.94	46.90	28.03	18.13
20.25	243	7290	24.84	9.35	4.51	0.27	20.31	45.96	23.98	47.14	28.04	18.14
20.33	244	7320	24.87	9.35	4.51	0.27	20.33	45.97	24.02	47.38	28.06	18.16
20.42	245	7350	24.90	9.35	4.50	0.27	20.35	45.99	24.06	47.62	28.08	18.17
20.50	246	7380	24.93	9.35	4.50	0.26	20.37	46.00	24.10	47.86	28.10	18.19
20.58	247	7410	24.96	9.36	4.50	0.26	20.39	46.01	24.14	48.10	28.12	18.20
20.67	248	7440	25.00	9.36	4.50	0.26	20.41	46.02	24.18	48.34	28.14	18.22
20.75	249	7470	25.03	9.36	4.50	0.26	20.43	46.04	24.22	48.58	28.16	18.23
20.83	250	7500	25.06	9.36	4.50	0.26	20.45	46.05	24.26	48.82	28.18	18.25
20.92	251	7530	25.09	9.36	4.50	0.26	20.48	46.06	24.30	49.06	28.20	18.26
21.00	252	7560	25.12	9.36	4.50	0.26	20.50	46.07	24.34	49.30	28.22	18.28
21.08	253	7590	25.16	9.37	4.50	0.26	20.52	46.08	24.38	49.54	28.23	18.29
21.17	254	7620	25.19	9.37	4.50	0.26	20.54	46.10	24.41	49.78	28.25	18.31
21.25	255	7650	25.22	9.37	4.50	0.26	20.56	46.11	24.45	50.02	28.27	18.32
21.33	256	7680	25.25	9.37	4.49	0.26	20.58	46.12	24.49	50.26	28.29	18.34
21.42	257	7710	25.28	9.37	4.49	0.26	20.60	46.13	24.53	50.50	28.31	18.35
21.50	258	7740	25.31	9.38	4.49	0.26	20.62	46.14	24.57	50.74	28.33	18.37
21.58	259	7770	25.34	9.38	4.49	0.25	20.64	46.16	24.61	50.98	28.34	18.38
21.67	260	7800	25.38	9.38	4.49	0.25	20.66	46.17	24.65	51.22	28.36	18.40
21.75	261	7830	25.41	9.38	4.49	0.25	20.68	46.18	24.69	51.46	28.38	18.41
21.83	262	7860	25.44	9.38	4.49	0.25	20.70	46.19	24.72	51.70	28.40	18.43
21.92	263	7890	25.47	9.38	4.49	0.25	20.72	46.20	24.76	51.94	28.42	18.44
22.00	264	7920	25.50	9.39	4.49	0.25	20.74	46.21	24.80	52.18	28.44	18.45
22.08	265	7950	25.53	9.39	4.49	0.25	20.75	46.23	24.84	52.42	28.45	18.47

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
22.17	266	7980	25.56	9.39	4.49	0.25	20.77	46.24	24.88	52.66	28.47	18.48
22.25	267	8010	25.59	9.39	4.48	0.25	20.79	46.25	24.91	52.90	28.49	18.50
22.33	268	8040	25.62	9.39	4.48	0.25	20.81	46.26	24.95	53.14	28.51	18.51
22.42	269	8070	25.65	9.39	4.48	0.25	20.83	46.27	24.99	53.38	28.52	18.53
22.50	270	8100	25.68	9.40	4.48	0.25	20.85	46.28	25.03	53.62	28.54	18.54
22.58	271	8130	25.71	9.40	4.48	0.25	20.87	46.29	25.07	53.86	28.56	18.55
22.67	272	8160	25.74	9.40	4.48	0.25	20.89	46.31	25.10	54.10	28.58	18.57
22.75	273	8190	25.77	9.40	4.48	0.24	20.91	46.32	25.14	54.34	28.60	18.58
22.83	274	8220	25.80	9.40	4.48	0.24	20.93	46.33	25.18	54.58	28.61	18.60
22.92	275	8250	25.83	9.40	4.48	0.24	20.95	46.34	25.21	54.82	28.63	18.61
23.00	276	8280	25.86	9.41	4.48	0.24	20.97	46.35	25.25	55.06	28.65	18.62
23.08	277	8310	25.89	9.41	4.48	0.24	20.99	46.36	25.29	55.30	28.66	18.64
23.17	278	8340	25.92	9.41	4.48	0.24	21.00	46.37	25.33	55.54	28.68	18.65
23.25	279	8370	25.95	9.41	4.47	0.24	21.02	46.38	25.36	55.78	28.70	18.66
23.33	280	8400	25.98	9.41	4.47	0.24	21.04	46.39	25.40	56.02	28.72	18.68
23.42	281	8430	26.01	9.41	4.47	0.24	21.06	46.40	25.44	56.26	28.73	18.69
23.50	282	8460	26.04	9.42	4.47	0.24	21.08	46.42	25.47	56.50	28.75	18.71
