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Geomorphology of the Upper Gila River Within the State of New Mexico

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New Mexico Interstate Stream Commission
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EXECUTIVE SUMMARY

This investigation of the Upper Gila River Basin in New Mexico was conducted by Mussetter Engineering, Inc. for the New Mexico Interstate Stream Commission (NMISC) to provide a basis for determining the geomorphic impacts on the Gila River, if any, due to annual diversion of up to 14,000 acre-feet (AF) of additional water as a result of implementation of the Consumptive Use and Forbearance Agreement (CUFA) in the 2004 Arizona Water Settlement Act. Geomorphic changes to the Gila River have the potential to adversely affect the physical habitat for a number of species listed under the Endangered Species Act, primarily, spikedace, loach minnow and the southwest willow flycatcher.

ES.1 PROJECT OBJECTIVES

The primary objectives of this investigation of the geomorphology, hydrology, hydraulics and sediment-transport characteristics of the Upper Gila River at five locations between the downstream boundary of the Gila Wilderness Area and the Arizona-New Mexico State Line (Figure 1.1) were to evaluate the existing dynamics of the river in the context of its dryland setting and then to identify the geomorphic impacts, if any, of two CUFA depletion scenarios (73- and 150-cfs bypass flows with a maximum diversion of 350 cfs) provided by the NMISC. An understanding of the geomorphological characteristics of the Gila River and their relation to the current flow regime provides a sound basis from which to evaluate potential changes to the physical system caused by additional flow diversions, and thus impacts on the habitats for the listed species.

ES.2. LITERATURE REVIEW

An extensive review of the dryland rivers literature, as well as the literature specific to the Gila River within and downstream of New Mexico, was conducted to establish the geomorphologic context of the reach of interest between the downstream boundary of the Gila Wilderness Area and the New Mexico-Arizona State line (Chapter 2). The documentation of Gila River response to infrequent, large floods of long duration, both within and downstream of New Mexico, supports the conclusion that dryland rivers are very susceptible to lateral erosion. In general, dryland channel change is dominated by widening that occurs during infrequent floods of long duration and by post-flood narrowing which occurs between the floods.

ES.3. STUDY SITES

Based on a reconnaissance investigation in December 2005, five sites that were considered to be representative of geomorphic conditions in the Upper Gila Basin, and that were also accessible, were selected for study (Chapter 3). The study sites, listed from upstream to downstream were:

1. Turkey Creek Site, located in the lower reaches of the Upper Box canyon, about 3 miles upstream of the Gila River near Gila USGS gage (No. 09430500),
2. Nature Conservancy Site (TNC), located in the Gila-Cliff Valley about 5 miles downstream of the Gila River near Gila USGS gage (No. 09430500),
3. Gila Bird Research Area (Birds) Site, located about 18 miles downstream of the Gila River near Gila USGS gage (No. 09430500) at the downstream end of the Gila-Cliff Valley,

4. Box Site, located at the downstream end of the Redrock Valley and immediately upstream of the Gila River below Blue Creek, near Virden USGS gage (No. 09432000), and

5. Virden Bridge Site, located immediately downstream of the NM Highway 92 Bridge in the Virden Valley.

ES.4. HYDROLOGY

The hydrological characteristics of the Upper Gila River Basin (Chapter 4) were evaluated by analyzing the peak streamflow and mean daily flow records from the USGS Gila River mainstem gages (Gila River near Gila, Gila River at Redrock, Gila River below Blue Creek, Near Virden) and the peak streamflow flow records from the USGS gages on the major tributaries (Mogollon Creek Near Cliff, New Mexico, Duck Creek at Cliff, New Mexico, Mangas Creek Near Cliff, New Mexico) (Table 4.1). Within the period of record, large floods (>15,000 cfs) have occurred in water years 1941, 1979, 1984, 1985, 1995, 1997 and 2005 (Figure 4.1). Flood-frequency curves were developed for all of the mainstem and tributary gages. The 2-year recurrence interval flood increases from about 1,930 cfs at the upstream Gila River gage to about 5,190 cfs at the downstream gage. Similarly, 100-year recurrence interval flood increase from about 40,800 cfs at the upstream gage to about 45,700 cfs at the downstream gage. Based on the flood frequency curves, the 2005 flood event was about a 25-year recurrence interval flood. The flow-duration curves, developed from the mean daily flow record for the Gila River near Gila, Gila River near Redrock and Gila River near Virden gages, and for Mogollon Creek (Figure 4.8). On the Gila River, 90 percent of the time, flows are equal to or exceed 38 cfs at the upstream gage and equal or exceed 22 cfs at the downstream gage as a result of existing flow diversions. Fifty percent of the time flows are equal to or exceed 74 cfs at the upstream gage and 90 cfs at the downstream gage due to flow accretion in the downstream direction. Similarly, the 10-percent exceedence flows increase from 302 cfs at the upstream gage to 431 cfs at the downstream gage.

For the purposes of evaluating the geomorphic impacts of CUFA diversions, the annual hydrographs for the Upper Gila River gages were sorted into three representative classes: dry, typical and wet on the basis of the number of days that bed material mobilization occurred in the year. Years with 0 days of bed-material mobilization were assigned to dry years. If there were between 1 and 4 days of bed-material mobilization the year was assigned to a typical class, and if the number of days of bed-material mobilization was five or more, the year was assigned to a wet class. Representative years for dry, typical and wet years are 1989, 1998 and 1993, respectively (Figures 4.9 through 4.11).

To evaluate the impacts of the diversions on sediment transport and thus the geomorphology of the river, annual hydrographs for the three representative year types with the two diversion scenarios applied were developed for the Gila River near Gila gage. For the representative dry year (1989), application of the two diversion scenarios results in diversion of 7,225 AF for the 73-cfs minimum bypass scenario, and 1,266 AF for the 150-cfs minimum bypass scenario (Figure 4.12). For the representative typical year (1998), application of the two diversion scenarios results in diversion of 12,946 AF for the 73-cfs minimum bypass scenario, and 22,037 AF for the 150-cfs minimum bypass scenario (Figure 4.13). For the representative wet year (1993), application of the two diversion scenarios results in diversion of 1,718 AF for the 73-cfs minimum bypass scenario, and 7,636 AF for the 150-cfs minimum bypass scenario (Figure 4.14).

ES.5. HYDRAULICS

One-dimensional HEC-RAS hydraulic models were developed for all of the sites to quantify the hydraulic characteristics (velocity, depth, water-surface elevation) for a range of flows (Chapter 5). Output from the hydraulic models was used to quantify the hydraulic parameters for in-channel habitat assessment purposes and to quantify sediment-transport processes at each site. The models were calibrated to the flows at the time of the site topographic surveys in February 2006). Reach-averaged hydraulic parameters were summarized for each of the sites in Tables 5.1 through 5.5. At the Turkey Creek site, for the 2-year flow (1,930 cfs), the average channel velocity is about 5 feet per second (fps), hydraulic depth is about 4 feet, and the channel top width is about 98 feet. At the TNC site, for the 2-year flow (1,930 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 2 feet, and the channel top width is about 191 feet. At the Birds site, for the 2-year flow (5,930 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 7 feet, and the channel top width is about 151 feet. At the Box site, for the 2-year flow (5,190 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 7 feet, and the channel top width is about 108 feet, and at the Virden Bridge site, for the 2-year flow (5,190 cfs), the average channel velocity is about 6 fps, hydraulic depth is about 5 feet, and the channel top width is about 158 feet.

ES.6. SEDIMENT TRANSPORT

The HEC-RAS hydraulic model output for each site was also used to determine shear stresses for the range of modeled flows. Shear stress, in conjunction with the sediment gradations (Chapter 3), was used to evaluate the flows required to mobilize the coarse bed material at the Turkey Creek, TNC, Birds and Virden sites. Because of the sand bed at the Box site, no incipient-motion analysis was carried out. Output from the hydraulic models was also used to compute the volume of sediment transported on an annual basis for the period of record for the three Gila River gages for with- and without CUFA diversion conditions, and to determine the effective discharge at each site (Chapter 6).

The Turkey Creek site has a representative median (D_{50}) bed-material size of 49 mm, and D_{84} value of 101 mm, and critical discharges for bed mobilization and significant sediment transport of 2,500 and 4,000 cfs, respectively. The TNC site has representative D_{50} and D_{84} bed-material sizes of 61 and 111 mm, respectively, and critical discharges for bed mobilization and significant sediment transport of 1,300 and 3,500 cfs, respectively. The Birds site has representative D_{50} and D_{84} bed-material sizes of 47 and 85 mm, respectively, and critical discharges for bed mobilization and significant sediment transport of 2,500 and 5,500 cfs, respectively. The Virden Bridge site has representative D_{50} and D_{84} bed-material sizes of 57 and 100 mm, respectively, and critical discharges for bed mobilization and significant sediment transport of 1,200 and 3,000 cfs, respectively. On the basis of the results of the shear stress-based incipient-motion and significant sediment-transport computations flow diversions at flows less than critical for bed- material mobilization at each of the sites will have no geomorphic effect, since morphogenetic flows by definition must be able to mobilize the channel boundary sediments. Additionally, it can be argued that the diversion of flows above those required for significant sediment transport at each of the sites will have the most effect on geomorphic processes.

Effective discharge computations show that changes in the flow regime resulting from the proposed diversions will have an impact at the Box site where the bed material is composed of sand (Figure 6.9), and may increase the time required to return the channel bed to a gravel-cobble, pool-riffle morphology. At the remainder of the sites, where the bed materials are coarser, the effective discharge is, as expected, skewed towards the higher magnitude, less frequent flows, and will therefore, only be affected if there are significant diversions at the higher flows (Figures 6.6, 6.7, 6.8, 6.10). Based on the diversion estimates provided by NMISC, the maximum diversion is estimated to be 350 cfs, and therefore, unless the diversions occur in the range of the incipient-motion and significant sediment-transport thresholds, there should be no significant geomorphic impacts.

The sediment-transport computations (Table 6.2) show that the largest impacts of flow diversion will occur in the average year type (about 25 percent of the years) when flow diversions can have an effect on the sediment mobilization thresholds. In the inactive year type (about 50 percent of the years) there is little possibility of a significant geomorphic impact from diversion of the flows. In the active year type (about 25 percent of the years), the impact of diversions is minimized because of the relative size of the maximum diversion rate (350 cfs) to the river flows.

ES.8. INUNDATION FREQUENCY AND DURATION

The capacity of the channel governs the frequency and duration of inundation of the channel margin areas that support the riparian vegetation community along the Gila River (Chapter 7). At the five study sites, the willows are located primarily on the banks of the channel up to an elevation that correlates with the 1.5- to 2-year recurrence interval floods that have durations of between 1 and 2 days per year. Younger cottonwoods tend to be located on floodplain and lower terrace surfaces that correlate with the 2- to 5-year recurrence interval floods that have durations of inundation between 1 and 0.5 days per year. Older cottonwoods and sycamores tend to be located on terrace surfaces that correlate with the 10- to 20-year recurrence interval floods that have durations of inundation of less than 0.1 days per year. Upland plant species also tend to be located on the higher terraces. Diversion of a maximum of 350 cfs is unlikely to have a significant effect on water-surface elevations nor on durations of inundation for any of the geomorphic surfaces.

ES.9. CONCLUSIONS

1. The primary determinant of the channel morphology in the alluvial reaches of the upper Gila River is the occurrence of infrequent, large magnitude floods of long duration (1941, 1979, 1984,1985, 1995, 1997, 2005) that cause lateral erosion and widening of the channel. Between large floods, channel narrowing occurs. Man-made features such as diversions, bank protection and levees have local effects only.

2. On the basis of the annual frequency of bed-material mobilization, the hydrologic record in the upper Gila Basin can be divided into dry, typical and wet years, with representative years being, 1989, 1998 and 1993, respectively. Dry (inactive) years occur about 50 percent of the time, and typical (average) and wet (active) years each occur about 25 percent of the time.

3. Sediment-transport computations show that the greatest impacts of the flow diversions will occur in the typical or average year types, when flow diversions can have an impact on sediment mobilization thresholds.

4. Bed-material mobilization thresholds for the Turkey Creek, TNC, Birds and Virden Bridge sites, where the bed materials are composed of gravels and cobbles, are 2,500, 1,300, 2,500, and 1,200 cfs, respectively. Diversion of flows below these threshold values will have no geomorphic impacts.

5. Effective discharge calculations for all the sites except the Box site show that the maximum diversion rate of 350 cfs is unlikely to have a significant effect on sediment transport volumes during infrequent flows when the bulk of the sediment is being transported.

6. The effective discharge calculations show that diversion of flows is likely to increase the time it takes for the sand-bed Box site to recover to gravel-cobble bed material with an associated pool-riffle morphology.

7. Although the morphological characteristics of the upper Gila River sites are very complex, hydro-geo-botanical correlations can be made. Willows are located primarily on the banks of the channel up to an elevation that correlates with the 1.5- to 2-year recurrence interval floods that have durations of between 1 and 2 days per year. Younger cottonwoods tend to be located on floodplain and lower terrace surfaces that correlate with the 2- to 5-year recurrence interval floods that have durations of inundation between 1 and 0.5 days per year. Older cottonwoods and sycamores tend to be located on terrace surfaces that correlate with the 10- to 20-year recurrence interval floods that have durations of inundation of less than 0.1 days per year.

8. Diversion of a maximum of 350 cfs is unlikely to have a significant effect on water-surface elevations nor durations of inundation for any of the geomorphic surfaces.

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1. INTRODUCTION

The 2004 Arizona Water Settlement Act (2004 Act) provides additional water for the State of New Mexico in the Upper Gila Basin. By the U.S. Supreme Court Decree in AZ v. CA (1964), New Mexico is currently limited to approximately 30,000 acre-feet (AF) of depletions per year on an average annual basis. The Consumptive Use and Forbearance Agreement (CUFA) of the 2004 Arizona Water Settlement Act allows New Mexico an additional annual average of 14,000 AF (140,000 AF in a 10-year period) of depletions, or an almost 50 percent increase in available water supply. On a daily basis, New Mexico must bypass water to meet downstream water rights (Terms of the New Mexico Diversions): New Mexico water users are obligated only to bypass an additional 50 percent of any additional water rights that may be in the future adjudicated in Arizona with a priority date earlier than 1968, or 40 cfs, whichever is less.

The 2004 Act requires full compliance with all provisions of federal environmental mandates including the National Environmental Policy Act (NEPA) and the Endangered Species Act (ESA). The Upper Gila Basin in New Mexico has a number of species listed under the ESA, including spikedace, loach minnow, Gila chub, Chiricahua leopard frog, and the southwest willow fly catcher. The impacts on these species from any development of the water are a critical consideration in any decision on how to utilize the newly available water. The New Mexico Interstate Stream Commission (NMISC), the agency with the responsibility for implementing the 2004 Act, has adopted a policy to guide it through the planning and decision process:

> *The Interstate Stream Commission recognizes the unique and valuable ecology of the Gila basin. In considering any proposal for water utilization under Section 212 of the Arizona Water Settlement Act, the Commission will apply the best available science to fully assess and mitigate the ecological impacts on Southwest New Mexico, the Gila River, its tributaries and associated riparian corridors, while considering the historic uses of and future demands for water in the Basin and the traditions, cultures and customs affecting those uses.*

1.1. Project Objectives

The objectives of this investigation of the geomorphology, hydrology, hydraulics and sediment transport characteristics of the Upper Gila River at five locations within the State of New Mexico (**Figure 1.1**) were to evaluate the existing dynamics of the river and then to identify the geomorphic impacts, if any, of various depletion scenarios provided by the NMISC. An understanding of the geomorphological characteristics of the Gila River and their relation to the current flow regime provides a sound basis from which to evaluate potential changes to the physical system caused by additional flow diversions, and thus impacts on the habitats for the listed species. Companion studies are investigating the habitat issues.

1.2. Scope of Work

The following tasks were included in the scope of work for the project:

1. Obtain, review and summarize existing information and previous studies of the project reach.
2. Conduct a reconnaissance survey of the project reach to select study sites that are representative of the geomorphic characteristics of the reach.

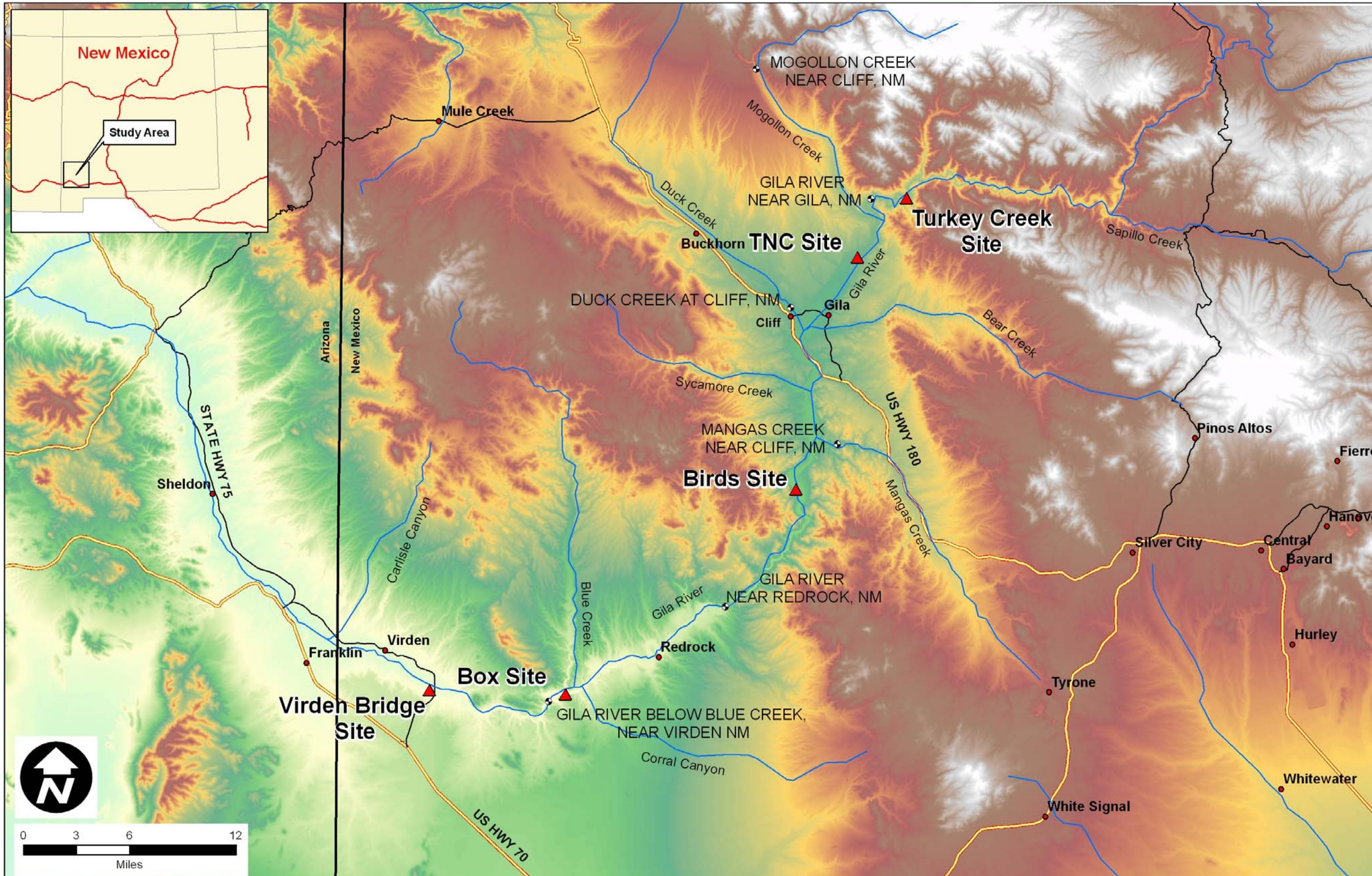


Figure 1.1. Map showing the location of the Upper Gila River Basin and the five study sites.

3. Conduct cross section and longitudinal surveys of the five study sites for incorporation into hydraulic models. Collect surface and subsurface sediment samples for gradation analysis for use in the sediment-transport investigation.
4. Conduct a hydrologic analysis of USGS gages within the project reach and develop peak flow-frequency curves and flow duration curves from the mean daily flow data for the periods of record. Develop typical hydrographs for dry, average and wet years. Based on diversion estimates for 73- and 150-cfs bypass flows for the Gila River at Gila gage develop typical hydrographs for dry, average and wet years.
5. Develop one-dimensional HEC-RAS hydraulic models for each of the study sites and use the output from the calibrated models to evaluate sediment transport, channel capacity and overbank flow frequency and duration.
6. Conduct incipient motion and sediment-continuity analyses for each study site for existing and with diversion conditions.
7. Based on the hydrologic, hydraulic and sediment-transport investigations identify channel forming or effective flows for existing conditions for each of the study sites.
8. Based on the hydrologic, hydraulic and sediment-transport investigations evaluate the effects of the flow diversions on the channel morphology and channel-forming or effective flows.
9. Prepare draft and final reports.

1.3. Authorizations

This investigation of the geomorphology of the Upper Gila River within the State of New Mexico was conducted by Mussetter Engineering, Inc. (MEI) for the New Mexico Interstate Stream Commission (NMISC) under a subcontract to SWCA Environmental Consultants, Inc. The NMISC project managers were Mr. Peter Wilkinson and Ms. Danielle Smith, and the SWCA project manager was Mr. Bill Liebfried. The MEI project manager was Dr. Mike Harvey, P.G and he was assisted by Dr. Stanley Schumm, P.G., Mr. Chad Morris, P.E., and Mr. Steve Sanborn, E.I.

2. BACKGROUND INFORMATION

The Gila River is part of the Colorado River system. The three major tributaries forming the mainstem Gila River in New Mexico are the East, West, and Middle Forks. The Gila River flows about 34 miles through the narrow canyon reach of the Gila Wilderness Area. The river leaves the Gila National Forest and the mountainous portions of its watershed at the downstream end of the Upper Box near its confluence with Mogollon Creek and enters the broad 22-mile long Cliff-Gila Valley (**Figure 2.1**).

The Gila River then re-enters the Gila National Forest and Bureau of Land Management land and flows through the 9-mile canyon reach of the "Middle Box" above Redrock, New Mexico. Below the Middle Box, the river leaves the Gila National Forest and flows about 30 miles through private and Federal lands, the Lower Box and Duncan-Virden Valley to the Arizona-New Mexico state line. The Gila River in Arizona continues about 45 miles to the confluence of the San Francisco River. The rivers flows another 95 miles through another narrow canyon above Safford, Arizona, and eventually reaches San Carlos Reservoir.

The riparian communities along the upper Gila River Valley are dominated by large broadleaf vegetation, such as cottonwood, sycamore, hackberry, walnut, boxelder, and willow. Gila River water discharge and sediment loads vary seasonally and year-to-year. The annual hydrologic cycle of the Gila River usually consists of short, high volume discharge as a result of winter rainstorms and snowmelt at higher elevations followed by a substantial period of low flows. Highest flows typically occur during winter rainstorms, spring snowmelt, and the late summer monsoon season.

2.1. River Changes

In low gradient, alluvial streams in humid climates, where the bankfull discharge has a recurrence interval of approximately 1.5 to 2 years, there is a reasonable basis for relating the bankfull discharge to the channel forming, or dominant discharge that can then be used for engineering design or restoration purposes (Wolman and Leopold, 1957; Andrews, 1984). In contrast, identification of design flows for engineering or restoration purposes in steep, externally formed configuration rivers (Grant and Swanson, 1995; Montgomery and Buffington, 1997; Curran and O'Connor, 2003) in arid and semi-arid regions of the southwestern U.S. is considerably more complex. Graf (1983b) has argued that dryland channels are not equilibrium forms, and that as a result, it is not possible to define a dominant discharge (Graf, 2002). Larger and more infrequent flows are more geomorphically effective (Baker, 1977) and dryland rivers transport 60 percent of their sediment loads in 10-year or larger events (Neff, 1967). Compound or braided channels with poorly defined floodplains between bounding terraces make identification of bankfull capacity very difficult and large, infrequent floods tend to have a strong influence on channel geometry that in turns confined subsequent lower magnitude flows (Graf, 2002). Local tributary contribution of sediments causes great variation in the distribution of particle sizes that comprise the bed of dryland rivers (Rhoads, 1986).

Clearly, dryland rivers have some characteristics that differ from those of more humid regions. They are characterized by large floods that can wreak havoc on the channel and floodplain. Also, they have high transmission losses downstream. Frequently, they have compound channels that are related to high- and low-water conditions. The channels can contain ephemeral or intermittent flows as well as discontinuous flows (Bull and Kirkby, 2002).