23.58	283	8490	26.07	9.42	4.47	0.24	21.10	46.43	25.51	56.74	28.77	18.72
23.67	284	8520	26.10	9.42	4.47	0.24	21.12	46.44	25.55	56.98	28.78	18.73
23.75	285	8550	26.13	9.42	4.47	0.24	21.14	46.45	25.58	57.22	28.80	18.75
23.83	286	8580	26.16	9.42	4.47	0.24	21.15	46.46	25.62	57.46	28.82	18.76
23.92	287	8610	26.19	9.42	4.47	0.24	21.17	46.47	25.66	57.70	28.83	18.77
24.00	288	8640	26.21	9.43	4.47	0.24	21.19	46.48	25.69	57.94	28.85	18.79
24.08	289	8670	26.24	9.43	4.47	0.23	21.21	46.49	25.73	58.18	28.87	18.80
24.17	290	8700	26.27	9.43	4.47	0.23	21.23	46.50	25.76	58.42	28.89	18.81
24.25	291	8730	26.30	9.43	4.46	0.23	21.25	46.51	25.80	58.66	28.90	18.83
24.33	292	8760	26.33	9.43	4.46	0.23	21.26	46.52	25.84	58.90	28.92	18.84
24.42	293	8790	26.36	9.43	4.46	0.23	21.28	46.53	25.87	59.14	28.93	18.85
24.50	294	8820	26.39	9.43	4.46	0.23	21.30	46.54	25.91	59.38	28.95	18.87
24.58	295	8850	26.42	9.44	4.46	0.23	21.32	46.55	25.94	59.62	28.97	18.88
24.67	296	8880	26.44	9.44	4.46	0.23	21.34	46.56	25.98	59.86	28.98	18.89
24.75	297	8910	26.47	9.44	4.46	0.23	21.35	46.57	26.02	60.10	29.00	18.91
24.83	298	8940	26.50	9.44	4.46	0.23	21.37	46.59	26.05	60.34	29.02	18.92
24.92	299	8970	26.53	9.44	4.46	0.23	21.39	46.60	26.09	60.58	29.03	18.93
25.00	300	9000	26.56	9.44	4.46	0.23	21.41	46.61	26.12	60.82	29.05	18.94
25.08	301	9030	26.58	9.45	4.46	0.23	21.43	46.62	26.16	61.06	29.07	18.96
25.17	302	9060	26.61	9.45	4.46	0.23	21.44	46.63	26.19	61.30	29.08	18.97
25.25	303	9090	26.64	9.45	4.46	0.23	21.46	46.64	26.23	61.54	29.10	18.98
25.33	304	9120	26.67	9.45	4.45	0.23	21.48	46.65	26.26	61.78	29.11	19.00
25.42	305	9150	26.70	9.45	4.45	0.23	21.50	46.66	26.30	62.02	29.13	19.01
25.50	306	9180	26.72	9.45	4.45	0.22	21.51	46.67	26.33	62.26	29.15	19.02
25.58	307	9210	26.75	9.45	4.45	0.22	21.53	46.68	26.37	62.50	29.16	19.03
25.67	308	9240	26.78	9.46	4.45	0.22	21.55	46.69	26.40	62.74	29.18	19.05
25.75	309	9270	26.81	9.46	4.45	0.22	21.57	46.70	26.44	62.98	29.19	19.06
25.83	310	9300	26.84	9.46	4.45	0.22	21.58	46.71	26.47	63.22	29.21	19.07
25.92	311	9330	26.86	9.46	4.45	0.22	21.60	46.72	26.51	63.46	29.22	19.09
26.00	312	9360	26.89	9.46	4.45	0.22	21.62	46.73	26.54	63.70	29.24	19.10
26.08	313	9390	26.92	9.46	4.45	0.22	21.64	46.74	26.58	63.94	29.26	19.11
26.17	314	9420	26.94	9.46	4.45	0.22	21.65	46.75	26.61	64.18	29.27	19.12
26.25	315	9450	26.97	9.47	4.45	0.22	21.67	46.76	26.64	64.42	29.29	19.14
26.33	316	9480	27.00	9.47	4.45	0.22	21.69	46.77	26.68	64.66	29.30	19.15
26.42	317	9510	27.03	9.47	4.44	0.22	21.71	46.78	26.71	64.90	29.32	19.16
26.50	318	9540	27.05	9.47	4.44	0.22	21.72	46.79	26.75	65.14	29.33	19.17
26.58	319	9570	27.08	9.47	4.44	0.22	21.74	46.79	26.78	65.38	29.35	19.18
26.67	320	9600	27.11	9.47	4.44	0.22	21.76	46.80	26.81	65.62	29.36	19.20
26.75	321	9630	27.13	9.47	4.44	0.22	21.77	46.81	26.85	65.86	29.38	19.21
26.83	322	9660	27.16	9.48	4.44	0.22	21.79	46.82	26.88	66.10	29.39	19.22
26.92	323	9690	27.19	9.48	4.44	0.22	21.81	46.83	26.92	66.34	29.41	19.23
27.00	324	9720	27.21	9.48	4.44	0.22	21.82	46.84	26.95	66.58	29.42	19.25
27.08	325	9750	27.24	9.48	4.44	0.21	21.84	46.85	26.98	66.82	29.44	19.26
27.17	326	9780	27.27	9.48	4.44	0.21	21.86	46.86	27.02	67.06	29.46	19.27
27.25	327	9810	27.29	9.48	4.44	0.21	21.87	46.87	27.05	67.30	29.47	19.28
27.33	328	9840	27.32	9.48	4.44	0.21	21.89	46.88	27.09	67.54	29.49	19.29
27.42	329	9870	27.35	9.49	4.44	0.21	21.91	46.89	27.12	67.78	29.50	19.31
27.50	330	9900	27.37	9.49	4.44	0.21	21.92	46.90	27.15	68.02	29.52	19.32
27.58	331	9930	27.40	9.49	4.43	0.21	21.94	46.91	27.19	68.26	29.53	19.33
27.67	332	9960	27.43	9.49	4.43	0.21	21.96	46.92	27.22	68.50	29.54	19.34

Duration of flow diversion			Percent change in bank-full cross sectional area from pre-op									
Years	Months	Days	TS3	TS4	TS7A	TS9	TS12	TS12A	TS13A	TS13B	TS14	AVG
27.75	333	9990	27.45	9.49	4.43	0.21	21.97	46.93	27.25	68.74	29.56	19.35
27.83	334	10020	27.48	9.49	4.43	0.21	21.99	46.94	27.29	68.98	29.57	19.37
27.92	335	10050	27.51	9.49	4.43	0.21	22.01	46.95	27.32	69.22	29.59	19.38
28.00	336	10080	27.53	9.50	4.43	0.21	22.02	46.96	27.35	69.46	29.60	19.39
28.08	337	10110	27.56	9.50	4.43	0.21	22.04	46.96	27.38	69.70	29.62	19.40
28.17	338	10140	27.58	9.50	4.43	0.21	22.06	46.97	27.42	69.94	29.63	19.41
28.25	339	10170	27.61	9.50	4.43	0.21	22.07	46.98	27.45	70.18	29.65	19.43
28.33	340	10200	27.64	9.50	4.43	0.21	22.09	46.99	27.48	70.42	29.66	19.44
28.42	341	10230	27.66	9.50	4.43	0.21	22.11	47.00	27.52	70.66	29.68	19.45
28.50	342	10260	27.69	9.50	4.43	0.21	22.12	47.01	27.55	70.90	29.69	19.46
28.58	343	10290	27.71	9.50	4.43	0.21	22.14	47.02	27.58	71.14	29.71	19.47
28.67	344	10320	27.74	9.51	4.43	0.21	22.15	47.03	27.61	71.38	29.72	19.48
28.75	345	10350	27.76	9.51	4.43	0.21	22.17	47.04	27.65	71.62	29.74	19.50
28.83	346	10380	27.79	9.51	4.42	0.20	22.19	47.05	27.68	71.86	29.75	19.51
28.92	347	10410	27.81	9.51	4.42	0.20	22.20	47.06	27.71	72.10	29.76	19.52
29.00	348	10440	27.84	9.51	4.42	0.20	22.22	47.06	27.74	72.34	29.78	19.53
29.08	349	10470	27.87	9.51	4.42	0.20	22.23	47.07	27.78	72.58	29.79	19.54
29.17	350	10500	27.89	9.51	4.42	0.20	22.25	47.08	27.81	72.82	29.81	19.55
29.25	351	10530	27.92	9.51	4.42	0.20	22.27	47.09	27.84	73.06	29.82	19.56
29.33	352	10560	27.94	9.52	4.42	0.20	22.28	47.10	27.87	73.30	29.83	19.58
29.42	353	10590	27.97	9.52	4.42	0.20	22.30	47.11	27.91	73.54	29.85	19.59
29.50	354	10620	27.99	9.52	4.42	0.20	22.31	47.12	27.94	73.78	29.86	19.60
29.58	355	10650	28.02	9.52	4.42	0.20	22.33	47.13	27.97	74.02	29.88	19.61
29.67	356	10680	28.04	9.52	4.42	0.20	22.34	47.14	28.00	74.26	29.89	19.62
29.75	357	10710	28.07	9.52	4.42	0.20	22.36	47.14	28.03	74.50	29.91	19.63
29.83	358	10740	28.09	9.52	4.42	0.20	22.38	47.15	28.06	74.74	29.92	19.64
29.92	359	10770	28.12	9.53	4.42	0.20	22.39	47.16	28.10	74.98	29.93	19.65
30.00	360	10800	28.14	9.53	4.42	0.20	22.41	47.17	28.13	-11.42	29.95	19.67