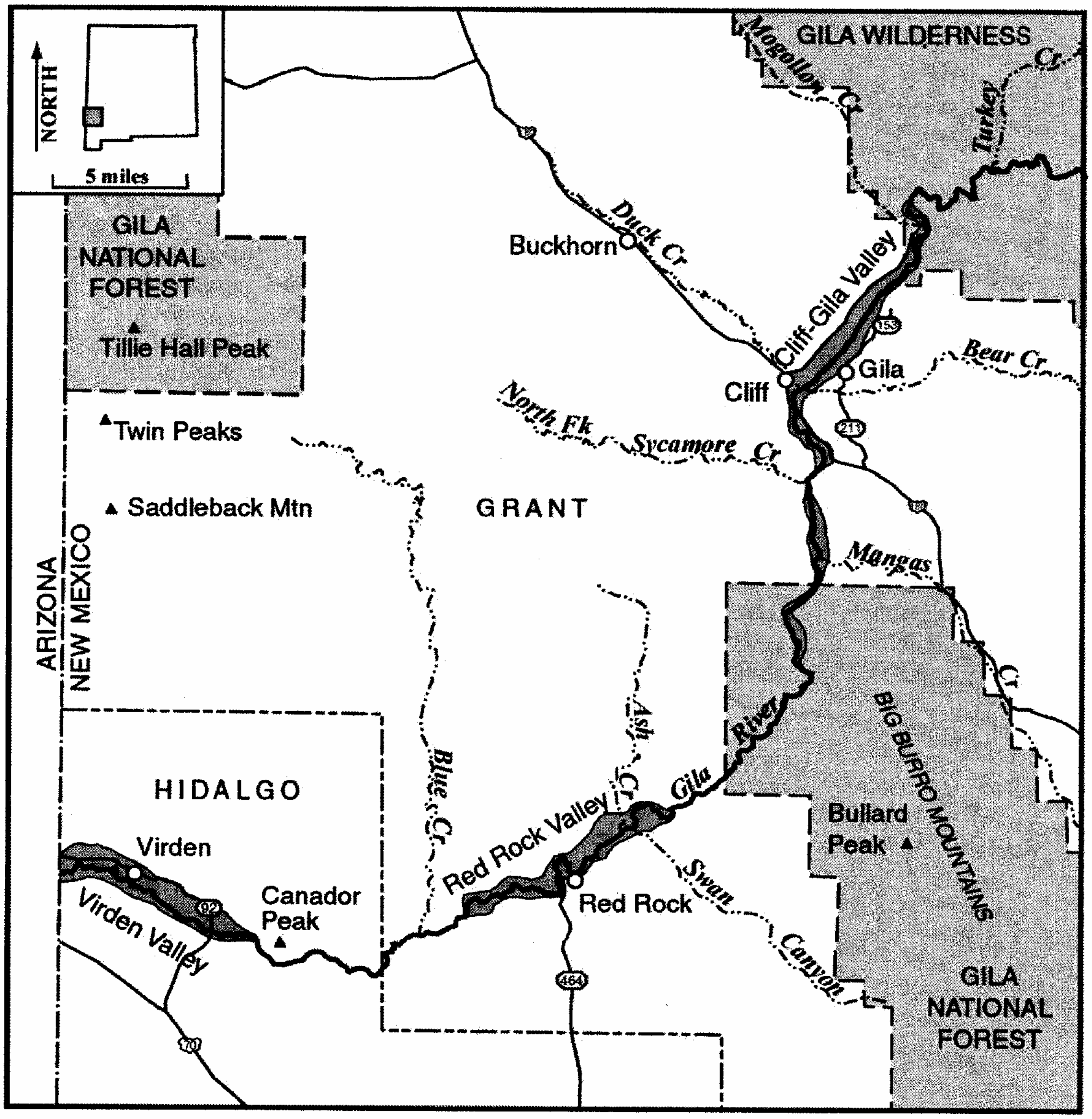


Figure 2.1. Index map of Gila River in southwestern New Mexico (from Bureau of Reclamation, 2002).

Of greatest interest for prediction of channel dimensions and overall morphology is the effect of hydrologic change on channels. For example, some rivers undergo a complete change of morphology, pattern, dimensions and gradient during large floods. Almost all rivers are subject to change through time with meander growth and cutoffs being very common. A more dramatic change is avulsion. Changes that appear to be characteristic of dryland channels are widening following by narrowing with only minor changes in channel depth. This type of change has been documented for the Gila, Cimarron, and Platte Rivers, among others, and these changes will be considered in some detail after a brief review of documented channel changes.

According to Tooth (2000), the concern with widespread channel erosion in the American Southwest in the late 1800s and early 1900s caused much of the early literature on change in dryland rivers to be focused on the causes of arroyo cutting and gully development (see Cooke and Warren, 1973; Cooke and Reeves, 1976; Graf, 1983a). Thornes (1994) and Schumm et al. (1984) provide summaries of later field-based and experimental work on channel initiation, headcut formation, and knickpoint migration in dryland channels.

There are numerous documented examples of major historical changes resulting from one or more large floods (e.g., Schumm and Lichty, 1963; Burkham, 1972; Thornes, 1977; Baker, 1977; Marker, 1977; Graf, 1983a and 1983b; Osterkamp and Costa, 1987; Garcia, 1995). Channel changes have included adjustments of pattern (Graf, 1988a), pronounced widening (Schumm and Lichty, 1963; Burkham, 1972; Osterkamp and Costa, 1987), rapid lateral migration (Graf, 1983b), entrenchment (Marker, 1977; Graf, 1983a), and floodplain erosion and deposition. The rapid enlargement of the Santa Cruz River during the Tucson flood of October 1983 is one of the most widely documented examples of flood-related channel change in drylands (Baker, 1984; Saarinen et al., 1984; Kresan, 1988).

Too often in the consideration of unstable channels, the emphasis is only on degradation or aggradation of the channel. Observations along the Cimarron River clearly show, however, that both channel widening and narrowing may occur without a major change in the elevation of the channel bed. Similar changes have been noted along other rivers. For example, the widening of the channel of Washita River, as described by Coldwell (1957), occurred without significant changes in the elevation of the bed of the stream. Hefley (1935) stated that the Canadian River in eastern Oklahoma widened since the major flood of 1906 from less than one-half mile to more than two miles in some places.

Bryan (1927) reported that the Rio Salado, a tributary of the Rio Grande near San Acacia, New Mexico, ranged from 12 to 49 feet in width in 1882, but in 1918, its width ranged from 330 to 550 feet. Bryan (1927, p. 19) stated that "*Unlike many similar streams in New Mexico, which have not only widened their channels, but deepened them in the same period, the Rio Salado, at least in the vicinity of Santa Rita, has even yet banks that are only 3 to 10 feet high and average 5 feet high.*"

Smith (1940) reported on recent channel changes of several rivers in western Kansas. The Smoky Hill River originally *"had alternating sandy stretches and grassy stretches with series of pools. Later the former were widened and the latter were sanded up….."* Smith further stated that the Republican River was greatly affected by the flood of 1935. "*Formerly a narrow stream with a practically perennial flow of clear water and with well-wooded banks, the Republican now has a broad, shallow sandy channel with intermittent flow. The trees were practically all washed out and destroyed, much valuable farmland…was sanded over, and the channel has been filled up by several feet.*"

The Red River floodplain near Burkburnett, Texas, was the object of intensive study as a result of the boundary dispute between Oklahoma and Texas (Glenn, 1925; Sellards, 1923). The Red River was never a narrow, meandering stream in historic times; a survey in 1874 showed the river to be about 4,000 feet wide. The channel, however, has undergone some important changes. For example, comparison of a special map prepared in 1920 (Sellards, 1923) with aerial photographs taken in 1953 showed enlargement of the floodplain. Over a 10-mile reach of the river, 5.5 square miles of floodplain were added. In 1937, the river averaged three-quarters of a mile in width, close to the average for the 1874 survey. In 1953, the average width had decreased to half a mile. In 1957, the river averaged two-thirds of a mile wide, indicating a significant widening between 1953 and 1957. These dramatic changes can only be caused by hydrologic fluctuations, and during the period of 1953-1958, there were three large floods.

Sensitivity is a term which has been employed in different ways in the fluvial geomorphic literature (Downs and Gregory, 1993), but it has often been used to indicate either the propensity for flood-related channel change or the ability to recover from change. On both accounts, dryland channels are often considered to be highly sensitive to the effects of large floods.

In contrast to floods observed in humid regions (Wolman and Eiler, 1958), floods in semiarid and arid environments may be tremendously destructive to the channel and floodplain. This destruction by floods may be a characteristic of erosion in a semiarid region where climatic fluctuations are common and the streams are ephemeral or carry low flows during long periods. Often these streams cannot adjust as readily as perennial streams to a change in stream regimen or a climatic fluctuation. Large floods may trigger an adjustment by initiating periods of severe bank erosion and widening.

Two examples of the effects of hydrologic change on dryland rivers follow. These examples provide a basis for predicting Gila River changes, as a result of flow regulation.

2.1.1. Cimarron River, Kansas

Dramatic changes of channel characteristics occurred along the Cimarron River in western Kansas. The river, apparently as a result of precipitation and hydrologic influences, changed from a narrow, deep sinuous channel to a wide braided channel and then it narrowed as woody vegetation invaded the channel. These changes are similar to those of the Gila River and its major tributaries as described in Arizona (Graf, 1981, 1983b, 1988b, 2002; Burkham, 1972; Huckleberry, 1996, 1999), and therefore, the Cimarron River changes will be described in detail.

The Cimarron River in Kansas appeared to be typical of streams in a more humid environment at the turn of the century. Haworth (1897, p. 22) stated that "*The Cimarron seems to have reached baselevel and to have begun meandering across its floodplain. Beautiful oxbow curves are frequent, and a sluggish nature is everywhere manifest during times of low water."* According to Johnson (1902, p. 664): *Wherever within the High Plains belt the Cimarron Valley shows a living stream, it is always a meandering looping stream of uniform width, narrow, clear and deep… The bottom land upon which is wanders supports a coarser and longer-stemmed grass than the uplands, the grass roots reaching to the groundwater, which lies at a depth here, as a rule, of only 2 or 3 feet....*

Information on the width of the Cimarron River is available as a result of the survey of 1874. In 1874, the river averaged 50 feet in width through the six counties of southwestern Kansas. The channel of the river in Kansas between 1874 and 1914 was narrow and probably relatively stable. The floodplain was grassed and afforded excellent grazing. Wild hay and alfalfa were cut and stacked on the floodplain during these early days. The contrast between the river at that time and during the following 16 years is remarkable.

Beginning in 1914 and continuing intermittently until 1942, the channel of the Cimarron River widened until almost all of the floodplain was destroyed. The channel widening began, according to the testimony of residents of the Cimarron valley, during the major flood of May 1914. This flood is the greatest of record, having an estimated gage height of 13 feet near Mocane, Oklahoma; peak discharge is estimated to have been 120,000 cfs.

During the 1874 survey, the channel north of Elkhart, Oklahoma, was 66 feet wide. Only minor changes in width occurred between 1874 and 1914; however, in 1916, a bridge 644 feet long was required to span the channel, and in 1939, the channel at the bridge was about 1,400 feet wide (McLaughlin, 1947, p. 82). Average channel widening during the period 1914 through 1939 was 1,150 feet.

Although aerial photographs are available to document channel changes between 1939 and 1954, other data indicate that the channel continued to widen through 1942. For example, a major flood near Liberal, Kansas, occurred in 1942 with a peak discharge of 69,000 cfs. This flood originated in the headwaters area (peak discharge 80,000 cfs near Boise City, Oklahoma), and it destroyed many bridges as it moved through the Cimarron River valley in Kansas. At the end of 1942, the river was at its maximum width, for the floodplain was completely destroyed at some locations. Good evidence for complete destruction of the floodplain north of Hugoton, Kansas, is provided by a photograph taken of the channel in 1943. At that time, the entire valley floor was river channel.

After the flood of 1942, a reversal of river activity occurred. Cross sections, when remeasured on aerial photographs taken in 1954, showed that the channel had become narrower. The narrowing was accomplished by floodplain construction and, to a minor extent, by island formation. The channel width, as measured on the 1954 photographs, decreased to an average of 550 feet. However, the channel in 1963 was only 110 feet wide.

In 12 years, the river had repaired about half the damage caused by widening during the period of 1914 through 1942. Great variability occurs among the data. At some cross sections, the river narrowed to one-fifth or less of its former maximum width; whereas at other cross sections, the river width did not change.

Aerial photographs allowed measurements to be made of 1960 channel widths. The measurements show that the period 1954 through 1960 was not a continuation of the period 1943 through 1954. Of 120 sections remeasured, only 10 showed continued narrowing of more than 50 feet; 70 sections were about the same width; and of the remaining 40 sections, 38 showed renewed widening of more than 50 feet; whereas, two have continued to widen since the first survey in 1874. The period may be characterized as one of relative stability with some tendency toward widening of the channel.

The major changes in width of the Cimarron River during the 46-year period (1914 through 1960) can be grouped into three distinct periods: (1) the period 1914 through 1942 was one of channel widening and floodplain destruction, (2) the period 1943 through 1954 was characterized by of channel narrowing and floodplain construction, and (3) the period 1955 through 1960 was one of relatively minor changes.

The period of channel widening was characterized by below-average precipitation and by floods of high peak discharge; whereas the period of floodplain construction was characterized by above-average precipitation and floods of low peak discharge. The influence of these conditions on tree growth is the key to the behavior of Cimarron River. Wet years and low water allow a vigorous growth of trees, which stabilized the existing deposits and promoted additional deposition. The stabilization of the new floodplain by vegetation was so effective that the floods of 1951 and 1958 did not cause great changes in the valley.

The channel changes along the Cimarron River appear to be similar to changes which have occurred along the Washita, Canadian, Smoky Hill, Republican, Gila, Red Rivers, and Rio Salado. The changes differ from the degradation and aggradation characteristic of other unstable streams, for these rivers widen and narrow their channels as an alternative to aggradation and degradation. As will be documented later, historic changes of the Gila River are similar to those of the Cimarron River.

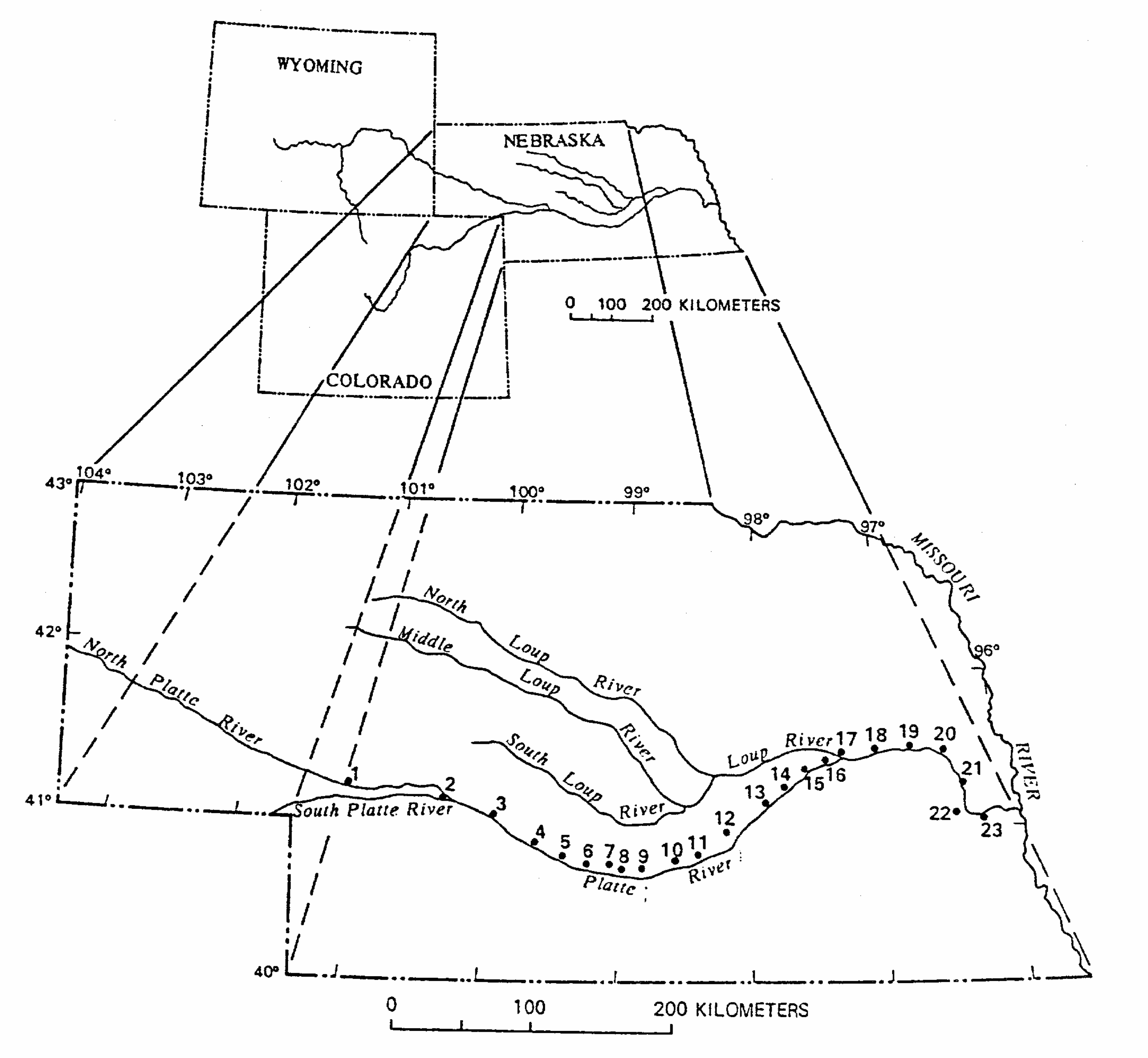
2.1.2. Platte River, Nebraska

Another example of dramatic channel change, as a result of hydrologic changes, is provided by the Platte River in Nebraska. The Platte River system has been affected by dams and reservoirs and especially irrigation diversions and irrigation return flows (Schumm, 2005), but in the middle of the 19th century, travelers along the Oregon Trail were astonished by the width and character of the Platte River in Nebraska. It was unlike any river east of the Mississippi River and as a result, the pioneers and Army officers commented on it in their journals (Mattes, 1969). By the middle of the 20th century, the river had been greatly modified by hydrologic change, as a result of impoundments and irrigation diversions. A series of maps (1860, 1938, 1957, 1983) prepared by the University of Nebraska's Remote Sensing Applications Laboratory (Peake et al., 1985) provides a record of this change (see also Eschner et al., 1983). These maps show the active channel and the vegetation type adjacent to the active channel for each U.S. Geological Survey (USGS) topographic map from about the junction of the North and South Platte Rivers near Brady to just downstream of Grand Island (**Figure 2.2**). The area of active channel was given for each map so when area was divided by the length of the channel, an average channel width for each map was obtained for 1860, 1938, 1957, 1983, and 1995 (**Figure 2.3**).

Human-induced hydrologic changes in the Platte River drainage basin undoubtedly commenced in the late 19th century, but continuous hydrologic records only began in the mid-1930s. It was not until the drought years of the 1930s, the completion of Kingsley Dam in 1941 at Keystone, and the filling of its reservoir (Lake McConaughy) on the North Platte River that great changes in mean annual discharge, flood peaks, and flow duration were recorded.

During the drought years of the 1930s and following closure of Kingsley Dam, the average annual discharge decreased significantly except for some wet years in the early 1970s. High peak discharges were also less frequent after 1940. These hydrologic changes contributed to the major narrowing of the Platte River. Early photographs show that the South Platte, North Platte, and Platte Rivers were classic examples of very wide braided streams. The Platte River in 1860 was about one mile wide.

The dramatic changes of the channel width through time require an explanation. One can assume that the river in 1860 was essentially unchanged from natural conditions, although some diversions undoubtedly had commenced. Nevertheless, it should be noted that the Platte River during the 1860 surveys was hydrologically different from the present river. It was intermittent, as described by Ware (1911) in 1863 as follows:



Key to numbered towns:

1.	Keystone	13.	Central City
2.	North Platte	14.	Clarks
3.	Brady	15.	Silver Creek
4.	Cozad	16.	Duncan
5.	Lexington	17.	Columbus
6.	Overton	18.	Schuyler
7.	Elm Creek	19.	North Bend
8.	Odessa	20.	Fremont
9.	Kearney	21.	Venice
10.	Gibbon	22.	Ashland
11.	Wood River	23.	Louisville
12.	Grand Island		

Figure 2.2. Map showing location of towns along North Platte and Platte River in Nebraska (from Schumm, 2005).

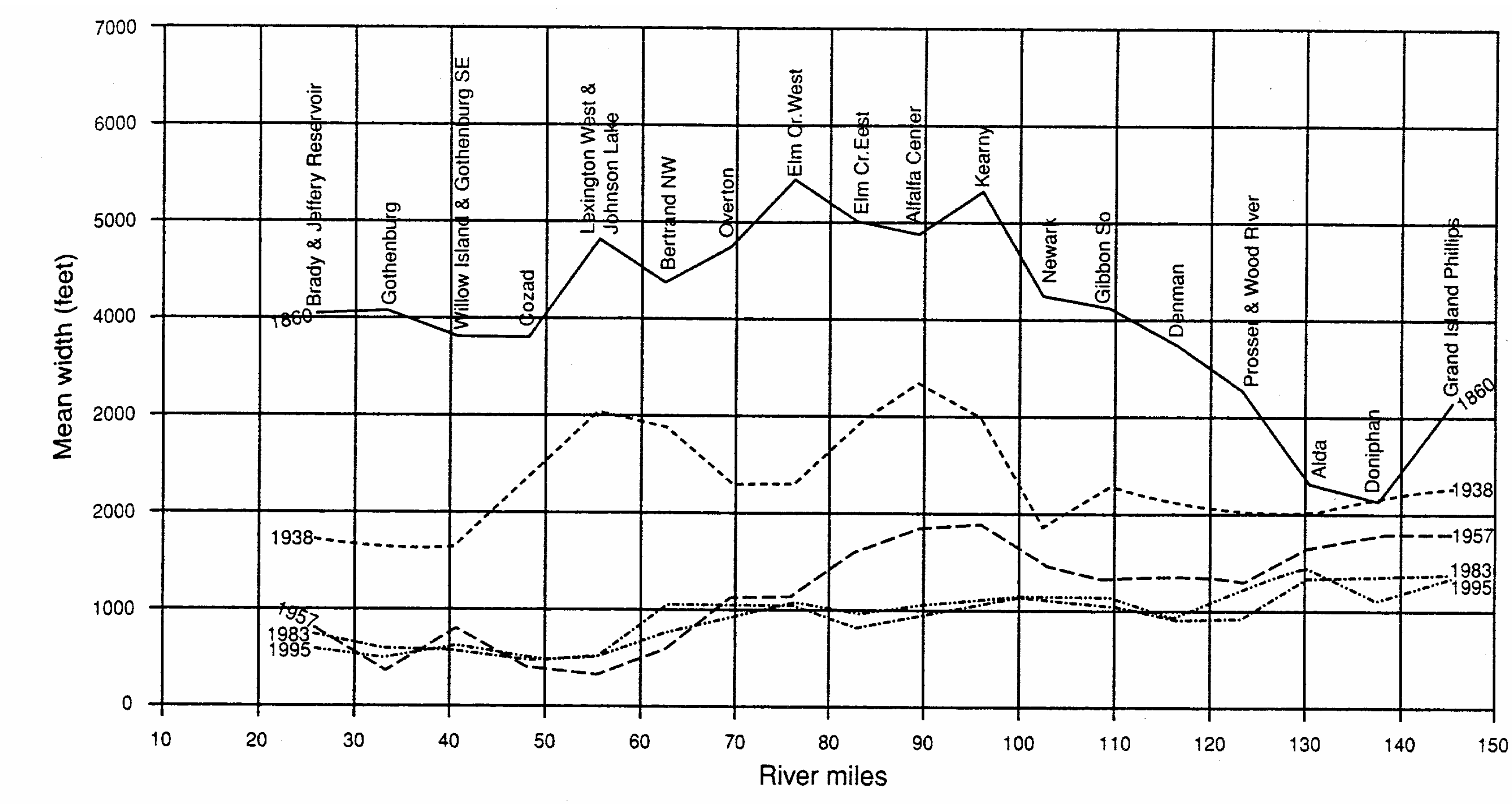


Figure 2.3. Mean width of Platte River in 1860, 1938, 1957, 1983, and 1995 (from Schumm, 2005).

From Fort Kearney, for many miles up, there was no water in the river. The water seemed to be in "the under-flow." *We not infrequently rode down to the river, and with shovels dug watering-places in the sand of the bed. We always found permanent water within eighteen inches of the top, no matter how dry the sand on top appeared to be. We were told that 75 miles of the river were then dry, and that generally about 125 miles of it were dry in the driest season.*

The large number of no-flows days was a characteristic of some reaches of the river until about 1942, when the impact of Kingsley Dam and Lake McConaughy on the Platte River became significant. Hydrologic data show that before 1942 (pre-project), the average annual number of no-flow days at Overton was 78, but there were zero no-flow days at this gage after 1941 (post-project). At Odessa, there were, on average, 150 no-flow days a year before 1942, but only 19 no-flow days per year at this gages after 1941, and there were zero no-flow days after 1957. At Grand Island, there was an average of 150 no-flow days per year before 1942, but only 23 for the 1942 to 1978 period. There were zero no-flow days at Grand Island after 1978. Clearly, the hydrologic character of the river had changed from intermittent to perennial, which undoubtedly had a major effect on channel width. The large number of no-flow days in the 1930s also reflected the drought conditions of that decade.

Johnson (1994, p. 77) attributed width reduction during the drought years to low flows, which exposed large areas of the channel bed to colonization by vegetation (woodland expansion). The low flows maintained the water table, whereas a long series of no-flow days caused lowering of the water table and a high mortality of seedlings. Therefore, conversion of the Platte River between Overton to Grand Island from an intermittent river with many no-flow days to a perennial river allowed colonization of the exposed channel bed by vegetation (woodland expansion) and major narrowing of the channel.

Johnson's (1994) conclusions and the recognition of the nature of the hydrologic changes in the Platte River permit the development of explanations of the width changes between 1860 and 1995. The marked decrease of width between 1960 and 1938 can logically be attributed to the effects of diversions, large dam construction and the drought years of the 1930s. The limited hydrologic data for this period show that the number of no-flows days at Overton and Grand Island were numerous.

For the period 1930 through 1957, an additional significant decrease of width occurred between Brady and Grand Island (Figure 1.3). The average annual number of no-flow days for this period at Overton was 11 per year; whereas, at Grand Island, the average was 59 per year. At Overton, there were zero no-flow days after 1941, and the channel adjusted to discharges released from Lake McConaughy and irrigation return flow. By 1957, width upstream of the Elm Creek West quadrangle appears to have stabilized, and there were only minor width changes between 1957 and 1995. However, downstream of the Elm Creek West Quadrangle, the decrease of width continued through 1983 (Figure 1.3). It was not until 1978 that there were zero no-flow days at Odessa and Grand Island. The absence of no-flow days permitted adjustment of this part of the channel to a relatively stable condition during the period 1984 through 1995.

In summary, at Overton, Odessa, and Grand Island, river width decreased as irrigation return flows eliminated no-flow days between Overton and Grand Island. The establishment of perennial flow and a raised water table promoted vegetation establishment on the floodplain and in the channel. A similar conclusion was reached by Nadler and Schumm (1981) for the South Platte River. In contrast, a series of no-flow days in the wide sandy channel created a harsh environment for plant growth. The bare sand surface and the decline of the water table prevented survival of plants that were established in the channel during previous wetter months.

During low flow, the wide pre-1938 river made large areas available for colonization by plants (Johnson, 1994, p. 77), but the probability of mortality later in the year was high, especially when there were a number of no-flow days. The conversion of the Overton to Grand Island channel from intermittent to perennial undoubtedly maintained a high water table and favorable conditions for colonization and survival of vegetation. Therefore, the change of channel width downstream of Overton after 1941 was due to the modification of flow characteristics by the construction and operation of Kingsley Dam and Lake McConaughy (Kircher and Karlinger, 1983; Simons and Simons, 1994).

The trend of average channel width downstream of Brady in 1860 is unusual. Average width generally increased in a downstream direction from the Brady quadrangle to the Kearny quadrangle as expected. However, between the Kearny and Doniphan quadrangles, average width decreased dramatically (Figure 2.3). In this reach, the river was not braided, but rather it was anastomosing. That is, the single braided channel became a multiple channel complex. The total width of the multiple anastomosing channels was less than the width of the upstream braided channel. If the same volume of water moved through the braided channel at Kearny, as through the anastomosing channels streams, then each anabranch must have been deeper than the braided channel. Nanson and Huang (1999) conclude that the anastomosing channels will be narrower, deeper, and more efficient than a single channel. A possible explanation for this pattern change is that the gradient was about 5 percent less in the anastomosing reach.

In addition, the valley widens at Kearny and the contours on topographic maps are no longer deflected upstream, as they cross the river. This suggests that the anastomosing reach occurs where floodwaters are likely to spread across the valley and form multiple channels. In the braided reaches, even during high water, the banks were not overtopped, according to accounts of the early travelers (Mattes, 1969; pp. 163-164, 240), and near Kearny, the river had the appearance of flowing at the level of the floodplain (Mattes, 1969, pp. 163, 240). Near Grand Island in 1860, the river reverted to a braided pattern, which is the present condition.

The two different channel patterns of the Platte River in 1860 responded differently to the hydrologic changes that caused width reductions between 1860 and 1995. The Platte River between Brady and Grand Island provides an excellent example of river variability in location and through time. For example, the braided reach of 1860 by 1938 contained many more vegetated islands, and it had become an island-braided river (**Figure 2.4**). However, the river undoubtedly contained vegetated islands in 1860, but they were ignored by the early surveyors. Nevertheless, these islands coalesced and increased in size, the single-channel braided stream became a smaller multiple-channel anastomosing river, which with time and abandonment of secondary channels became a much narrower single-braided channel. In contrast, in the anastomosing reach near Newark (Figure 2.3), just east of Kearney, two secondary anabranches, which were narrower and shallower channels, were abandoned between 1860 and 1938 (**Figure 2.5**). Two channel remained, the northern anastomosing channel much reduced in size, and the southern, apparently dominant, braided channel. By 1957, the northern channel was becoming a narrow single channel and the southern channel remained essentially as it was in 1860. In 1983, the northern channel was approaching a single-channel morphology, but the southern channel was island-braided.

Although the Platte River became narrower between 1986 and 1995, the adjustment differed between the braided (upstream of Kearny) and anastomosing reaches (Kearny to Grand Island). **Figure 2.6** presents an idealized evolutionary sequence of channel changes through time for both types of channel, although neither type has achieved the final stage of a single channel.

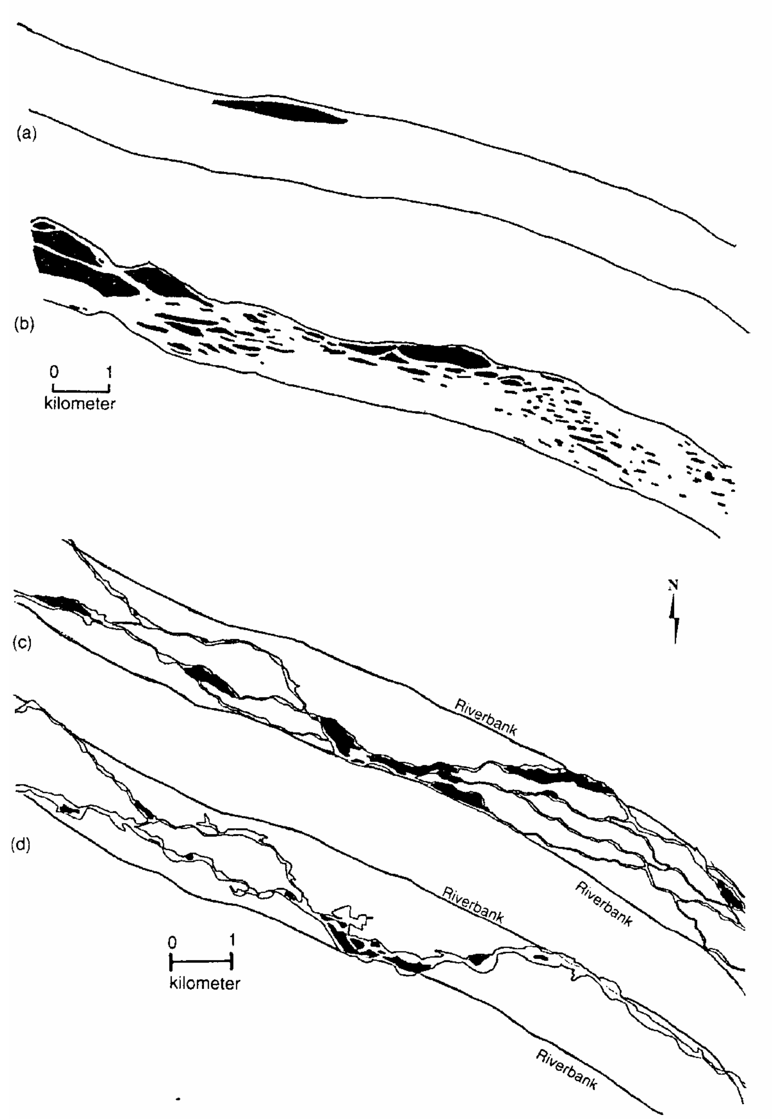


Figure 2.4. Platte River on Cozad quadrangle (see Figure 2.2) in (a) 1860; (b) 1938, (c) 1957, and (d) 1983 (from Peake et al., 1985). Dark areas are islands. 1860 riverbank indicates former channel width (from Schumm, 2005).

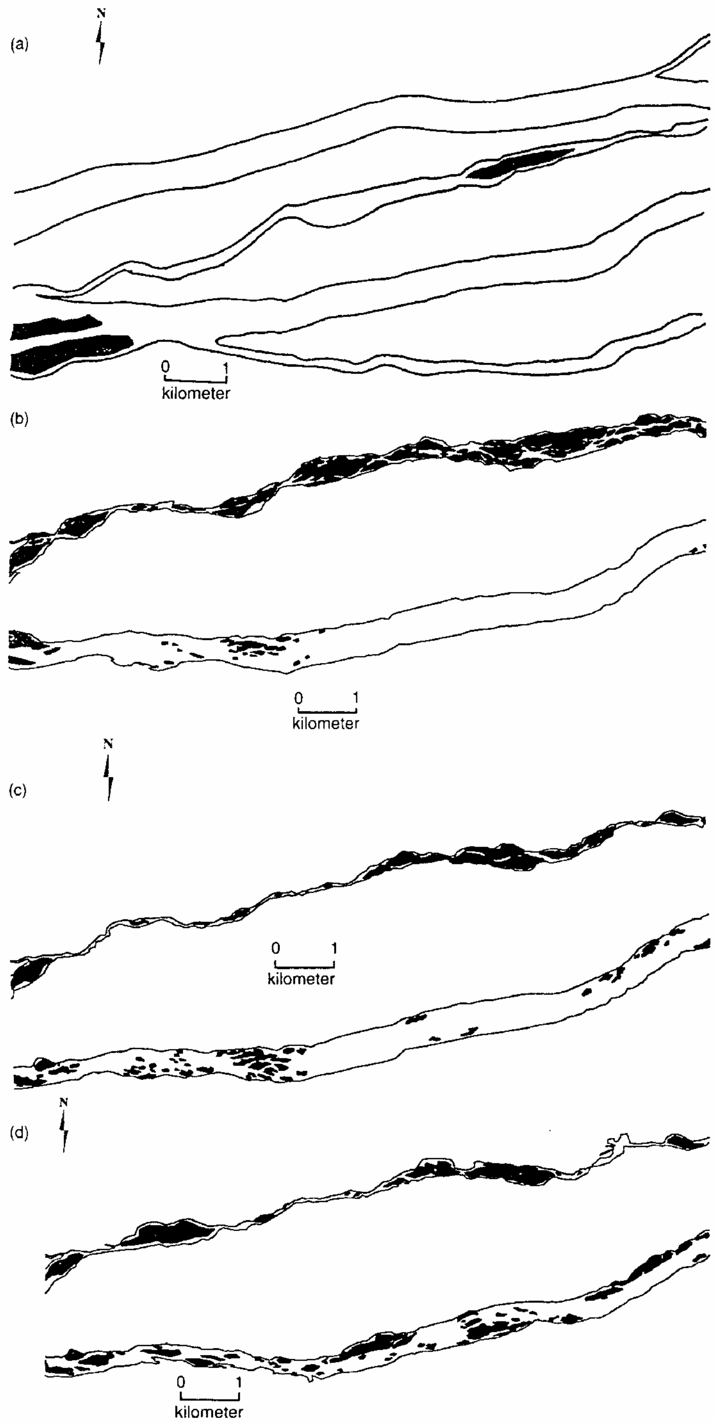


Figure 2.5. Platte River anastomosing channel on Newark quadrangle. Dark areas are islands (from Peake et al., 1985); (a) 1860, (b) 1938, (c) 1957, and (d) 1983 (from Schumm, 2005).

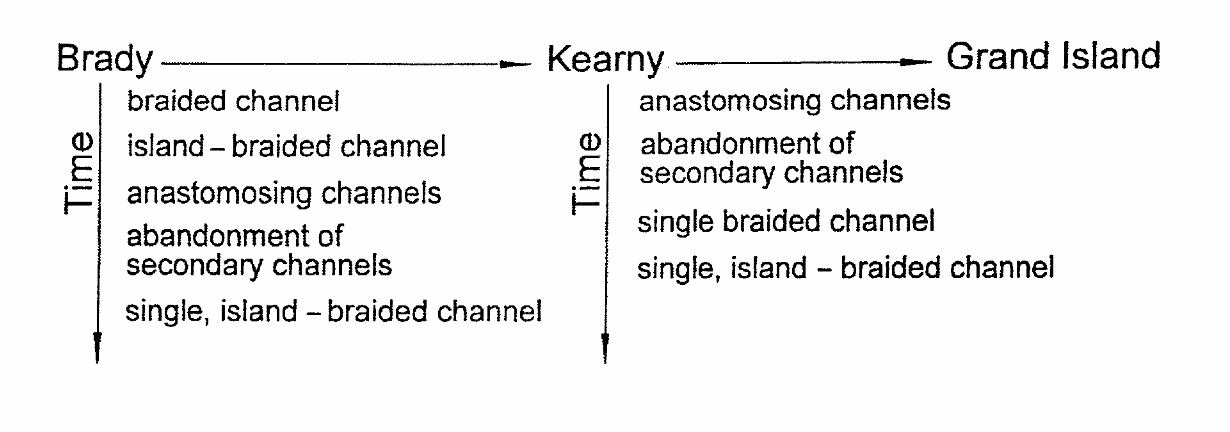


Figure 2.6. Change of Platte River downstream (left to right) and through time (top to bottom) (from Schumm, 2005).

The Platte River in Nebraska provides a good example of the response of braided and anastomosing channels to hydrologic change. The braided channel narrowed significantly by island formation and the development of small side channels (anastomosing), which were then abandoned. The result was a narrower braided channel. The anastomosing reach was converted to a narrow island-braided channel by abandonment of secondary channels and concentration of flow in one channel. Reduced mean annual discharge, reduced peak discharge, and the development of perennial flow all contributed to the metamorphosis of the Platte River.

In terms of downstream variability, hydrologic and climatic variability can strongly influence channel morphology. A tributary changing sediment loads and flow characteristics, although a local control, can transform a river from braided to meandering and vice versa (Schumm, 2005).

Although largely the effect of human activity, the changes of the Platte River indicate how a channel can adjust if the water table rises or falls naturally. It is likely that the Cimarron River responded to drought and a falling water table, which caused loss of riparian vegetation. Large floods then easily attacked the banks. With the return of more humid conditions and a rising water table, vegetation colonized the higher parts of the channels and the channel was significantly narrowed like the Platte River.

Mean annual discharge, flood peaks, and even no-flow days have major impacts on channel morphology. Even a reversal of the hydraulic geometry occurs when discharge decreases downstream. Similar channel changes could have occurred along the Gila River, as diversions became important in the 19th century.

2.1.3. Gila River System

The lower Gila River (junction of Salt River to the Colorado River) and its major tributaries (Salt and Verde Rivers) display changes similar to those of the Cimarron and Platte Rivers. In addition, because the valley of the Gila River is very wide, avulsion is a common occurrence.

The Gila River is characterized by inherent instability and frequent and destructive channel migration (Chin, 1988; Graf, 1981), and there are reaches of relative stability and instability. For example, during a flood in 1941, the channel shifted 0.5 miles near Buckeye (Chin, 1988). According to Graf et al. (1994, p. 32), the lower Gila River “typified braided streams, variable in channel configuration and dimensions…" According to Ross (1923, p. 36), the river in 1917 was an interrupted stream, that is, one that has local reaches of flow while most of the river was dry. Clearly then, the river had intermittent flow. "Gila River below Salt River is a winding stream subject to considerable changes of volume… Between terraces is a floodplain which in most places from one mile to several miles wide, incised into the floodplain and channel one foot to 10 feet or more deep and a few feet to the mile wide. The position, size, and number of channels change with every flood." (Ross, 1923, p. 76)

Huckleberry (1996, p. 16) summarizes the character of the Gila River as follows: "The Gila River is a classic example of a dryland river that seldom seeks an equilibrium form. Unlike rivers in humid regions that have more stable channels that are adjusted for more continuous streamflow with less variance in discharge, the dryland rivers are inherently more unstable and more prone to changes in channel configuration. In such unstable fluvial systems, channel configuration depends much upon the history of previous flood events. Periods of high flood frequency are likely to correlate to periods of increased channel instability." Clearly, a braided river will respond to hydrologic changes and especially to large floods.

Descriptions of the river that have been compiled by Graf et al. (1994) and Rea (1983) and others generally agree that the river was bordered by willows and cottonwoods. It ranged in width from 240 to 1,300 feet with 450 feet being the most common estimate. Depth ranged from almost 0 to 4 feet. Cooke (1878) complained that "*the river, where I have wanted it as a barrier to the mules, has always been but a few inches deep; here, where I must cross it, it is swimming*." This shows how variable the river was. For example, a very different river is described near Powers Butte near Arlington. John Montgomery, a rancher states that *"in the summer of 1889, when a boy of 12…the river had a well-defined channel with hard sloping banks lined with cottonwoods and bushes. The water was clear, was 5 or 6 feet deep, and contained many fish."* (Ross, 1923, p. 66) If accurate, this is a description of a river that is very different from that described elsewhere, but this variability is expected for most rivers.

According to Darton (1933, p. 228), *"The Gila River channel has changed materially in a century or less. When it was originally discovered, there was a well-defined channel with hard banks sustaining cottonwoods and other trees and plants. The current was swift and deep in places, so that the stream could be navigated by flat boats of moderate size, and it contained sufficient fish to be relied upon as food for many Indians… Now (1933), the Gila River is depositing sediment in its lower part and its braided course follows many narrow sand-clogged channels."*

As described by earlier travelers, and shown on the early maps, the Gila River had a relatively narrow single channel, but surveys after 1910 show a much wider channel. The average width of the channel of the Gila River increased during 1905-1917 to about 2,000 feet, mainly as a result of large winter floods. The meander pattern of the river and the vegetation in the floodplain were destroyed completely by the floods. The channel of the Gila River narrowed during 1918-1970 and the maximum width was 200 feet in 1964. The channel developed a sinuous pattern and the floodplain became densely covered with vegetation.

According to Burkham, major floods were the causes of the dramatic channel changes. Huckleberry (1996) reached the same conclusions regarding the middle Gila River. The early surveys showed the middle Gila as a narrow single channel until 1891. In 1891, the middle Gila River experienced a large flood that caused channel widening and large floods in 1905 and 1906 radically transformed the relatively narrow channel to a wide braided channel. Huckleberry (1996, 1994) concluded that major channel changes are related more to the duration of a flood than to its magnitude. Beginning in 1905, the channel experienced great widening as a result of bank cutting during periods of sustained flow. For example, it was reported for U.S. Geological Survey gaging station near Dome that there were "*radical changes in channel in 1905 and 1906*" (U.S. Geological Survey, 1954, p. 707). During those two years, there were five months of high flow in 1905 and six months of high flow in 1906. Prolonged flow of this magnitude undoubtedly contributed to channel widening.

During the floods of 1905-1906, the Geological Survey had difficulty maintaining their gaging stations. For example, the gage at Dome was established in 1903, but in 1905, the river had shifted one mile north (U.S. Geological Survey, 1906, p. 164). Further description of the river in 1905 revealed that its channel was not amenable to navigation. For example, *"The Gila carries an enormous amount of mud and sand. At times, the waves of sand…are so large, the current is so swift, and the stream to [sic] shallow, that the water is broken into a uniform succession of waves two feet high and over. During 1905, there have been 10 floods… At every flood, the channel shifts."* (U.S. Geological Survey, 1906, p. 164)

Channel transformation from a meandering to a braided pattern during a period of large and prolonged flooding is not restricted to the Gila River, as the discussion of the Cimarron River shows.

As an example of the effects of the 1905-1906 floods on the Gila River, the tribulations of Clarence Maddox are impressive. Maddox, on April 19, 1903, filed a homestead entry on Sections 29 and 30, T8S, R22W, east of Yuma. In a June 21, 1909, letter from a special agent of the General Land Office to the Commissioner, the special agent wrote that:

"the only time (the Maddox's) were absent from said land up until June 1908, was at such times as it was unsafe to live thereon by reason of the overflow of the Gila River…Maddox claims that at one time to have had about 40 acres cleared and planted, but that the river washed away all of said cultivation, and that the Gila River has changed its course three or four times during the period he had lived on said land and that at the present time most of said entry is in the bed of said river, there being only about 20 acres left; that his other houses were built on the north side of the Gila River, while his present house is on the south side; that the channel of the river has so changed during the past five or six years that while at the time he made his entry all his entry was on the north side of the river that most of it is now on the south side of the river."

(Homestead Entry Patent File for 1034203, 1903, Serial Land Patents, Record Group 49, U.S. General Land Office, U.S. National Archives, Washington, D.C., LRA Box/File 28/21)

Another document in Maddox's file, written by his wife on February 21, 1912, stated that:

"the first big flood came about a year after establishing residence. The Gila River overflowed its natural course and washed over our land…We returned to the land about three months subsequent thereto and again lived in the house, until about a year when the Gila and Colorado Rivers again overflowed and drove us from the land, absolutely destroying the adobe house, pumps and all traces of our residence. About six months thereafter we built a small house, and continuously resided therein until a couple of months afterward when the river again rose, washed away out second house, and driving us from the land…I have exercised the utmost good faith in endeavoring to maintain residence on the land during the above period often-times at the risk of my life, and that of my child, the river oftertimes [sic] rising to a depth of seven or eight feet and forming a stream a mile wide in a single night." (Homestead Entry Patent File for 1034203, 1903, Serial Land Patents, Record Group 49, U.S. General Land Office, U.S. National Archives, Washington, D.C., LRA Box/File 28/21)

If the homestead entry was filed in April 1903 and the first big flood occurred "*about a year after establishing residence,"* it probably was the large long-duration flood of 1905. About a year later, the 1906 flood destroyed their house. The loss of agricultural land indicates major bank erosion and widening of the river during the 1905-1906 floods.

Further evidence of the great impact of these floods is the statement that: "*There was no historical evidence identified for this study that any profitable commercial enterprises were conducted using the Gila River for trade and travel as of the time of statehood. However, there is historical evidence that profitable commercial enterprises were conducted barely seven years prior to statehood."* (Arizona State Land Dept., 1996) Of course, seven years before statehood is 1905.

In addition to the preceding evidence of major lower Gila River channel changes, as a result of 1905-1906 floods, a comparison of pre- and post 1905 General Land Office surveys provides convincing information. **Figure 2.7** shows a significant widening of the Gila River in T1N, R2W between 1883 and 1907. This is true of reaches of the river near Florence (**Figure 2.8**) and below the Salt River confluence (**Figure 2.9**). All of the evidence indicates that the 1905-1906 floods dramatically widened the Gila River.

The evidence shows that the lower Gila River before the floods of 1891, 1905, and 1906 had a relatively narrow and deep channel that was bordered by trees and brush. It appeared to be relatively stable. The large, long-duration floods, especially those of 1905 and 1906 converted the relatively stable lower Gila River into a braided channel that was wide and shallow and unsuitable for navigation. The General Land Office surveys pre- and post-1905-1906, where available, reveal the dramatic alteration of the channel.

Huckleberry (1996) reached the same conclusion regarding the middle Gila River (**Figure 2.10**). The early surveys showed the middle Gila as a narrow single channel until 1891. In 1891, the middle Gila River experienced a large flood that caused channel widening and large floods in 1905 and 1906 radically transformed the relatively narrow channel to a wide braided channel. Huckleberry (1996) concluded that major channel changes are related more to the duration of a flood than to its magnitude. Beginning in 1905, the channel experienced great widening as a result of bank cutting during periods of sustained flow. During two years, there were five months of high flow in 1905 and six months of high flow in 1906. Prolonged flow of this magnitude undoubtedly contributed to channel widening.

During the floods of 1905-1906, the Geological Survey had difficulty maintaining their gaging stations, and indeed, the gage at McDowell was washed out during the flood of 1905 (USGS, 1906). Large floods resulted in degradation of the middle Verde River, and elimination of swampy marshland. It is possible that similar change occurred along the Lower Salt River, although only avulsion of the channel in excess of one mile has been documented (Graf, 1983a).

The detailed study of channel changes in the Safford Valley by Burkham (1972) provides the best documentation of Gila River response to hydrologic variations. It also provides the basis for predicting future river changes, as a result of both natural and human- induced hydrologic impacts.

The Safford Valley extends from the confluence of the Gila River and Bonita Creek to Coolidge Dam. The Gila River enters the valley a few miles northeast of Safford. The area studied by Burkham is about 45 miles long and extends from the confluence of the Gila and San Simon Rivers to Calva, Arizona, just above San Carlos Reservoir.

a

b

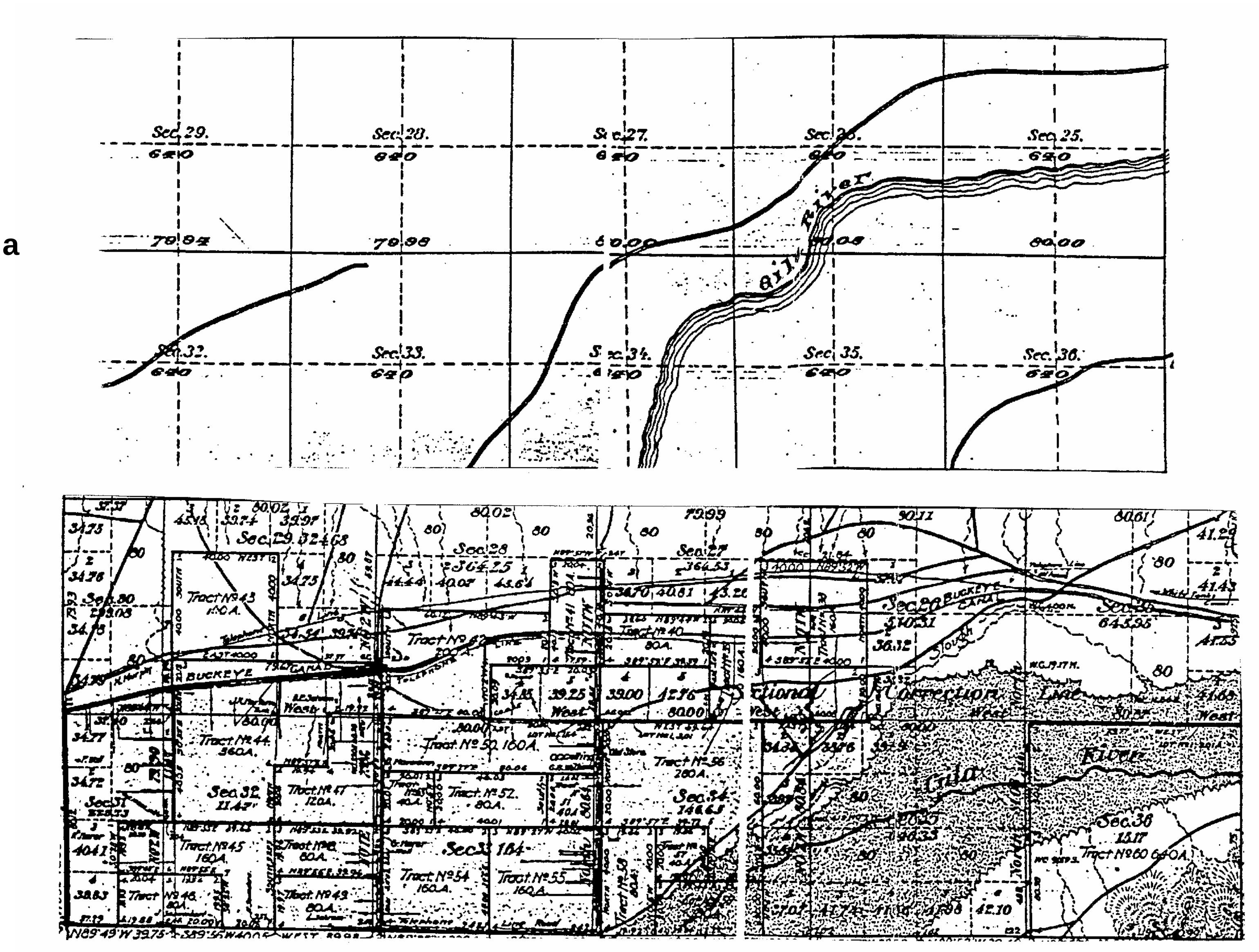


Figure 2.7. Gila River in T1N, R2W in a) 1883 and b) 1907.

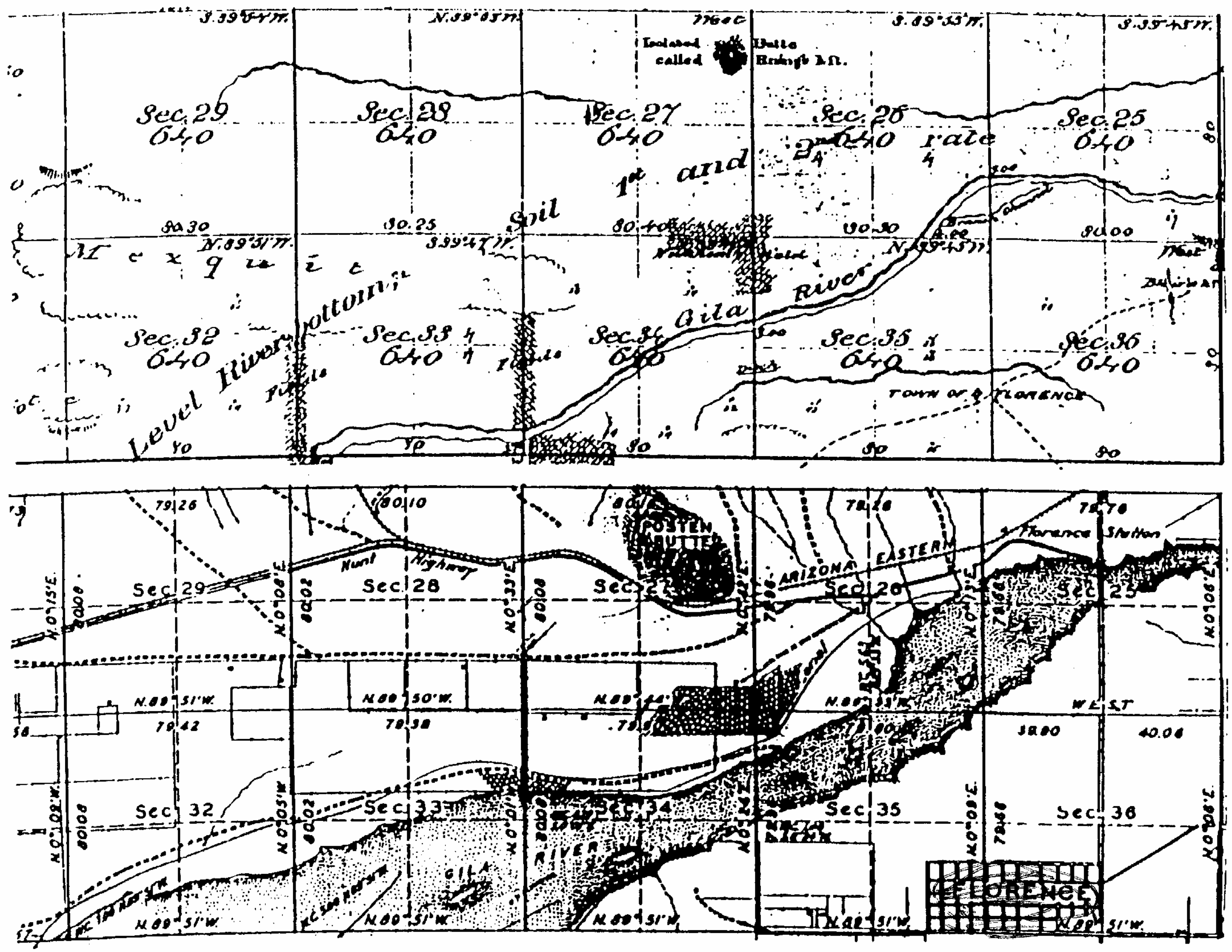


Figure 2.8. General Land Office plats of T4S, R9E as surveyed in 1869 (above) and 1928 (below).

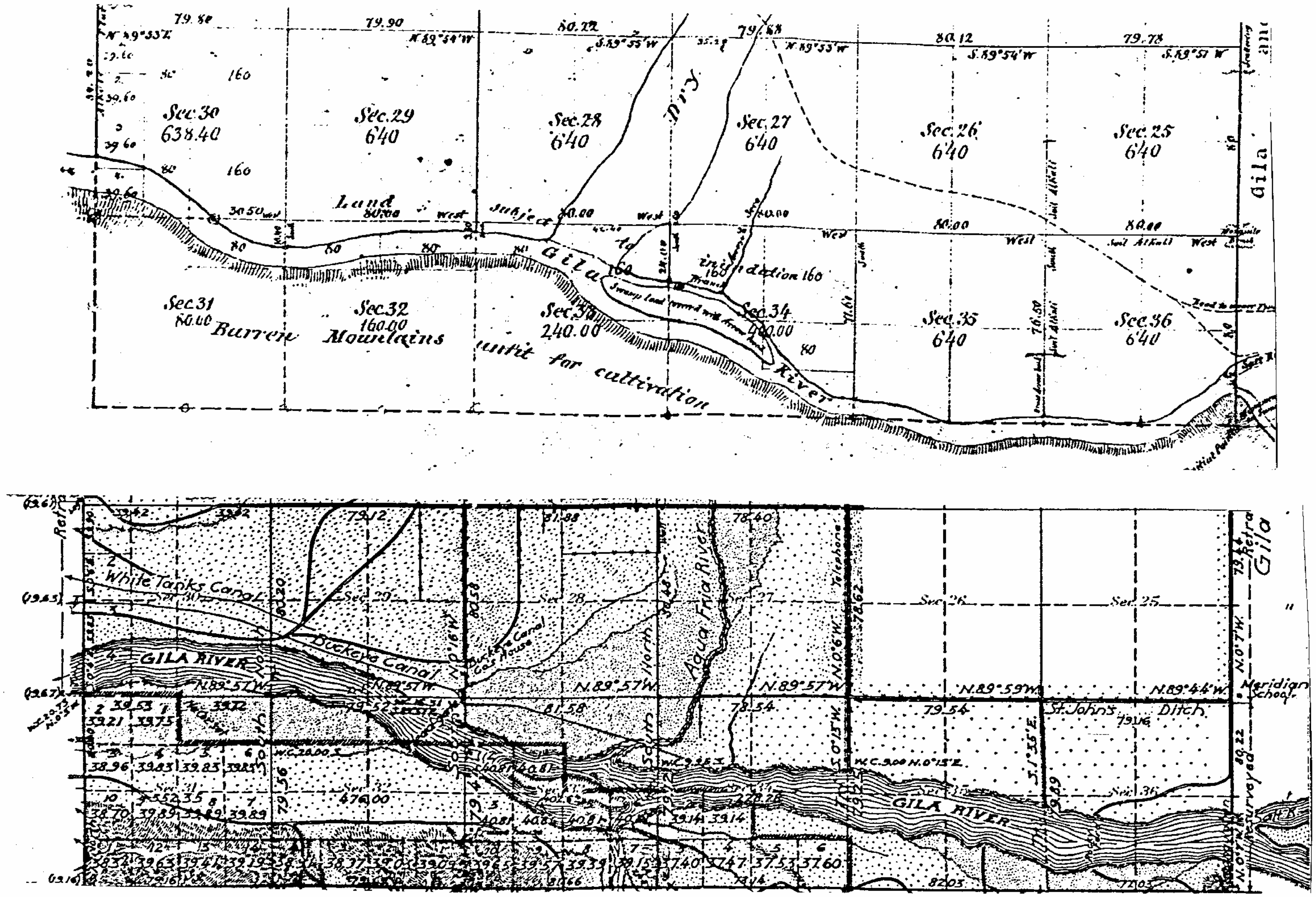


Figure 2.9. Gila River below Salt River confluence in a) 1867 and b) 1915.

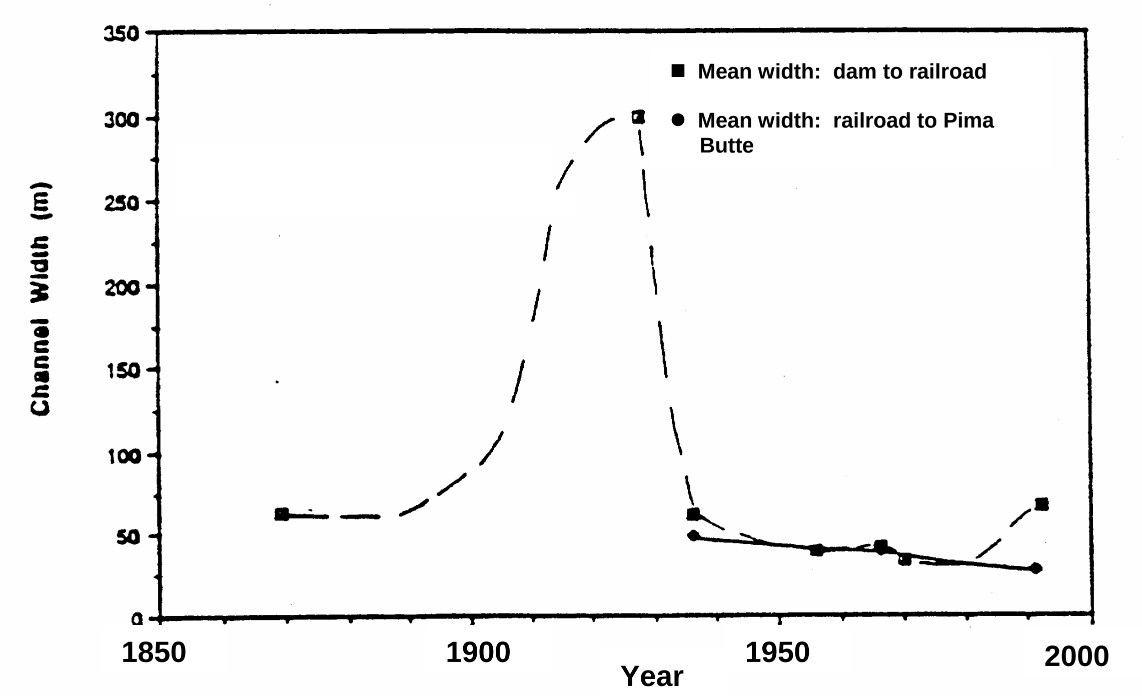


Figure 2.10. Changes in channel width for the middle Gila River (from Huckleberry, 1993).

According to descriptions of Gila River by early explorers and travelers, the river, before 1875, was less than 150 feet wide and 10 feet deep at bankfull. The river was sinuous and flanked by a floodplain that supported willow, cottonwood, and mesquite. According to Burkham (1972), the channel changes of the Gila River in the Safford Valley can be grouped into three periods as follows: (1) 1846-1904, (2) 1905-1917, and (3) 1980-1990. In 1875, width varied from 70 to 220 feet, and it is assumed that width was generally the same from 1846 to 1875, although the response to floods caused some variation. For example, width was about 140 feet in 1875, 500 feet in 1894, and 260 feet in 1903. Major widening of the Gila River began during the flood of 1904. The river widened to 2,000 feet by 1915 (**Figure 2.11**).

Following the major flood of 1916, the river narrowed and a new floodplain formed. Width decreased to between 290 and 530 feet in 1968. Floods of the 1960s and 1970s widened the channel so that by 1982, it was wider than in the 1940s and 1950s (Hooke, 1994).

It is clear that floods cause widening of the Gila River, but the magnitude of change varies widely. For example, Huckleberry (1994) compared the results of major storms. Floods of January and February 1993 caused major widening of Gila River. An earlier flood in 1983 had a higher peak discharge, but it caused little channel change. The 1993 flood was of larger volume and duration, which destabilized the banks and caused significant widening.

Burkham (1970) compiled information on some major floods starting with the 1891 flood. It is clear that the destructive floods of 1905-1906 resulted from abundant precipitation which saturated the soil, resulting in high runoff, which widen and deepen the channel. According to Hooke (1996), channel change as a result of a flood varies from place to place in the valley depending upon channel pattern. Although the 1983 flood was nearly comparable to the 1905 flood, the impact was much less. Nevertheless, moderate floods do play a role causing lateral shifting, bank erosion, and building of bars.

In the dryland streams, preconditions are very important. A long period of drought will weaken riparian vegetation and can cause major bank erosion. A series of closely spaced floods will saturate banks and leave them susceptible to collapse during floods.

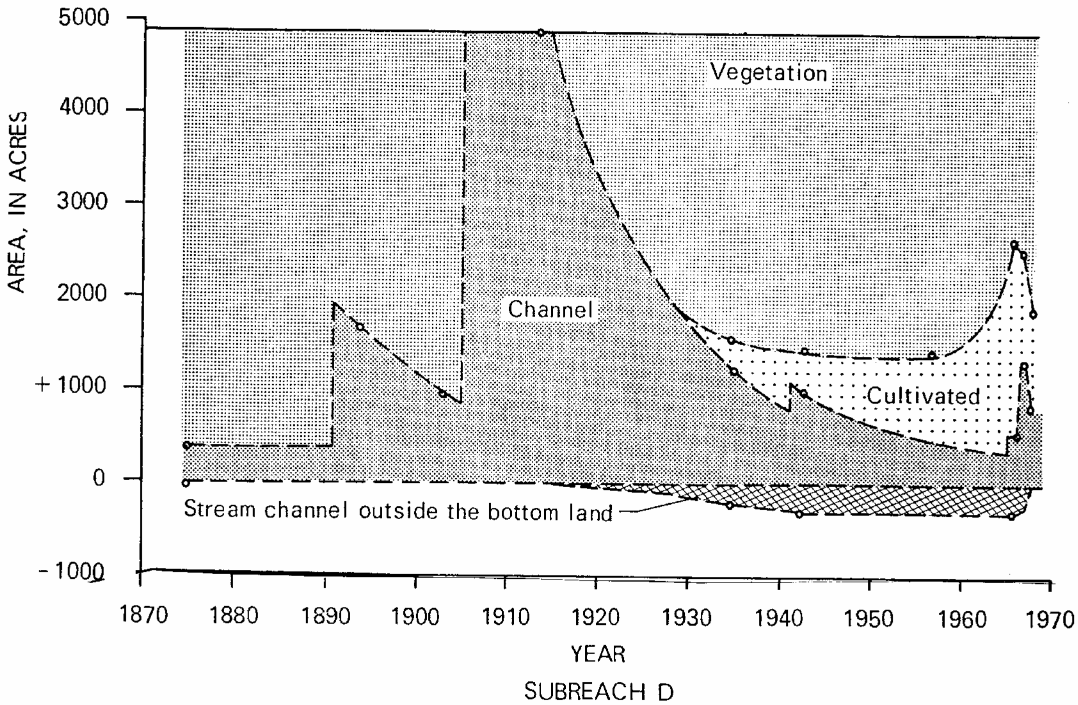


Figure 2.11. Historical changes in channel area of upper Gila River (San Simon to Pima) (from Burkham, 1972).

Variability of response from location to location can depend upon local river morphology. For example, a straight reach could develop a sinuous pattern; whereas, a sinuous reach could straighten. A steep reach could degrade, but a flat reach could aggrade.

2.1.4. Gila River, New Mexico

The Gila River upstream of the border between Arizona and New Mexico can be divided into six distinct reaches, as described by the Bureau of Reclamation (2004a). Downstream of the junction of the Gila River and the East Fork Gila River, the river can be divided into canyon reaches and open valley reaches as follows (Figure 2.1):

1. Upper Box: a 37-mile canyon reach,
2. Cliff Gila Valley: an 18-mile open-valley reach,
3. Middle Box: a 9-mile canyon reach,
4. Lower Box: a 4.5-mile canyon reach, and
5. Virden Valley: a 7.8-mile open-valley reach.

The river is obviously more susceptible to change during floods, in the valley reaches in contrast to the canyon reaches (boxes). This is shown by data collected near Virden, New Mexico (**Figure 2.12**). During a period of low peak discharge (1950-1970), the channel narrowed. During a period of high peak discharges, the channel widened. This corresponds well with channel changes in the Middle Gila River as described earlier (Burkham, 1970; Huckleberry,

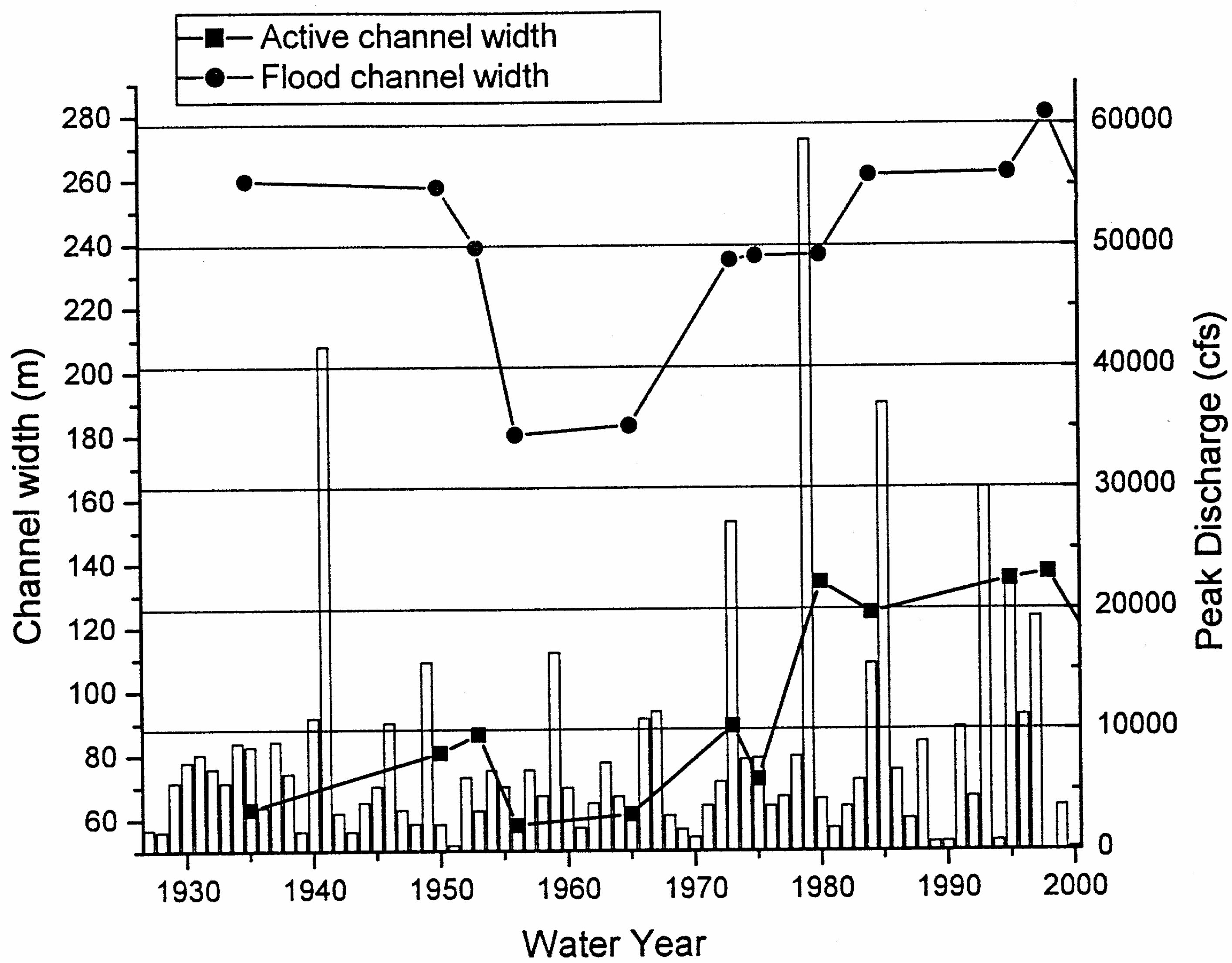


Figure 2.12. Average width data by photograph year. Active channel widths and flood channel widths are superimposed on the stream gage record at the Gila River below Blue Creek near Virden, New Mexico (from Bureau of Reclamation, 2004b).

1994). As documented by the Bureau of Reclamation (2002b), elsewhere along the Gila River, the period 1980-2000 was one of channel widening in response to large floods (Figure 2.12).

The floods of 1905 had a major impact on the Gila River in Arizona. For example, Murphy and others (1906) state that the river at least doubled in width near Solomonsville and the railroad bridge at San Carlos was washed away as was the gage. Huckleberry (1993, 1995) describes changes of the Middle Gila River in Arizona through time that are identical to the changes described previously for the Platte River.

A study by Soles (2003) of a 12-mile reach of the Gila River upstream of Cliff reveals how complex the river can be through time and at different locations. She stresses that a snapshot of river history can give a very false impression of long-term river conditions (for example see Figures 2.10 and 2.11). She states that

> *In the late 1800's the Gila River in southwestern New Mexico occupied a single deep channel with thickly vegetated banks. In the Gila Valley, just downstream of a National Forest boundary, the river today is wide, shallow, and braided among cobble floodplains largely devoid of vegetation. The Gila River's current condition could be the result of natural events, a series of major floods on the river between 1971 and 1997. Or it could reflect the river's response to human efforts that include diversions for irrigation and the construction of check dams and levees beginning about 1950. Morphological and flood data indicate that the current condition of the Gila Valley is due in part to levee construction and repair, and they suggest that major modifications to channel form for restoration purposes may have unpredictable consequences.* She concludes that, *The geomorphic effects of large floods in semi-arid valleys are extremely complex. Among other factors, duration of flooding, relative magnitudes of mainstem and tributary flooding, and patterns of existing vegetation can strongly influence patterns of erosion and deposition within the mainstem channel.*

A study by the Bureau of Reclamation (2002c) shows how the Gila River responded to hydrologic change. Nine locations were selected for study on aerial photographs for the period 1935 to, in some cases, 2001. The observation of importance is the variability of the channel in response to hydrologic change. For example, the large 1979 flood significantly widened the channel (Figure 2.12). It is very probable that the Gila River in New Mexico has responded to hydrologic fluctuations in the same way as the Gila River downstream of the New Mexico-Arizona border. However, the Bureau of Reclamation (2004a) has reached a different conclusion that change is the result of levee construction. They state

> *The pattern of historical geomorphic change observed along the Gila River in New Mexico is probably not the result of changes in the upper watershed or changes in hydrology. In every case where historical geomorphic change has been documented in this study, the proximate cause is human disturbance of the Gila River channel. In some cases, there are multiple disturbances that probably all contribute to bank erosion and property loss.*
>
> *It appears that levee construction and subsequent failure has resulted in the majority of geomorphic change observed in the Cliff-Gila and Virden Valleys. The lack of significant observable change in sediment flux and flood characteristics indicates control over geomorphic change in these areas is not external. That is, change is not the outgrowth of change in runoff or sediment yield from the upper drainage basin. This points to a causative mechanism*

present in both valleys. The Catalog of Historical Changes and the Geomorphic Map both record the close association between levee construction and geomorphic change. This provides the mechanism that is internal to both valleys and does not require geomorphic change to be the result of the change in external conditions, such as those in the Upper Box.

The hypothesis that local modifications of the Gila River channel is responsible for the observed geomorphic change in the Cliff-Gila and Virden Valleys is supported by all the available data. The fact that change in runoff and sediment flux from the upper Gila River basin can be discounted as the cause of geomorphic change points to a factor that must be present in each of the valleys. The Catalog of Historical Changes and the Geomorphic Map and Analysis document the close correspondence between levee construction and subsequent failure and redirection of flow by levees and significant geomorphic change along the Gila River in the Cliff-Gila and Virden Valleys. Further, the construction of levees led to decreased sediment transport resulting in channel aggradation. Finally, the straightening and channelization of steep tributaries from the point where they intersect the mainstem floodplain and the mainstem itself is causing rapid formation of prograding alluvial fans in the Gila River channel. In many cases, these out-of-place fans are shunting the mainstem flow against the opposite bank, eroding that bank and causing loss of land resources.

The Bureau appears to ignore all the evidence of dryland river response to hydrologic change, which is the most convincing explanation of Gila River change. Levee failure can explain local erosion, especially where levees not only act to confine water, but also reduce channel width (Geomorphic Maps 1, 3, 8, 9, 10). One cannot ignore the history of the Gila River, which clearly demonstrates the effect of large floods on channel dimensions (Figures 2.7 through 2.11). Clearly, even without levees, the Gila River would erode its banks and shift position on the floodplain in response to periodic floods of long duration.

A final example of the effect of floods on the Gila River is provided by Doeing et al. (1997). They studied, among others, pipeline failures as a result of Gila River scour, during the 1993 floods. Failures, as a result of scour and lateral erosion, occurred at Duncan, Winkelman, Coolidge, and Gillespie Dams, all in Arizona. Scour depths were calculated for the 100-year flood (**Table 2.1**), in order to provide the gas company with a guide for pipeline burial below the Gila River channel. Lateral erosion and channel shift (Table 2.1) were determined from before and after aerial photographs and other sources.

The failure of the Gillespie Dam during the floods probably increased the downstream depth of scour and lateral erosion, and therefore, these data are not useful as an indication of scour and lateral erosion during floods. At Coolidge, Doeing et al. (1997, p. 34) report the following:

Maximum scour depths at the pipeline were probably not extreme because of the great width of the channel and the floodplain during peak flows, but the channel shifted laterally over 2,000 feet (600 m) during the flood (Table 2.1)*. A meander belt is evident at this crossing with an estimated width between 5,000 and 6,000 feet (1,500 to 1,800 m). It provides evidence that the stream channel migrated significantly during previous floods. Failure of the pipeline resulted from this lateral shift in the channel, which undercut the pipe in an overbank area where pipeline burial depth was more shallow.*

Table 2.1. Hydraulic design parameters and results of scour analyses (from Doeing et al., 1997).							
Pipeline Crossing	Slope (m/km)	100-Year Discharge (m^3/s)	Top Width (m)	Maximum Velocity (m/sec)	Flow Depth (m)	Local Scour (m)	Lateral Erosion (m)
Gila River at Gillespie Dam	0.23	6,600	90	9.8	5.4	2.7	1,200
Gila River at Coolidge	0.34	3,700	460	4.7	3.8	2.2	600
Gila River at Winkelman	1.70	3,400	450	2.8	7.6	5.7	1,650
Gila River at Duncan	0.19	1,070	170	4.3	4.7	2.4	460

At Winkelman:

> *The flood water inundated the overbank areas and reached an elevation above the roofs of some of the homes in Winkelman Flats. Upstream of the housing development, the flow filled an old oxbow channel and caused significant lateral migration of this old channel. All of the pipelines were exposed throughout the overbank area as a result of either lateral migration of the old oxbow channel or local scour throughout Winkelman Flats* (Table 2.1).

At Duncan:

Doeing et al. (1997, p. 35; Table 2.1) recommended that maximum burial depth of the pipelines should extend for 1,500 feet (460 m) because lateral erosion of that magnitude can be expected.

2.2. Discussion

Although large floods are probably the cause of Gila River change, it has been proposed that land use in the upper watershed (grazing, timbering) could cause higher flood peaks and higher sediment loads downstream. However, studies by the Bureau of Reclamation (2002a, 2004b) have demonstrated that the effect of upstream variables is minimal.

In the BOR (2002a) report, the following conclusion is reached:

> *The information developed for this task does not support hypotheses that upstream changes in land use in the past two centuries has caused a major change of Gila River fluvial geomorphology downstream of the upper box. Based on this reconnaissance, the Gila River in the upper box has been stable over at least that period, and possibly much longer. In this case, stability of the river is defined as no major unidirectional change in bed elevation. A significant change in sediment delivery of a magnitude sufficient to cause major geomorphological change in the Gila River in the 66 miles of the downstream study reach should be obvious in the upper box. That is, the magnitude of change would be so great as to leave detectable physical record. This is not the case. Further, this apparent stability places doubt on changes in the upstream watershed as a major component of geomorphologic change from the downstream end of the upper box of the Gila River to the Arizona state line.*

The Bureau further concludes that (2004b):

> *Some attribute observed historical geomorphic change along the Gila River in New Mexico to changes in hydrology or land-use changes in the upper basin. Based on all geomorphic information gathered for this study this does not appear to be the case. In fact, the geomorphic and Holocene stratigraphic record of the Upper Box suggest that there has been very little impact on the Gila River system from historical change in the upstream watershed.*

This somewhat surprising conclusion can be explained based upon the relation between climate, vegetation, and sediment yields in dryland drainage basins. For example, a plot of sediment yield against precipitation (Langbein and Schumm, 1959) shows maximum sediment yield between 8 and 20 inches of precipitation (**Figure 2.13**). Within this range of precipitation, erosion is a maximum and human activities probably have a small effect on it.

Furthermore, experimental studies reveal that below about 15 percent vegetation cover, erosion is roughly constant (**Figure 2.14**), and therefore, a further reduction of vegetational cover below 15 percent will have a minor effect on sediment yield (Rogers and Schumm, 1991).

The impact of major floods on dryland channels is significant. Channel change occurs during major floods, which appear to occur randomly throughout the western U.S. and do not appear to be related to the drought of the 1930s or land use.

The character of a dryland river depends upon timing. Dryland channel changes is dominated by widening that occurs during infrequent major floods (Gila, Cimarron) and by subsequent narrowing that occurs after the floods (Platte) (Friedman and Lee, 2002). Therefore, the future character of Gila River will depend upon the occurrence of major floods. Hydrology is the dominant control.

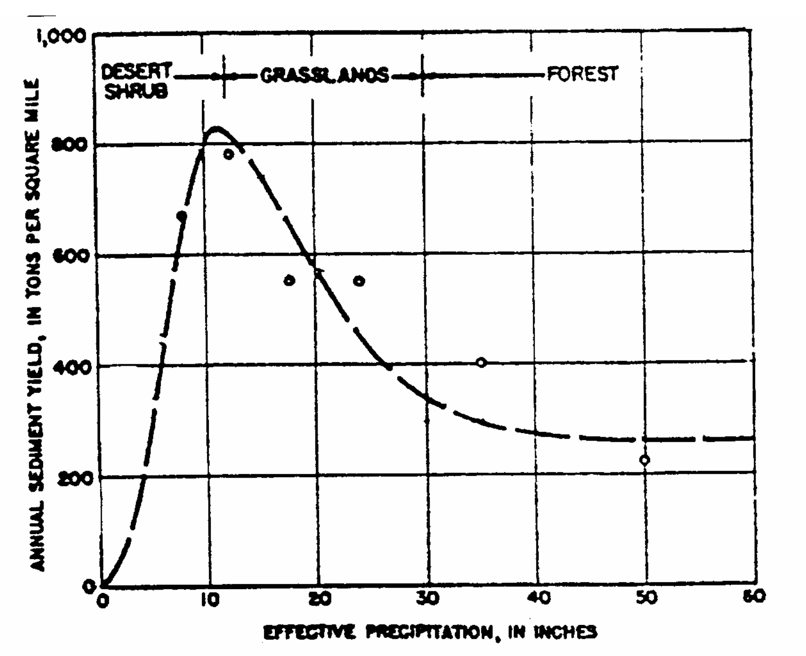


Figure 2.13. Variation of annual sediment yield with precipitation (from Langbein and Schumm, 1959).

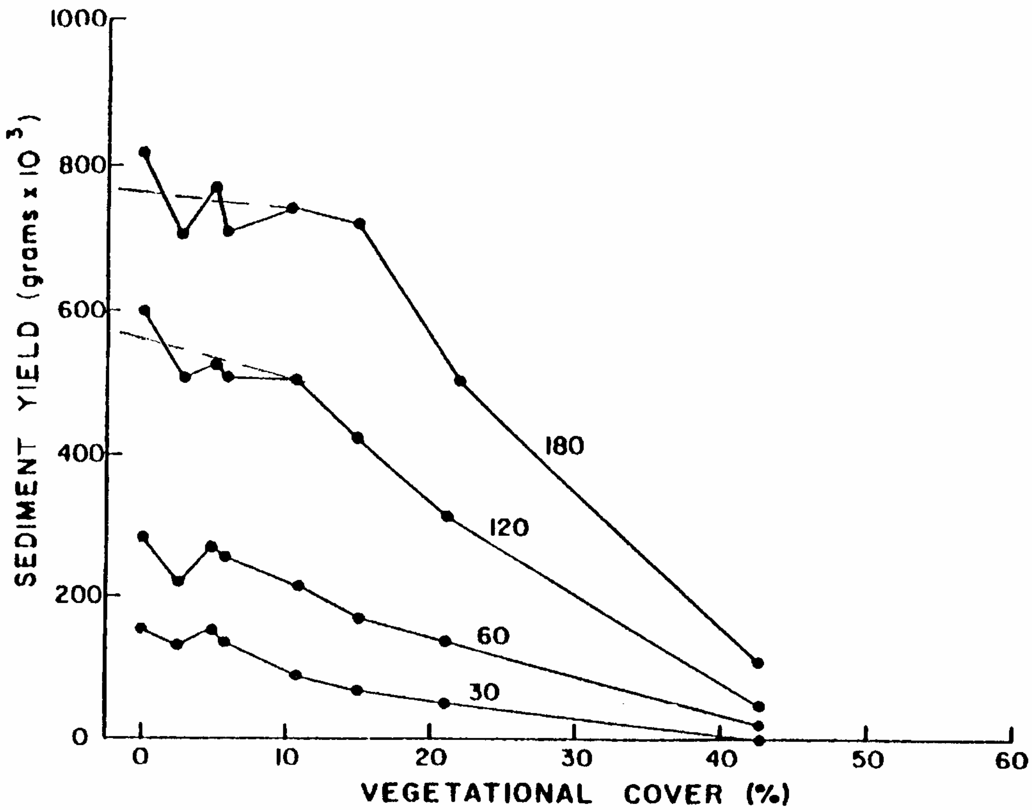


Figure 2.14. Effect of vegetational cover on sediment yield. Experiments performed on a 10-percent slope at 10, 60, 120, and 180 minutes of precipitation (from Rogers and Schumm, 1991).

3. STUDY SITE DESCRIPTIONS

3.1. General Description of the Study Reach

The Upper Gila River Basin is located in the southwestern portion of the State of New Mexico within Catron, Grant and Hidalgo Counties. The river rises within the Gila Wilderness Area at an elevation of about 11,000 feet in the Mogollon Mountains and flows in a southerly direction through the Upper Box canyon reach into the Gila-Cliff valley, and then in a southwesterly direction through the Middle Box canyon reach into the Redrock Valley and then through the Lower Box canyon reach into the Virden Valley to the Arizona State Line at an elevation of about 3,900 feet. The study reach for this project extends from the downstream end of the Wilderness area just upstream of the Gila River near Gila USGS gaging station to the Arizona State Line in the Virden Valley (Figure 1.1). On a reconnaissance visit to the project reach in December 2005, five sites that were considered to be representative of the range of geomorphic conditions in the reach, and that were also accessible, were selected for study by Mr. Wilkinson (NMISC) and Dr. Harvey. The locations of the five sites are shown on Figure 1.1. The study sites, located from upstream to downstream, are as follows:

1. Turkey Creek site, located in the lower reaches of the Upper Box canyon, about 3 miles upstream of the Gila River near Gila USGS gage (No. 09430500),
2. Nature Conservancy site (TNC), located in the Gila-Cliff Valley about 5 miles downstream of the Gila River near Gila USGS gage (No. 09430500),
3. Gila Bird Research Area (Birds) site, located about 18 miles downstream of the Gila River near Gila USGS gage (No. 09430500 at the downstream end of the Gila-Cliff Valley,
4. Box site, located at the downstream end of the Redrock Valley and immediately upstream of the Gila River below Blue Creek near Virden USGS gage (No. 09432000), and
5. Virden Bridge site, located immediately downstream of the NM Highway 92 bridge in the Virden Valley.

Photographs of the five sites are provided in **Appendix A**.

The spatial distribution of the alluvial and non-alluvial reaches within the project reach (Figure 2.1) is governed by the geologic setting. The Upper Gila River Basin, including the 37-mile long Upper Box canyon, is underlain by relatively erosion resistant Upper to Middle Tertiary-age volcanic rocks (basaltic, andesitic and rhyolitic lavas, and ash-flow tuffs) (Hawley, 1999). Northwest-southeast trending en-echelon fault zones and hydrothermal alteration zones create locally weaker and more erodible rocks and wider reaches within the canyon sections. The 18-mile long alluvial Gila-Cliff valley is bounded by coarse grained facies of the Quaternary to Pliocene-age Upper Gila Group that are comprised of interbedded alluvial, aeolian and colluvial sediments shed from the surrounding Mogollon Highlands (Hawley, 1999). The 9-mile long Middle Box reach of the Gila River is underlain by Pre-Cambrian granitic intrusive rocks (granites, diorites and syenites), Pre-Cambrian metamorphic rocks, Upper Cretaceous-age sedimentary rocks (sandstones, siltstones and shales) as well as Middle Tertiary-age rhyolitic dikes, plugs and diatremes (Hawley, 1999). The 16-mile long alluvial Redrock Valley reach is bounded by coarse grained facies of the Quaternary to Pliocene-age Upper Gila Group. The 5 mile-long Lower Box canyon reach is underlain by Middle Tertiary-age andesitic and latic lavas and ash-flow tuffs (Hawley, 1999). The 8-mile long alluvial Virden Valley is bounded by coarse grained facies of the Quaternary to Pliocene-age Upper Gila Group. The bulk of the alluvial sediments within the modern Gila River are thus derived from volcanic rocks, although granitic, metamorphic and sedimentary rocks are also present.

3.2. Turkey Creek Site

The Turkey Creek site is located about three miles upstream of the USGS Gila River near Gila gage (USGS Gage No. 09430500) (Figure 1.1). Although extensive coarse and fine grained alluvial deposits are present throughout the site, the geomorphic characteristics of the site are primarily controlled by the locations of outcrops of hydrothermally altered volcanic bedrock that define the overall geometry of the bend in the canyon (**Figure A.2**). Alluvial terraces, vegetated by large riparian (cottonwoods and sycamores) and upland (juniper) tree species are discontinuously present on both sides of the river (**Figure A.1**). Brock Canyon, a left bank (looking downstream) ephemeral flow tributary, has recently (2005) extended its active fan into the river and has caused a localized hydraulic contraction that is ponding flow upstream (**Figure A.3**). The margins of the coarse-grained debris flow deposits (**Figure A.4**) are being eroded by the river as it attempts to reduce the magnitude of the contraction, and the upstream hydraulic impacts. In general, the contraction ratio will reduce through time to about 0.5 (Kieffer, 1985; Webb et al., 1988). Boulders delivered to the river by previous debris flows create a number of boulder-dominated riffles in the lower reaches of the site (**Figure A.5**). Upstream of the boulder riffles are relatively deep pools (**Figure A.6**). A large number of chute channels are located across the very coarse grained point bar-like feature on the right side of the channel in the lower half of the site. The chute channels were active during the February 2005 floods when the peak discharge at the Gila River near Gila gage was about 20,000 cfs. Although the 2005 flood transported coarse-grained sediments (up to small boulders), and much of the present site appearance is related to the flood, the flood had little effect on the overall characteristics of this non-alluvially forced morphology site (Harvey et al., 1993; Montgomery and Buffington, 1997; O'Connor and Grant, 2003).

Figure 3.1 shows the general morphology of the site, and the locations of the 11 cross sections that were surveyed in February 2006 with RTK-GPS and Total Station methods. The cross sections and thalweg profiles were used to develop a 1-D step-backwater HEC-RAS (USACE, 2005) hydraulic model of the site (Chapter 5). Also shown are the locations of two boulder-count measurements in coarse-grained riffles (BC1, BC2), three Wolman pebble counts (Wolman, 1954) of surficial sediments in gravel/cobble riffles and mid-channel bars (WC1, WC2, WC3) and three sub-subsurface bulk samples collected in a pool (S1), the distal margin of the Brock Canyon fan (S2), and a mid-channel bar (S3), that was probably formed in the 2005 flood.

The boulder count data (**Figure 3.2**) show that the boulder-controlled riffles (Figure A.5) have median sizes (D_{50}) greater than 300 mm (~12 in.) and D_{90} (size of which 90 percent is smaller) sizes between 400 and 600 mm (16 to 24 in.). These coarse grained deposits are rarely if ever mobilized and form the local hydraulic controls in the channel. The surface gradations developed from the pebble counts (**Figure 3.3**) identify three classes of sedimentary deposits at the site. WC1 represents the surface gradation of the sediments introduced to the channel by the 2005 debris flow in Brock Canyon. The D_{50} is 44 mm (1.7 in.), and the D_{84} (size of which 84 percent is smaller) is 90 mm (3.5 in.) (**Figure A.7**). WC2 represents a gravel/cobble riffle in the channel at XS4, and is reasonably representative of the non-boulder riffles in this reach of the Gila River (**Figure A.8**). The D_{50} is 80 mm (3 in.), and the D_{84} is 160 mm (6.3 in.). WC3 represents the surface gradation of the sediments that were transported and deposited during the 2005 flood (**Figure A.9**). The D_{50} is 36 mm (1.4 in.), and the D_{84} is 70 mm (2.8 in.). The three bulk samples that were laboratory sieved (ASTM D422) by Vinyard & Associates, Inc., Albuquerque, NM, provide an indication of the caliber of material supplies by the Brock Canyon

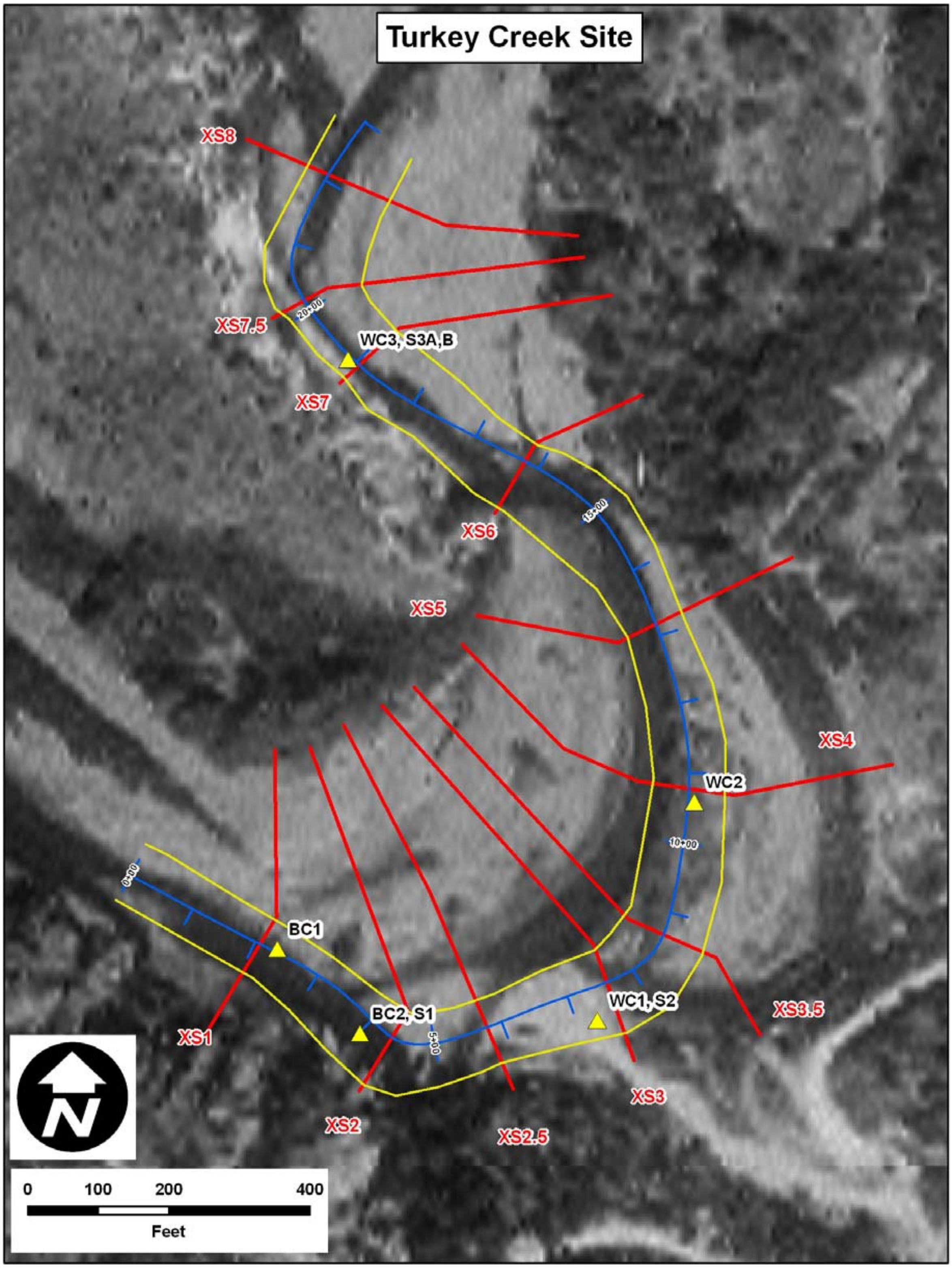


Figure 3.1. Aerial photograph showing the morphology of the Turkey Creek site, the locations of the surveyed cross sections and the locations of the sediment samples.

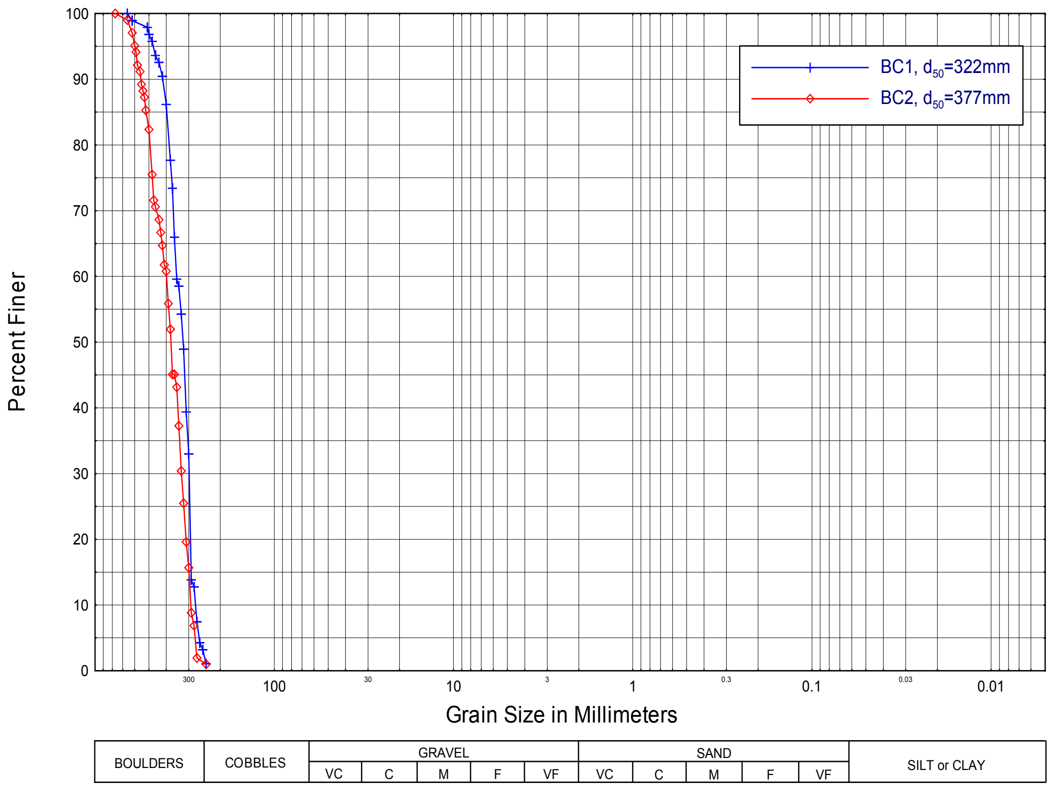


Figure 3.2. Gradation curves developed from non-randomized size measurements of boulders in riffles at Cross Sections 1 and 2.5 at the Turkey Creek site.

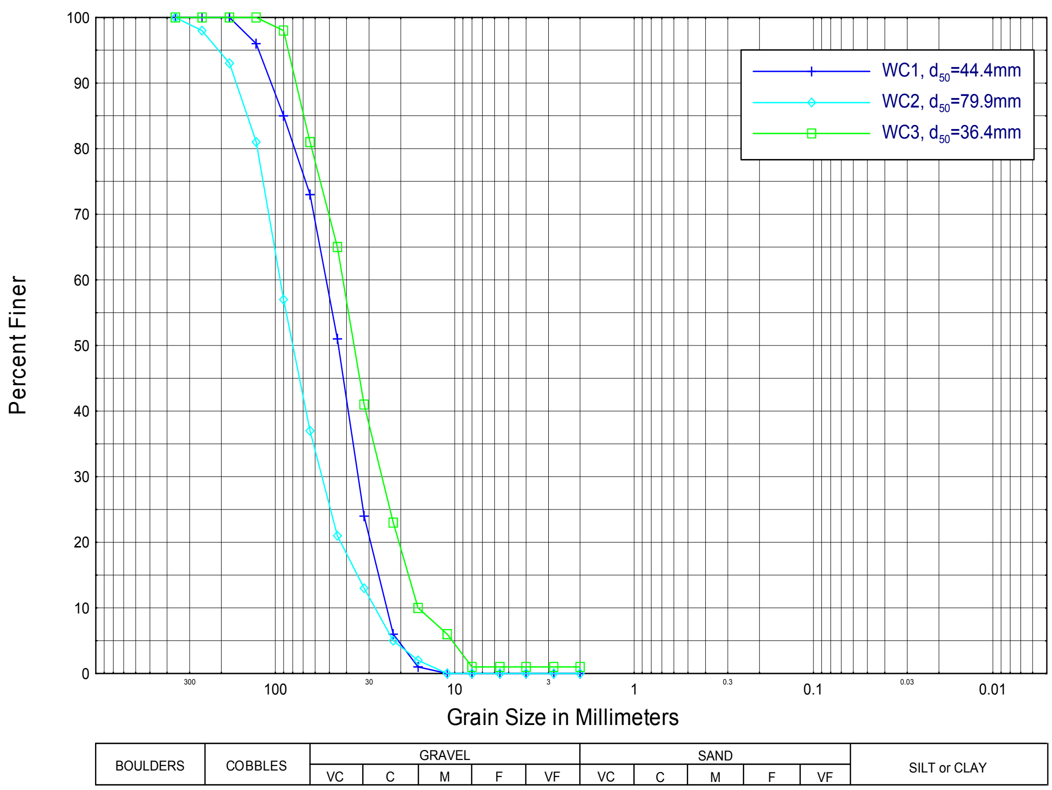


Figure 3.3. Gradation curves developed from pebble counts at the Turkey Creek site.

tributary and its subsequent sorting by the Gila River, and the sediment load transported in the Gila River in the 2005 flood. Sample Turkey 1 represents the finer fraction of the sediments delivered by the debris flow, and has a D_{50} of 5 mm (0.2 in.), and the D_{84} of 17 mm (0.7 in., **Figure 3.4**). Reworking of the finer fraction of the debris flow deposit (Turkey 2) does not significantly affect the D_{50} (5.2 mm), but it does increase the D_{84} size (28 mm) (**Figure A.10**). Between 30 and 35 percent of the samples are composed of sand-sized sediments. Sample Turkey 3 has a D_{50} of 7 mm (0.3 in.) and a D_{84} of 28 mm (1 in.), and is an indication of the sediment load transported and deposited during the 2005 flood. About 30 percent of the transported load was sand-sized and finer.

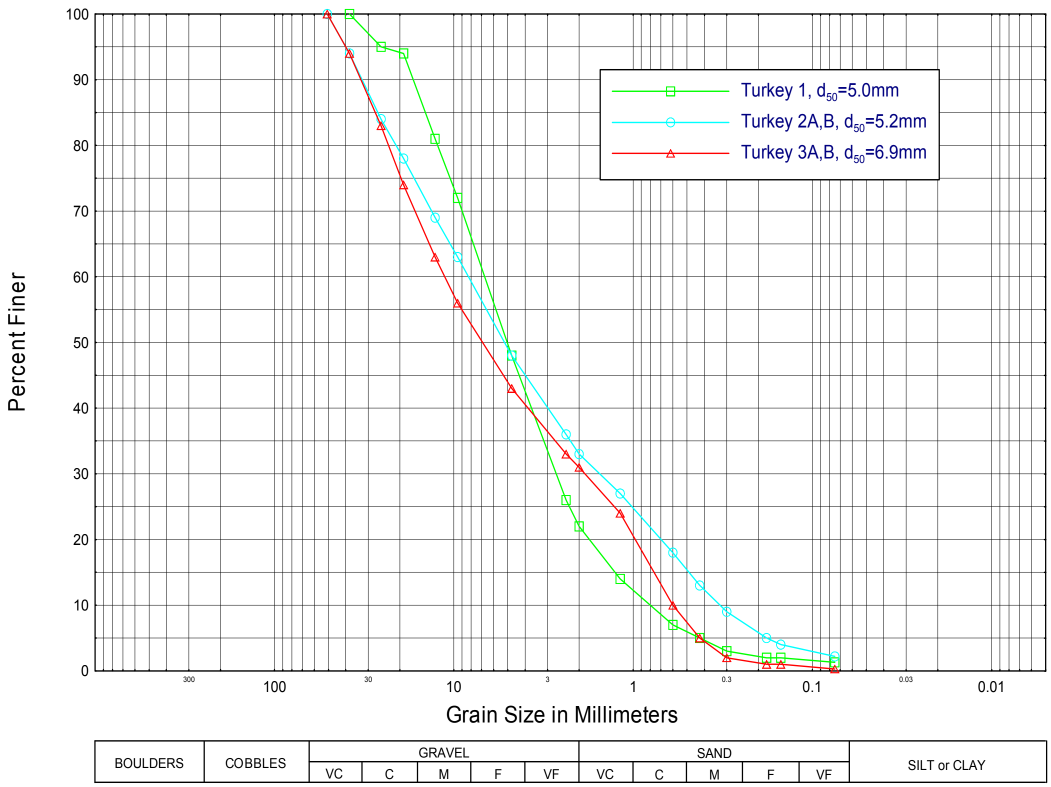


Figure 3.4. Gradation curves developed from bulk samples at the Turkey Creek site.

3.3. TNC Site

The TNC site is located about five miles downstream of the USGS Gila River near Gila gage (USGS Gage No. 09430500) (Figure 1.1). The site is located within the Gila-Cliff alluvial valley downstream of the confluence with Mogollon Creek. A man-made levee that has been breached by historical flood flows farther upstream forms the left (east) boundary of the site, and the remains of a man-made levee that was breached and eroded upstream during the 2005 flood forms the right (west) boundary of the site. A channel avulsion during the 2005 flood led to the formation of a bifurcated channel at the head of the site (**Figure A.11**). The east branch upstream of the site was the former channel of the Gila River, but currently the former channel location is occupied by a large pond, the origin of which is unclear. The west branch upstream of the site was formed by erosion during the 2005 flood (peak flow >20,000 cfs) and traverses an area of mature cottonwood trees (**Figure A.12**). The location of the channel within the site did not change significantly during the 2005 flood, but there was erosion along the east bank, and mainly deposition along the west bank (**Figure A.13**). The overall channel morphology at the site can be characterized as pool-riffle (**Figure A.14**), with a portion of the reach, exhibiting less well defined plane-bed morphology (**Figure A.15**) (Montgomery and Buffington, 1997).

Figure 3.5 shows the general morphology of the site, and the locations of the eight cross sections that were surveyed in February 2006 with RTK-GPS and Total Station methods. The cross sections and thalweg profiles were used to develop a 1-D step-backwater HEC-RAS (USACE, 2005) hydraulic model of the site (Chapter 5). Also shown on Figure 3.5 are the locations of six pebble counts that were made at in-channel riffles (WC1, WC2, WC3, WC,4, WC,5) and on a very coarse-grained mid-channel bar (WC6). Additionally, the locations of the two bulk samples that were collected on a mid-channel bar (S1) and a bank-attached bar (S2) are shown on Figure 3.5.

With the exception of WC1 which is located at the downstream most riffle at the site, the riffles (WC1-WC5) at the TNC site have D_{50} values between about 60 and 70 mm (2.4 to 2.8 in.), and the D_{84} values are between 100 and 130 mm (4 to 5 in., **Figure 3.6**) (**Figure A.15**). Bulk samples of the mid-channel (TNC1) and bank-attached (TNC2) (**Figure A.16**) bars have D_{50} values of 7 and 6 mm (0.3 to 0.2 in.), respectively, and D_{84} values of 20 and 24 mm (0.8 to 0.9 in.), respectively (**Figure 3.7**). Between 25 and 30 percent of the sediment load transported and deposited during the 2005 flood was sand-sized and finer (**Figure A.17**).

3.4. Birds Site

The Birds site is located about 18 miles downstream of the USGS Gila River near Gila gage (USGS Gage No. 09430500) and about 9 miles upstream of the USGS Gila River at Redrock gage (USGS Gage No. 09431500) (Figure 1.1). Three large tributaries, Duck Creek, Bear Creek and Mangas Creek, are tributary to the Gila River above the Birds site, and as a result the peak flow for the 2005 flood was about 22,900 cfs. The site is located towards the downstream end of the Gila-Cliff alluvial valley between the confluences of Moonfull Canyon on the west and Ira Canyon on the east side of the valley, and just upstream of the Middle Box canyon. Except for an outcrop of volcanic bedrock in the west valley wall at the upstream end of the site, the site is composed of alluvial sediments distributed in the channel, floodplain and bounding terraces. The channel morphology is primarily pool-riffle (**Figure A.18**), but 2005 flood-related sediment deposition in the reach has created a number of finer-grained mid-channel bars (**Figure A.19**) that create relatively long pools at lower flows (**Figure A.20**). Significant amounts of flow were conveyed on the cottonwood-vegetated floodplain and scoured large overbank channels where large woody debris accumulations concentrated flows or formed weir-like structures during the 2005 flood (**Figure A.21**). Dense willow growth along the channel margins in general survived the 2005 flood flows (**Figure A.22**).

Figure 3.8 shows the general morphology of the site, and the locations of the 10 cross sections that were surveyed in February 2006 with RTK-GPS and Total Station methods. The cross sections and thalweg profiles were used to develop a 1-D step-backwater HEC-RAS (USACE, 2005) hydraulic model of the site (Chapter 5). Also shown on Figure 3.8 are the locations of five pebble counts that were made at in-channel riffles (WC1-WC5) and four bulk samples that were collected from the surface of recently formed mid-channel bars (S1, S2) and from the subsurface on a coarser-grained bank-attached bar (S3) and mid-channel bar (S4).

With the exception of WC5, which is located in a very coarse grained riffle at XS8, the D_{50} values of the riffles within the site are between 40 and 46 mm (1.6 to1.8 in.), and the D_{84} values are between 70 and 100 mm (2.8 to 4 in., **Figure 3.9**). The D_{50} at WC5 is 64 mm (2.5 in.) and the D_{84} is 115 mm (4.5 in.), and may reflect introduction of colluvial material due to some

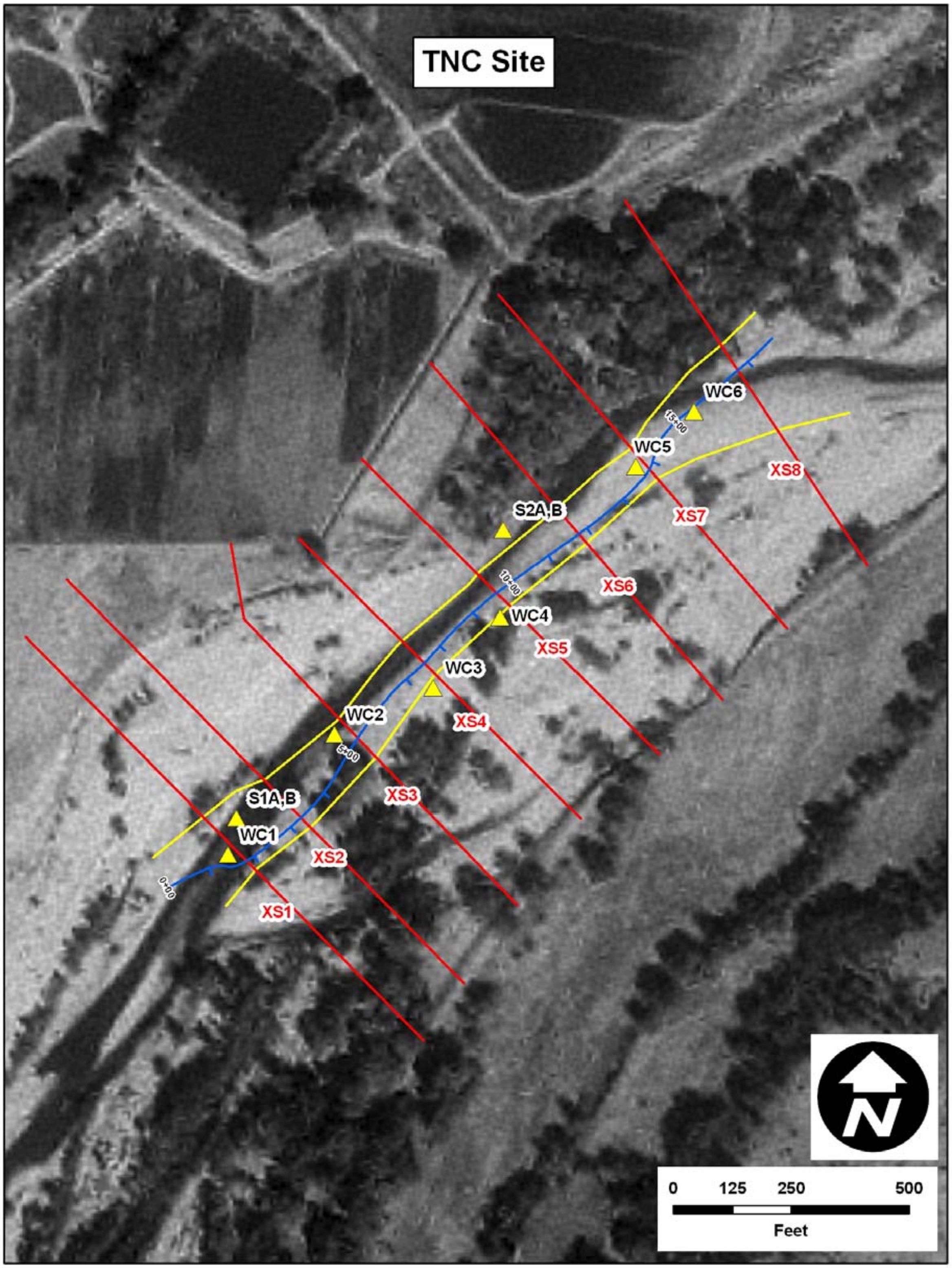


Figure 3.5. Aerial photograph showing the morphology of the TNC site, the locations of the surveyed cross sections and the locations of the sediment samples.

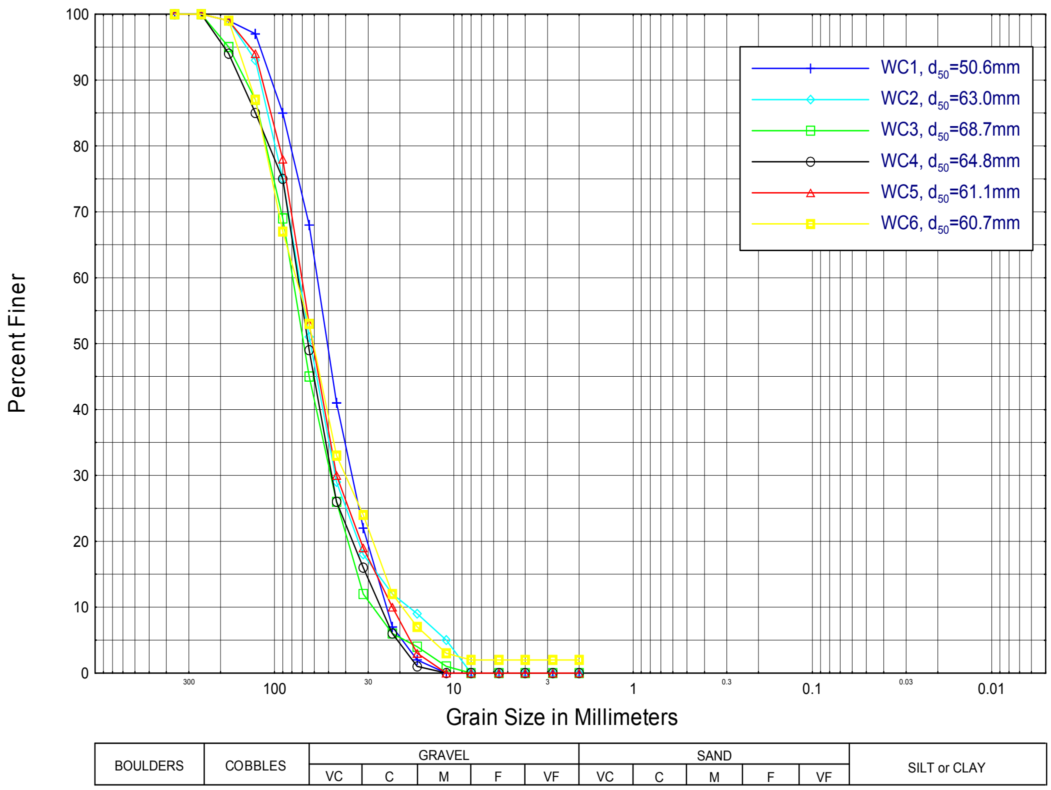


Figure 3.6. Gradation curves developed from pebble counts at the TNC site.

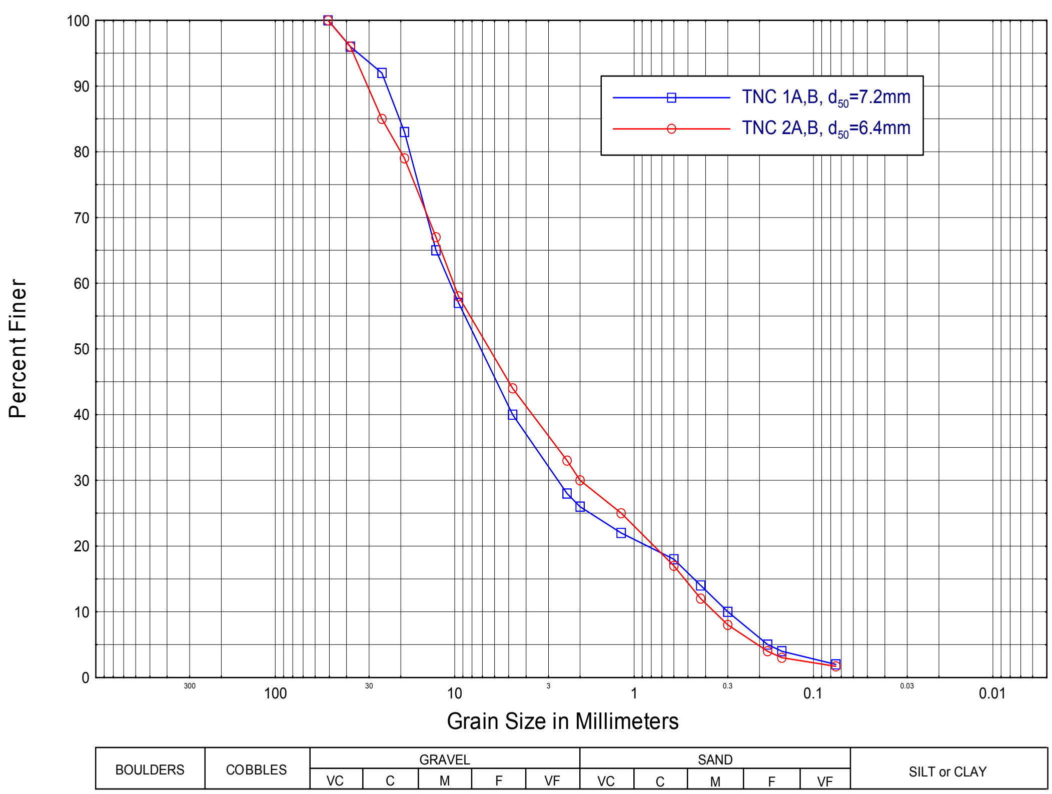


Figure 3.7. Gradation curves developed from bulk samples at the TNC site.

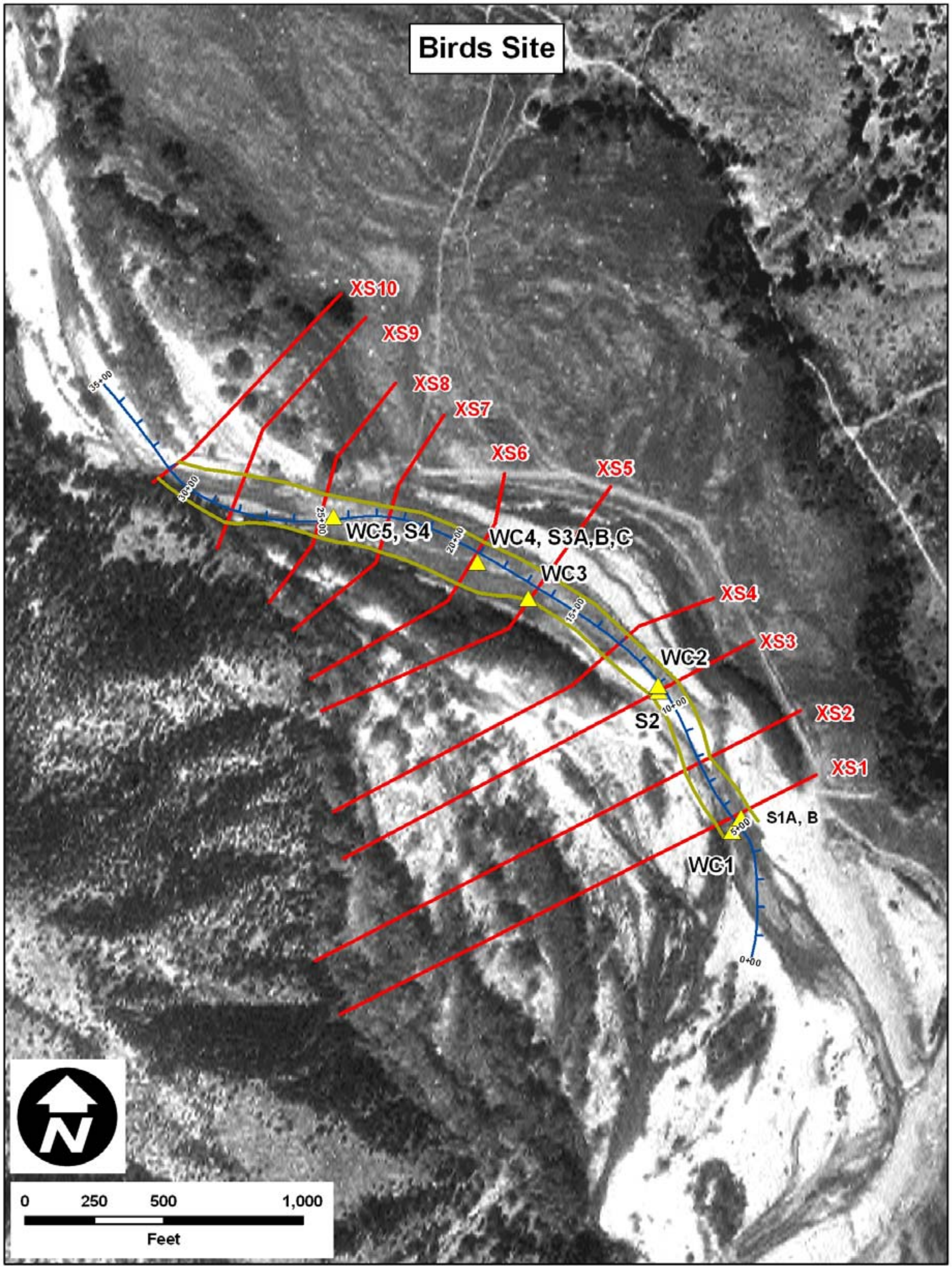


Figure 3.8. Aerial photograph showing the morphology of the Birds site, the locations of the surveyed cross sections and the locations of the sediment samples.

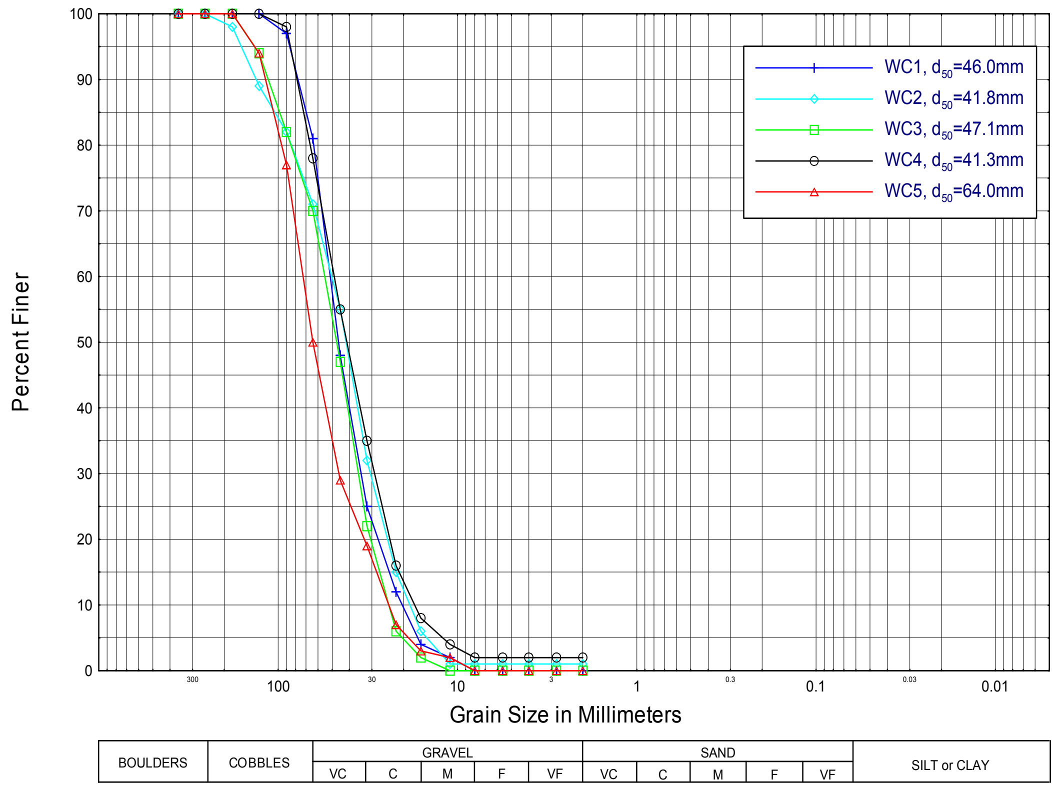


Figure 3.9. Gradation curves developed from pebble counts at the Birds site.

undercutting of the hillslope at that location during the 2005 flood. The D_{50} values of the two bar samples near the downstream end of the site, S1 and S2 (**Figure A.23**) are 3 and 4 mm (0.1 in.), respectively, and the D_{84} values are 16 and 18 mm (0.6-0.7 in., **Figure 3.10**). These finer-grained bars that contain about 35 to 46 percent sand appear to be recently formed in-channel features, and probably will not persist following moderate to high flows. In contrast, the samples collected from the bank-attached bar (S3) (**Figure A.24**) and the coarser mid-channel bar (S4) have D_{50} values of 24 and 11 mm (0.9 to 0.4 in.), respectively, and D_{84} values of 45 mm (1.8 in.), and contain between 17 and 30 percent sand-sized and finer sediments. The high sand contents of the samples collected at the Birds site probably reflects upstream tributary contribution as well as extensive erosion of the floodplain.

3.5. Box Site

The Box site is located about 16 miles downstream of the USGS Gila River at Redrock gage (USGS Gage No.09431500) and immediately upstream of the USGS Gila River below Blue Creek, Near Virden gage (USGS Gage No. 09432000) (Figure 1.1). The site is composed of alluvial sediments located in channel, floodplain and terraces that have been deposited over time in response to the backwater created during floods by the bedrock contraction at the head of the Lower Box canyon (**Figure A.25**). Numerous overbank channels conveyed flows and sediment during the 2005 flood (peak flow 35,700 cfs) (**Figure A.26**), but the densely willow-lined primary channel persisted in its pre-flood location (**Figure A.27**). High-water marks and large woody debris jams in the larger cottonwoods on the floodplain, as well as thick silt-clay rich slackwater deposits in the overbank areas confirm the backwater impacts on the site during the 2005 flood. The basic channel morphology at the site is pool-riffle with the riffles being composed of cobble-boulder-sized materials (**Figure A.28**). However, the pool-riffle spacing greatly exceeds the expected 5 to 7 times channel width norm (Leopold et al., 1964; Richards, 1982), primarily because the 2005 flood caused in excess of 3 feet of sand and fine gravel deposition within the channel and the deposition masks the normal-pool riffle spacing. At the time of the survey, the bed of the channel between the riffles was composed of migrating sand-wave mesoforms spaced at approximately one channel width intervals. Active dune bedforms were present on the tops of the sand waves.

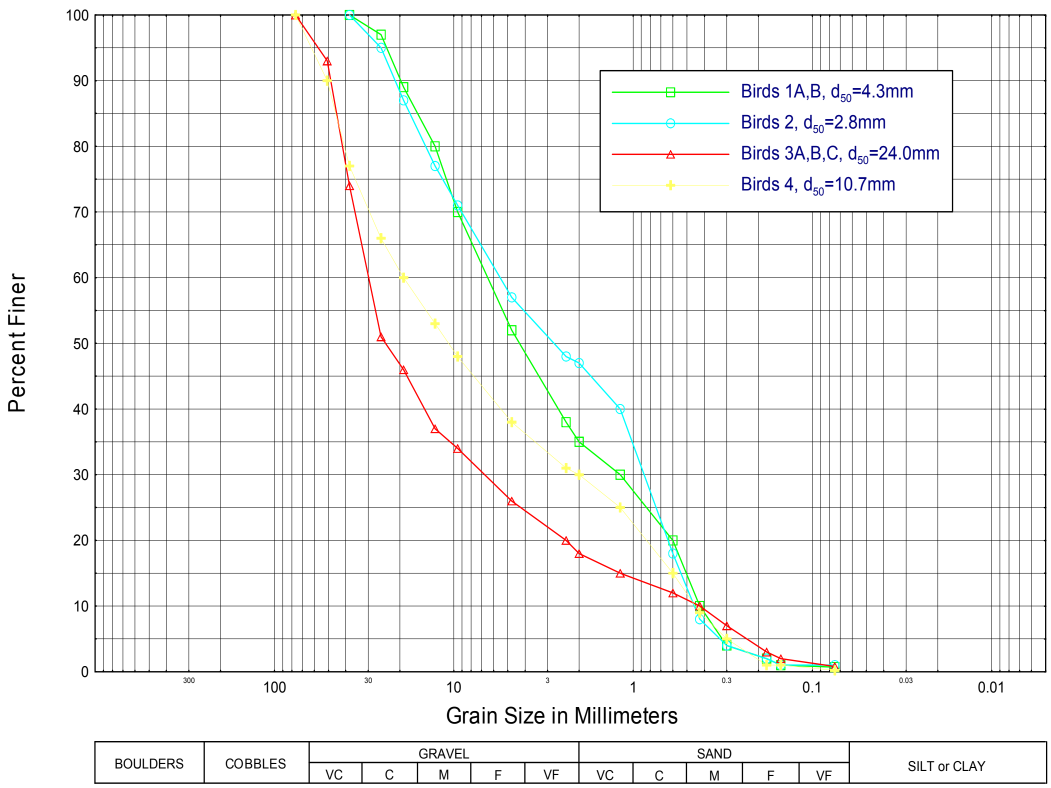


Figure 3.10. Gradation curves developed from bulk samples at the TNC site.

Figure 3.11 shows the general morphology of the site, and the locations of the 12 cross sections that were surveyed in February 2006 with RTK-GPS and Total Station methods. The cross sections and thalweg profiles were used to develop a 1-D step-backwater HEC-RAS (USACE, 2005) hydraulic model of the site (Chapter 5). Also shown on Figure 3.11 are the locations of the three pebble counts (WC1-WC3) that were conducted on the coarse-grained riffles, and the locations of the five bulk samples that were collected from the bed of the channel (S1-S5).

D_{50} values of the riffles within the site are between 95 and 157 mm (3.8 to 6.2 in.), and the D_{84} values are between 190 and 280 mm (7.5 to 11 in., **Figure 3.12**). D_{50} values of the sandy bed material range from 0.8 to 2.4 mm (0.03 to 0.1 in., **Figure 3.13**). Sand- and finer-sized sediments range from 44 to 70 percent of the samples (**Figure A.29**). Depending on the upstream sediment supply, the existing sand bed should revert to a gravel-cobble bed over time, provided that large floods that are backwatered do not occur.

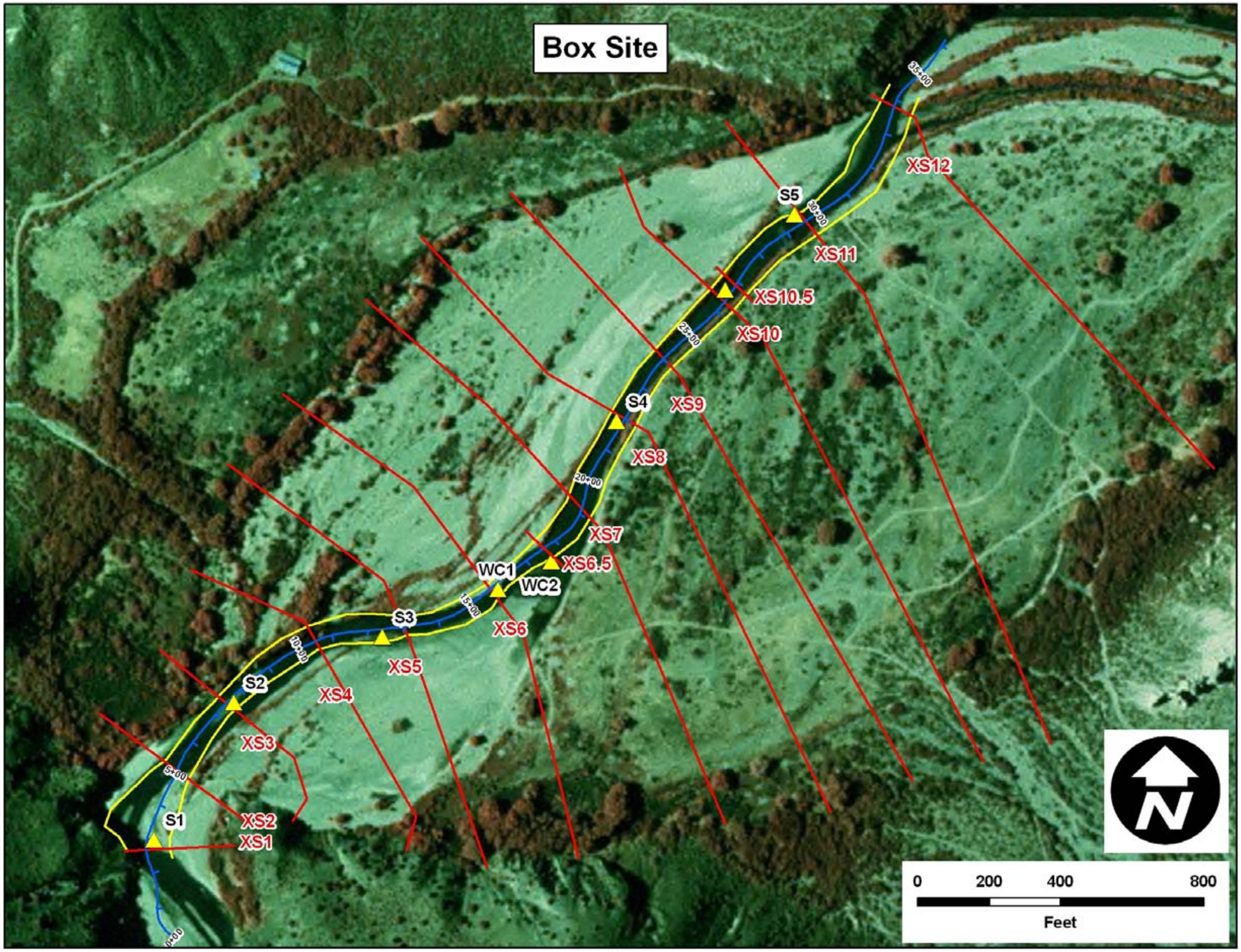


Figure 3.11. Aerial photograph showing the morphology of the Box site, the locations of the surveyed cross sections and the locations of the sediment samples.

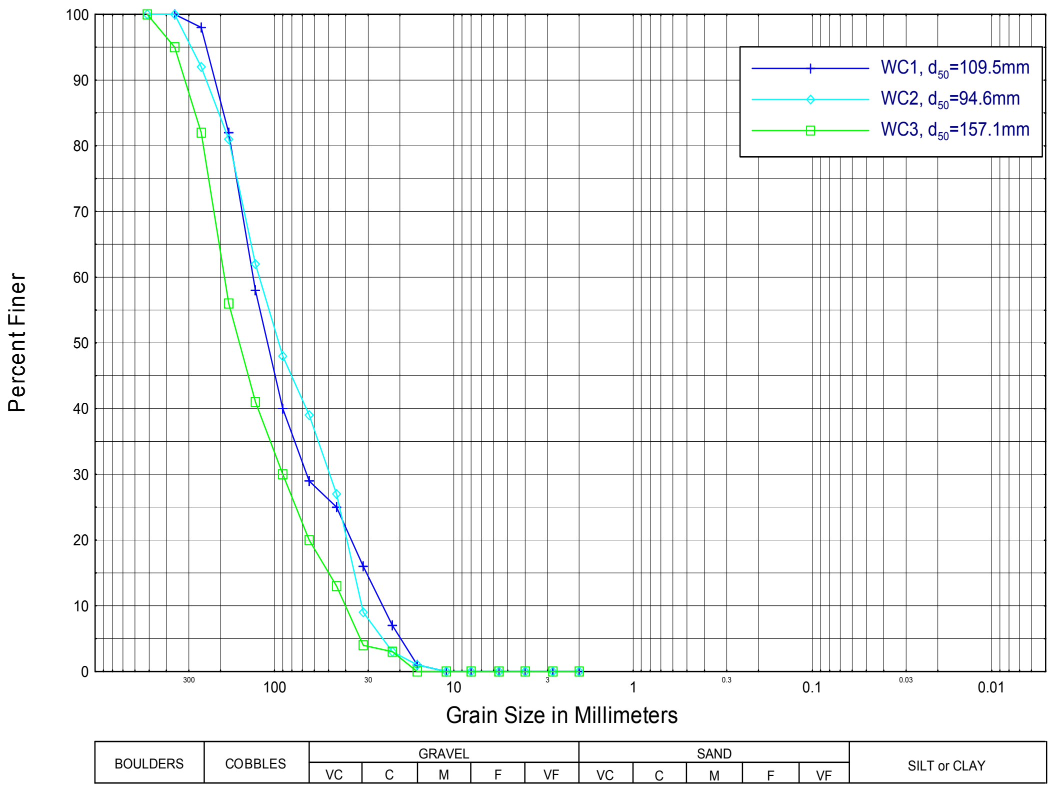


Figure 3.12. Gradation curves developed from pebble counts at the Box site.

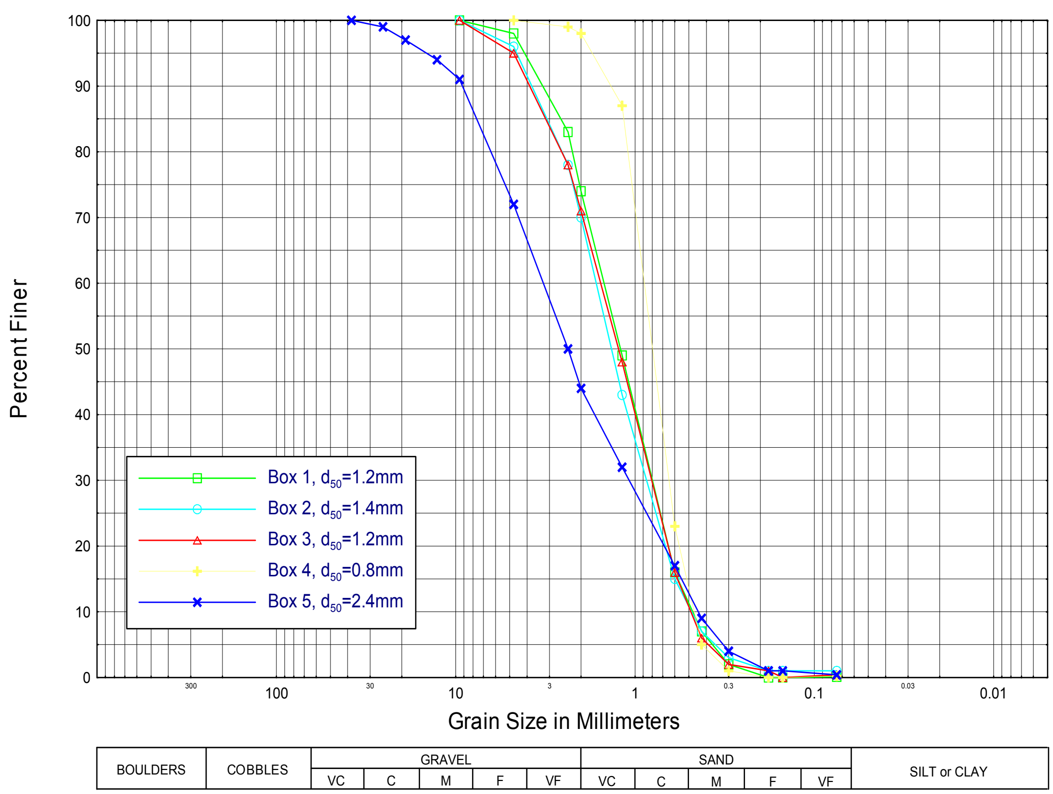


Figure 3.13. Gradation curves developed from bulk samples at the Box site.

3.6. Virden Bridge Site

The Virden Bridge site is located about six miles downstream of the USGS Gila River below Blue Creek, Near Virden gage (USGS Gage No. 09432000) and immediately downstream of the New Mexico Highway 92 Bridge across the Gila River (Figure 1.1). The site is composed of alluvial sediments located in the channel, floodplain and bounding terraces (**Figure A.30**). An alluvial fan and the hillslope form the east boundary of the site (**Figure A.31**), and the west boundary is formed by a man-made levee. During the 2005 flood, there was some erosion of the west bank in the upstream part of the site (**Figure A.32**), but the overall location of the channel within the site did not change. The basic channel morphology at the site is pool-riffle (**Figure A.33**), but flow expansion and loss of sediment-transport capacity in the lower part of the site during the 2005 flood caused in-channel deposition of finer sand and gravels and a low-flow braided channel morphology (Figure A.31). With time the braided morphology is likely to revert to a single-channel pool-riffle morphology as the finer flood-deposited sediments are transported downstream.

Figure 3.14 shows the general morphology of the site, and the locations of the 11 cross sections that were surveyed in February 2006 with RTK-GPS and Total Station methods. The cross sections and thalweg profiles were used to develop a 1-D step-backwater HEC-RAS (USACE, 2005) hydraulic model of the site (Chapter 5). Also shown on Figure 3.14 are the locations of the five pebble counts (WC1-WC5) that were conducted on the coarse-grained riffles, and the locations of the two bulk samples that were collected from low-elevation bank-attached bars (S1, S2).

D_{50} values of the finer riffles within the lower part of the site (WC1, WC2) are between 50 and 34 mm (2 to 1.3 in.), and the D_{84} values are between 78 and 58 mm (3 to 2.3 in., **Figure 3.15**). For the coarser riffles farther upstream D_{50} values range from 65 to 74 mm (2.6 to 2.8 in.) and D_{84} values range from 120 to 130 mm (4.7 to 5 in., Figure 3.15). D_{50} values for the bar deposits range from 1.3 to 4 mm (0.05 to 0.2 in.), and D_{84} values range from 17 to 20 mm (0.7 to 0.8 in., **Figure 3.16, Figures A.33 and A.34**).

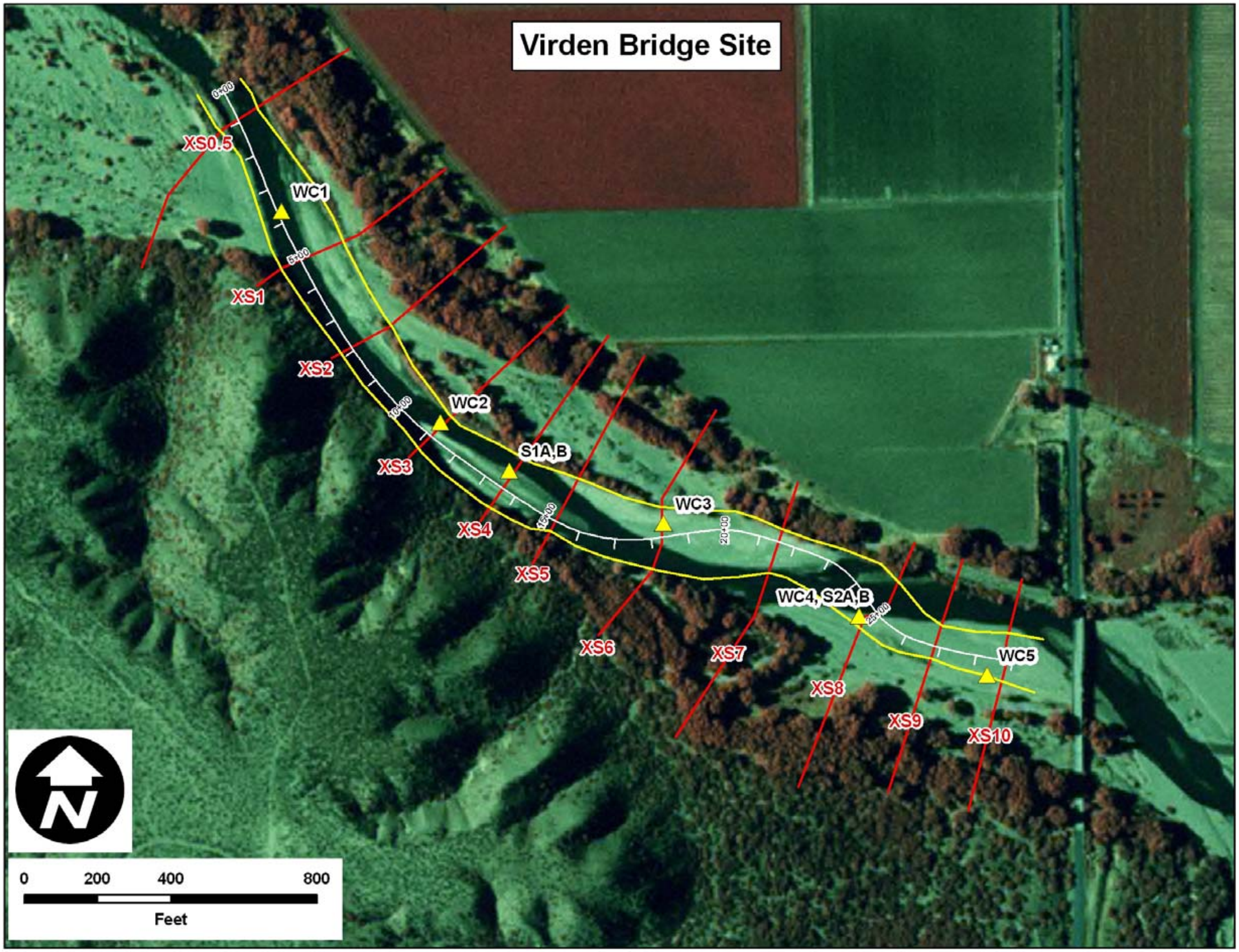


Figure 3.14. Aerial photograph showing the morphology of the Virden Bridge site, the locations of the surveyed cross sections and the locations of the sediment samples.

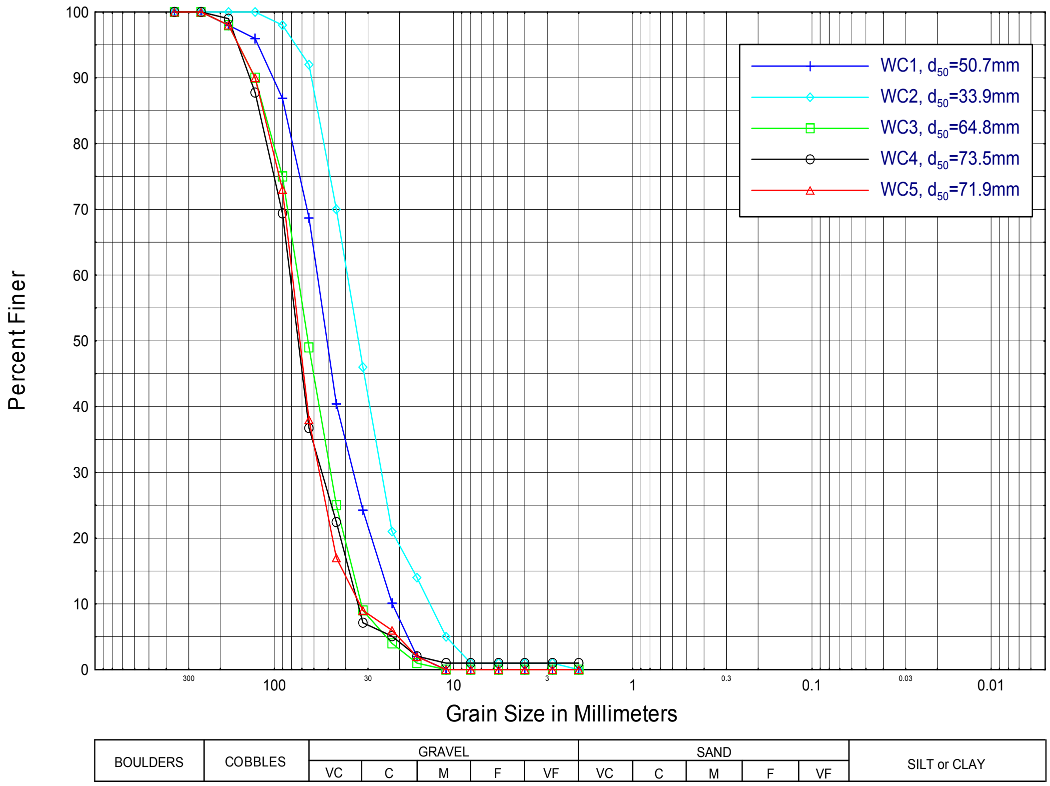


Figure 3.15. Gradation curves developed from pebble counts at the Virden Bridge site.

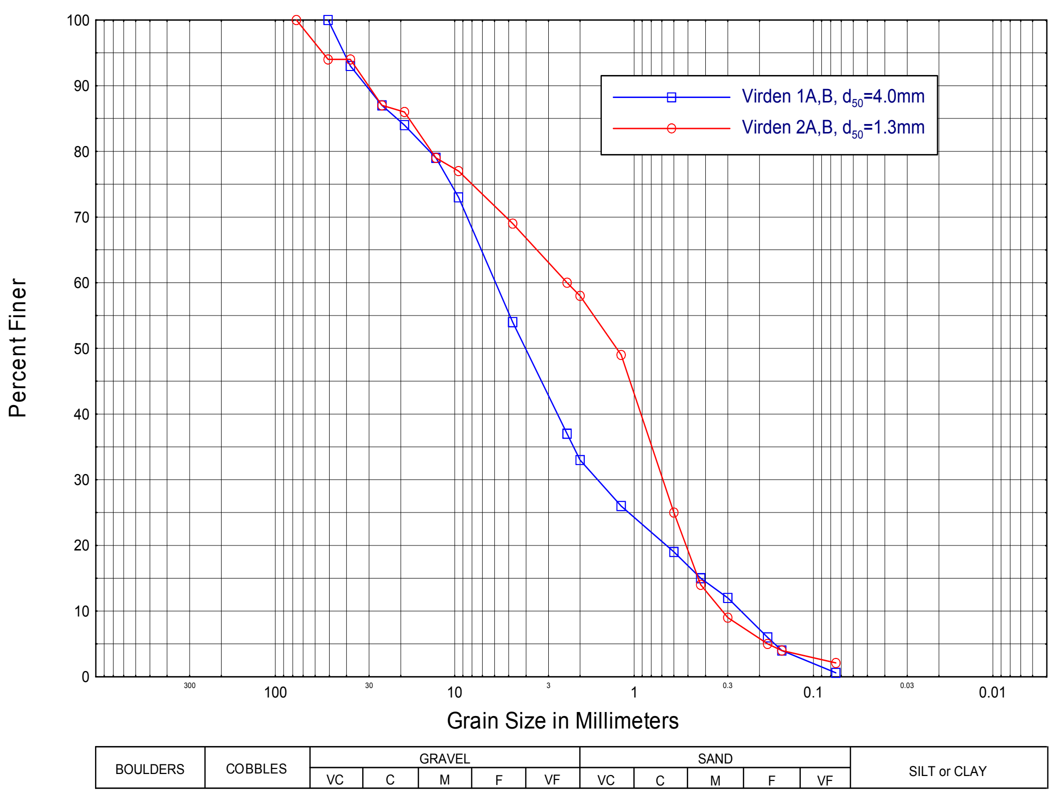


Figure 3.16. Gradation curves developed from bulk samples at the Virden Bridge site.

4. HYDROLOGY

Rains from fall and winter storm systems cause the major floods in the Gila River Basin (Bureau of Reclamation, 2004b). The rainfall events are caused by cold frontal systems colliding with warm, moist air or tropical storms. Extreme flood-producing storms are widespread and cover the majority of the Upper Gila River Basin. The largest floods are produced by rainfall or rain on snow events. Within the period of record, large floods (≥15,000 cfs) have occurred in water years 1941, 1979, 1984, 1985, 1995, 1997, and 2005 (**Figure 4.1**).

The hydrological characteristics of the Upper Gila River Basin were evaluated by analyzing the peak streamflow and mean daily flow records from the USGS Gila River mainstem gages (Gila River near Gila, Gila River at Redrock, Gila River below Blue Creek, Near Virden) and the peak streamflow flow records from the USGS gages on the major tributaries (Mogollon Creek Near Cliff, New Mexico, Duck Creek at Cliff, New Mexico, Mangas Creek Near Cliff, New Mexico) (Figure 1.1). **Table 4.1** summarizes the available data at each of the gages.

Table 4.1. Summary of available USGS gage data for Upper Gila River Basin.

Gage Name/Number	Peak Streamflow Period of Record	Mean Daily Streamflow Period of Record
Gila River Near Gila, NM 09530500	8/23/1928 – 4/5/2005	12/1/1927 – 9/30/2004
Gila River Near Redrock, NM 09431500	11/26/1905 – 8/18/2005	10/1/1930 – 9/30/2004
Gila River Below Blue Creek, Near Virden, NM 09432000	9/22/1927- 9/25/2005	7/1/1927 – 9/30/2005
Mangas Creek Near Cliff, NM 09431130	8/16/1988 – 7/28/2003	
Duck Creek at Cliff, NM 09430900	8/13/1957 – 7/31/2003	
Mogollon Creek Near Cliff, NM 09430600	8/12/67 – 3/8/04	2/21/67 – 9/3/04

4.1. Flood Frequency Analysis

Using the annual peak flow record for the gages listed in Table 4.1, flood frequency curves were developed for the individual gages using the U.S. Army Corps of Engineers HEC-FFA computer program (USACE, 1992), which is based on the procedures outlined in Water Resource Council (WRC) Bulletin 17B (WRC, 1981), with a generalized skew coefficient of +0.30L.

Figures 4.2 through 4.4 shows the peak flood frequency curves for the Gila River near Gila gage, the Gila River near Redrock Gage, the Gila River below Blue Creek, near Virden gage, respectively. The exceedence probabilities and return periods for these gages for the 1-year to 500-year floods are summarized in **Table 4.2**. The 2-year recurrence interval flood increases from about 1,930 cfs at the upstream gage to about 5,190 cfs at the downstream gage. Similarly, 100-year recurrence interval flood increase from about 40,800 cfs at the upstream gage to about 45,700 cfs at the downstream gage. Based on the flood frequency curves, the 2005 flood event was about a 25-year recurrence interval flood (19,900 cfs) at the Gila River near Gila gage, and about a 50-year event (35,700 cfs) at the Gila River near Virden gage, based on USGS provisional data.

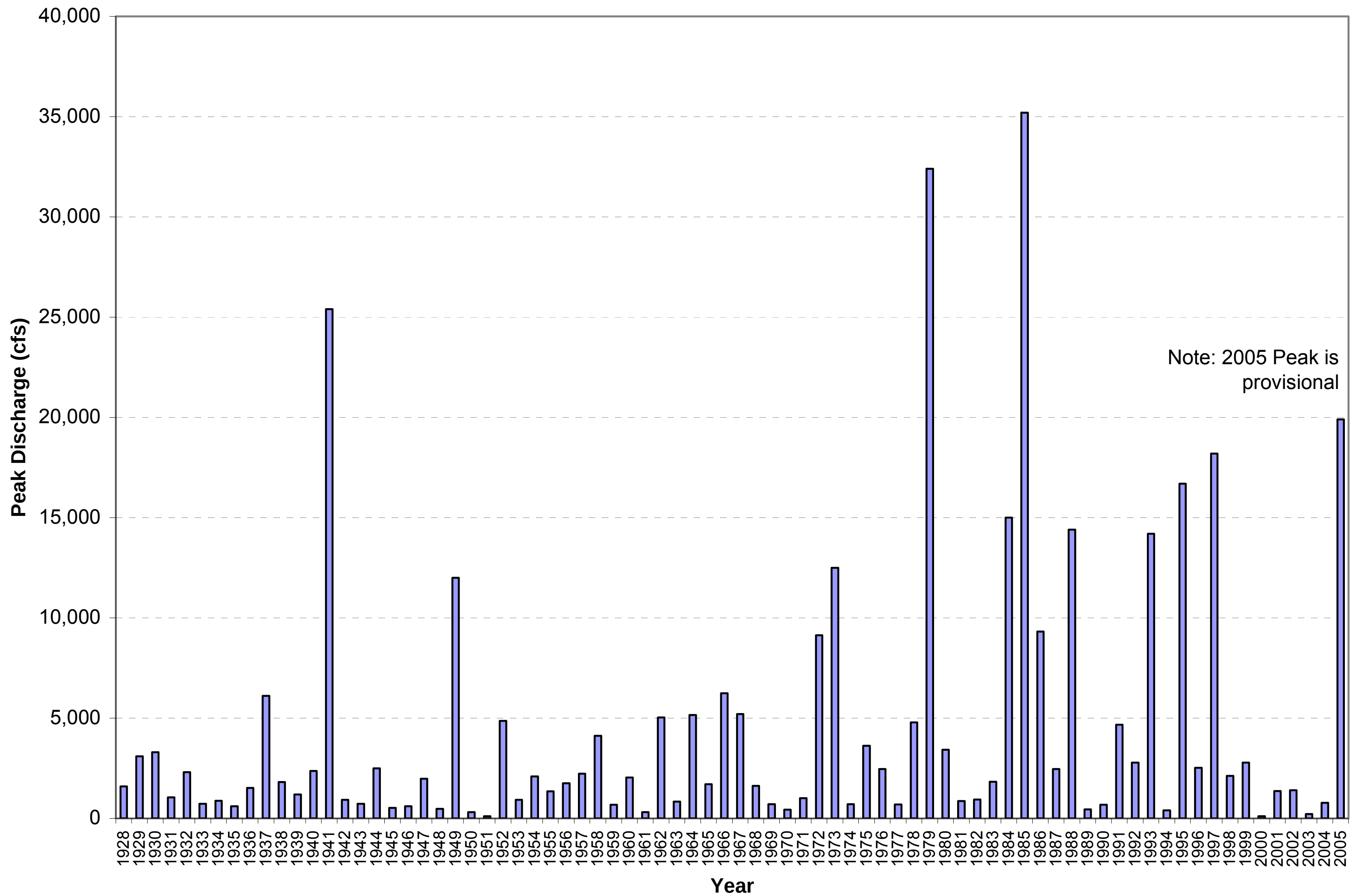


Figure 4.1. Annual peak flows for the period of record (WY1928-WY2005) at the USGS Gila River at Gila gage.

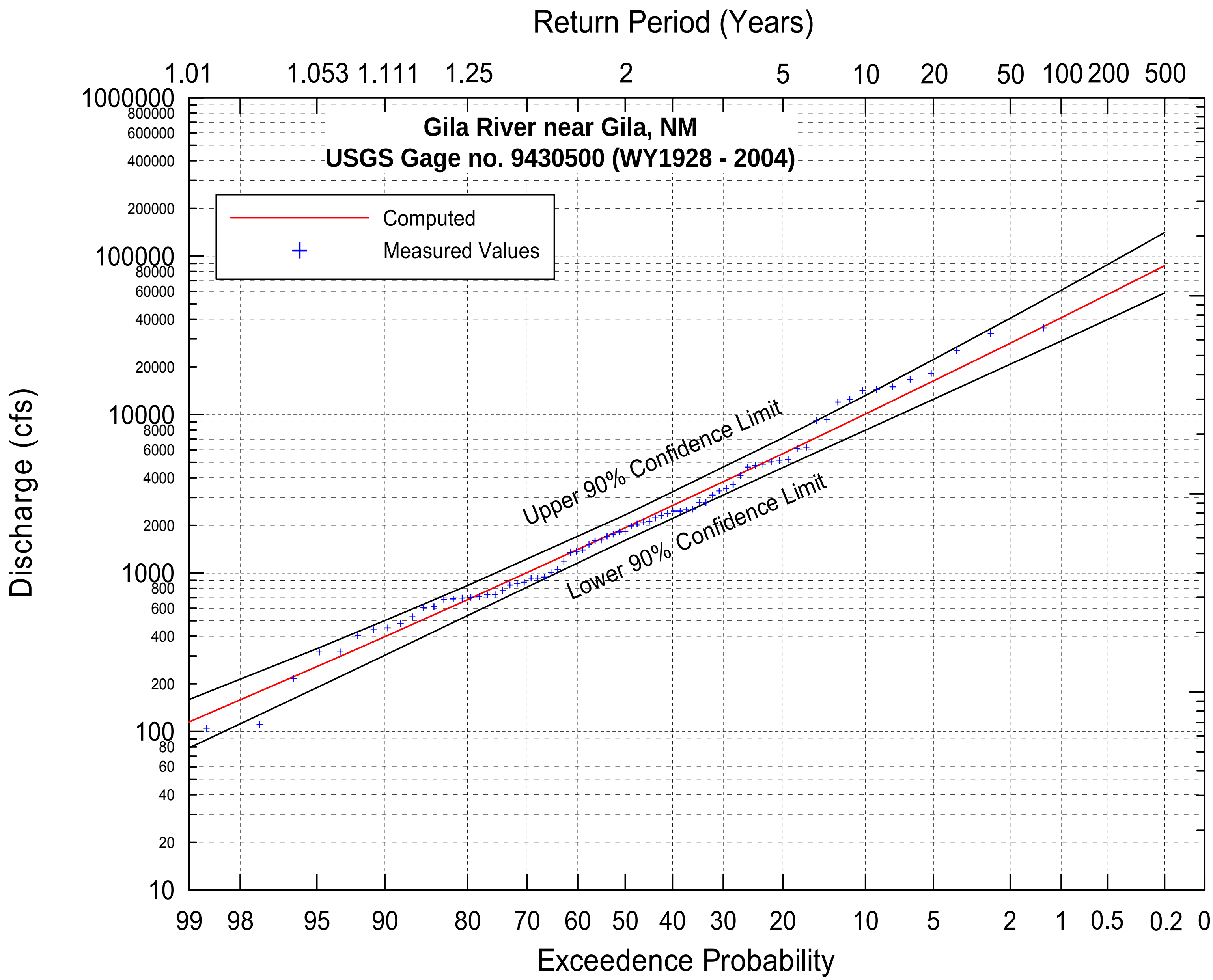


Figure 4.2. Flood-frequency curve for USGS Gila River near Gila, NM (9430500) gage, WY1928-WY2004.

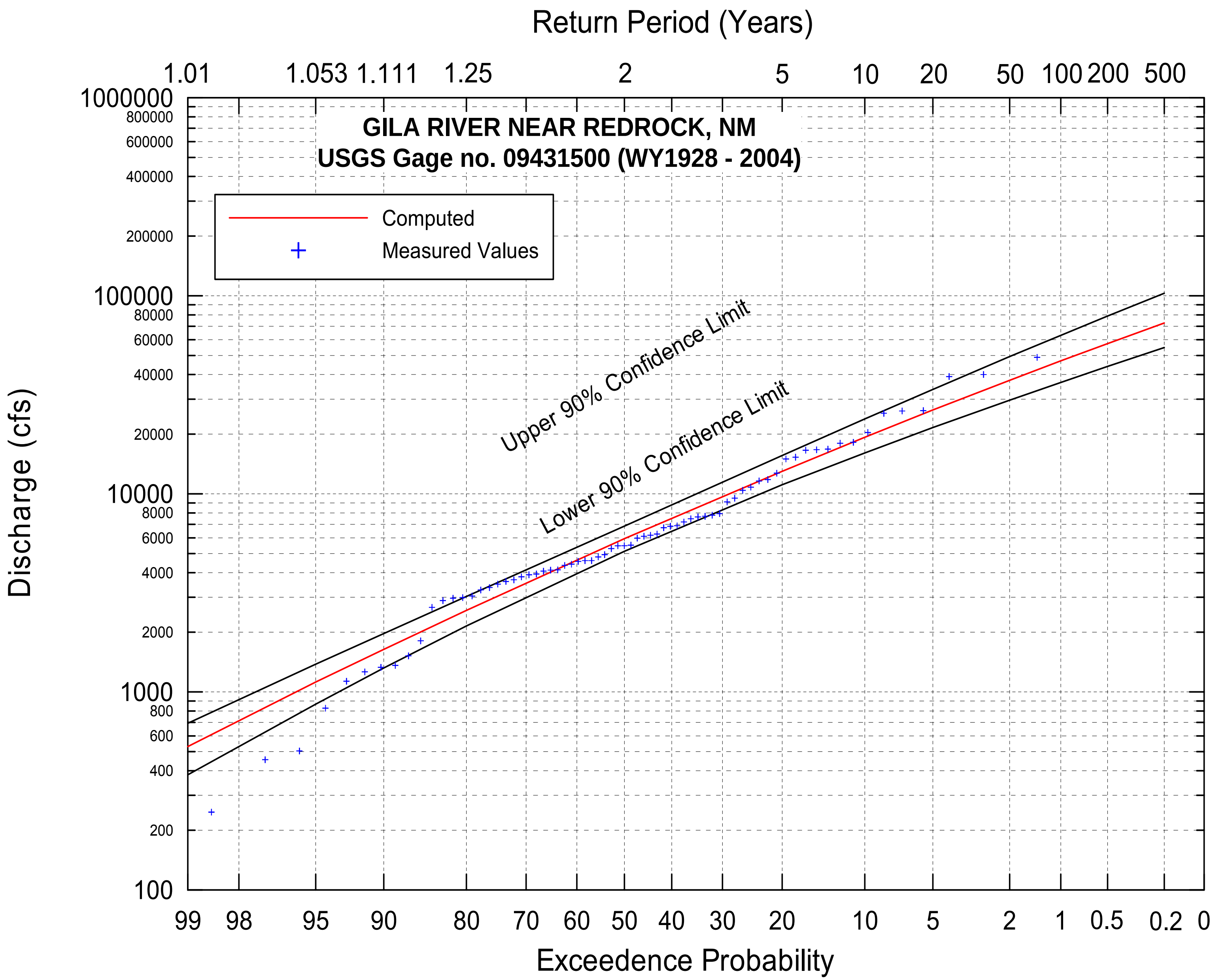


Figure 4.3. Flood-frequency curve for USGS Gila River near Redrock, NM (9431500) gage, WY1928-WY2004.

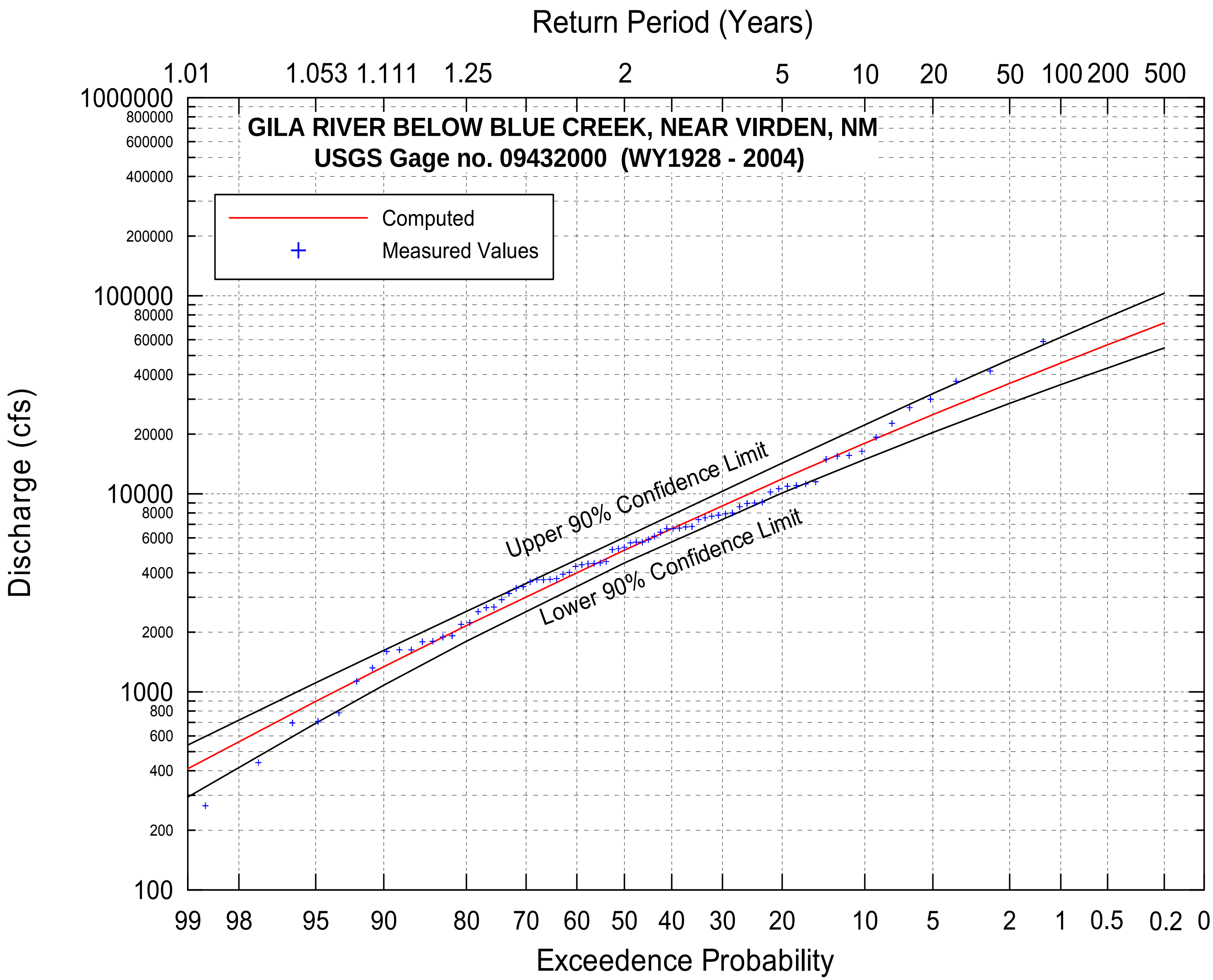


Figure 4.4. Flood-frequency curve for USGS Gila River below Blue Creek, near Virden, NM (9432000) gage, WY1928-WY2004.

Table 4.2. Summary of flood frequencies for mainstream gages on the Upper Gila River.							
Exceedence Probability	Return Period (years)	9430500 Gila		9431500 Redrock		9432000 Virden	
		Discharge (cfs)	Days/Year	Discharge (cfs)	Days/Year	Discharge (cfs)	Days/Year
0.2	500	87,100		72,900		72,800	
0.5	200	57,400		57,300		56,600	
1	100	40,800		46,900		45,700	
2	50	28,200		37,400		36,100	
5	20	16,300	0.03	26,500		25,100	
10	10	10,100	0.05	19,300	0.06	18,000	0.04
20	5	5,680	0.28	13,000	0.13	11,900	0.19
50	2	1,930	1.53	5,930	0.51	5,190	0.68
80	1.25	679	11.03	2,580	1.95	2,160	2.85
90	1.111	397	25.98	1,640	4.26	1,340	7.23
95	1.053	257	44.12	1,120	8.94	896	14.09
99	1.01	115	108.03	530	29.21	409	38.59

Figures 4.5 through 4.7 shows the peak flood frequency curves for the Mogollon Creek near Cliff, Duck Creek at Cliff and Mangas Creek near Cliff gages, respectively. The exceedence probabilities and return periods for these gages for the 1- to 500-year floods are summarized in **Table 4.3**. The 2-year recurrence interval peak flows for the three gages are 749, 3,710, and 652 cfs, respectively. The 100-year recurrence interval peak flows for the three gages are 17,100, 14,400, and 8,090 cfs, respectively. The only provisional peak flow value for the 2005 flood is that for Mogollon Creek (5,800 cfs), which has a recurrence interval of about 15 years.

Table 4.3. Summary of flood frequencies for tributary gages on the Upper Gila River.					
Exceedence Probability	Return Period (years)	9430600 Mogollon Creek		9430900 Duck Creek	9431130 Mangas Creek
		Discharge (cfs)	Days/Year	Discharge (cfs)	Discharge (cfs)
0.2	500	35,900		19,200	13,400
0.5	200	23,900		16,400	10,200
1	100	17,100		14,400	8,090
2	50	11,800		12,400	6,220
5	20	6,830		9,890	4,130
10	10	4,190		8,040	2,820
20	5	2,320	0.12	6,220	1,750
50	2	749	0.72	3,710	652
80	1.25	242	4.98	2,150	224
90	1.111	134	17.06	1,600	123
95	1.053	82	34.20	1,240	74
99	1.01	33	73.83	764	27

The Bureau of Reclamation (2002) conducted a trend analysis of the peak flows for the Upper Gila River Basin. The analyses showed that there were significant positive (increasing) trends in the 3-day maximum flood discharge at the Gila River near Gila gage and the Gila River near

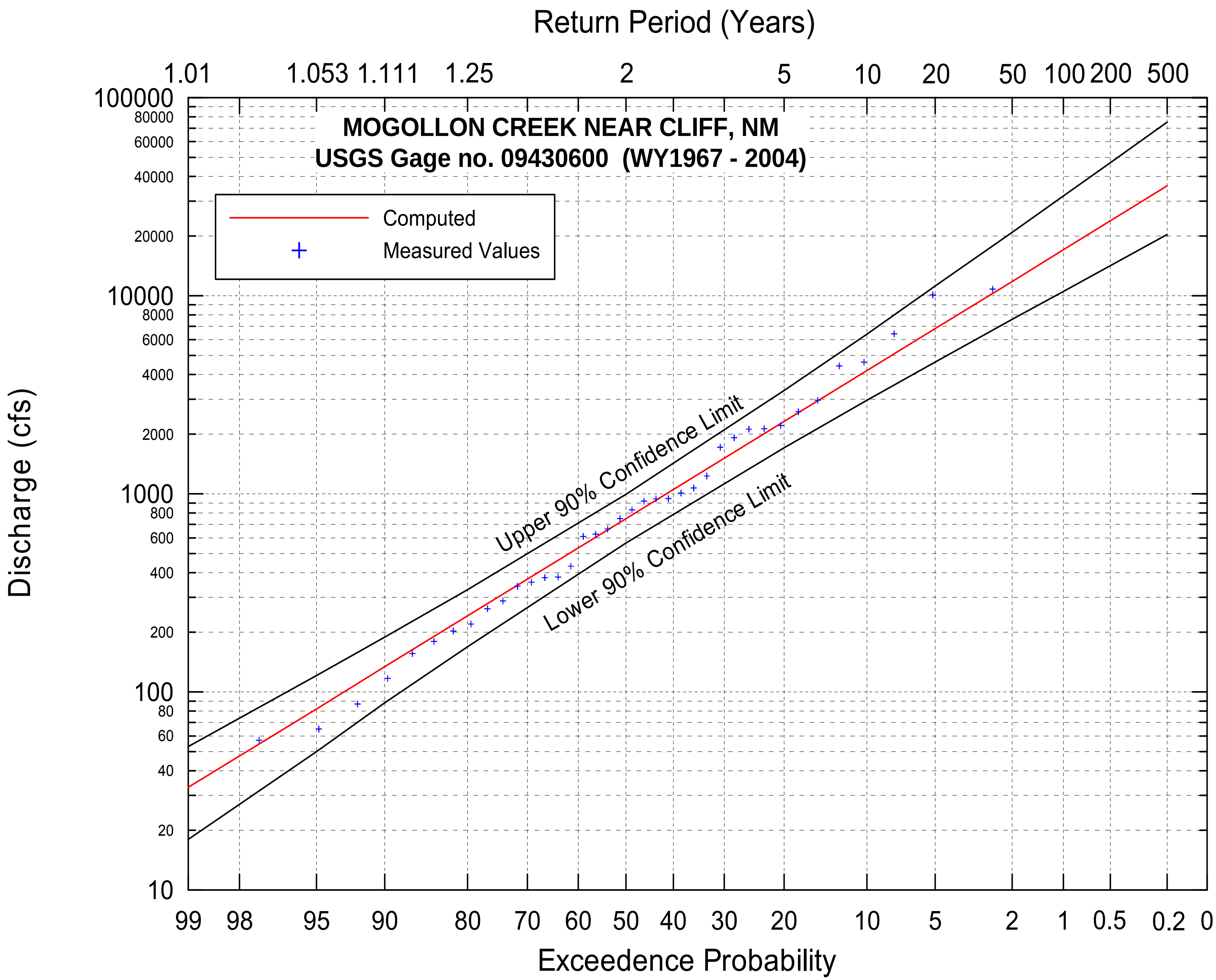


Figure 4.5. Flood-frequency curve for USGS Mogollon Creek near Cliff, NM (9430600) gage, WY1967-WY2004.

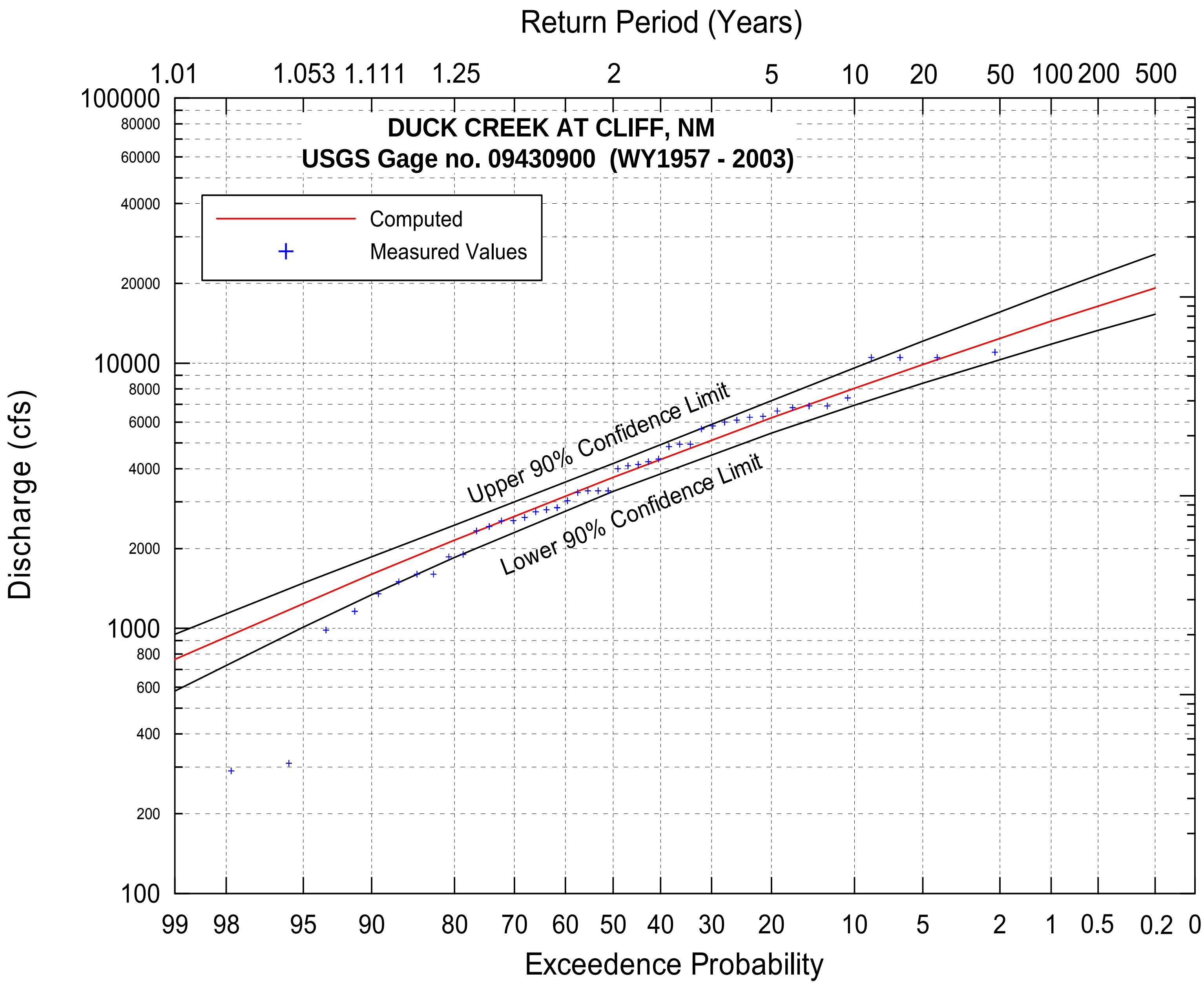


Figure 4.6. Flood-frequency curve for USGS Duck Creek at Gila, NM (9430900) gage, WY1957-WY2003.

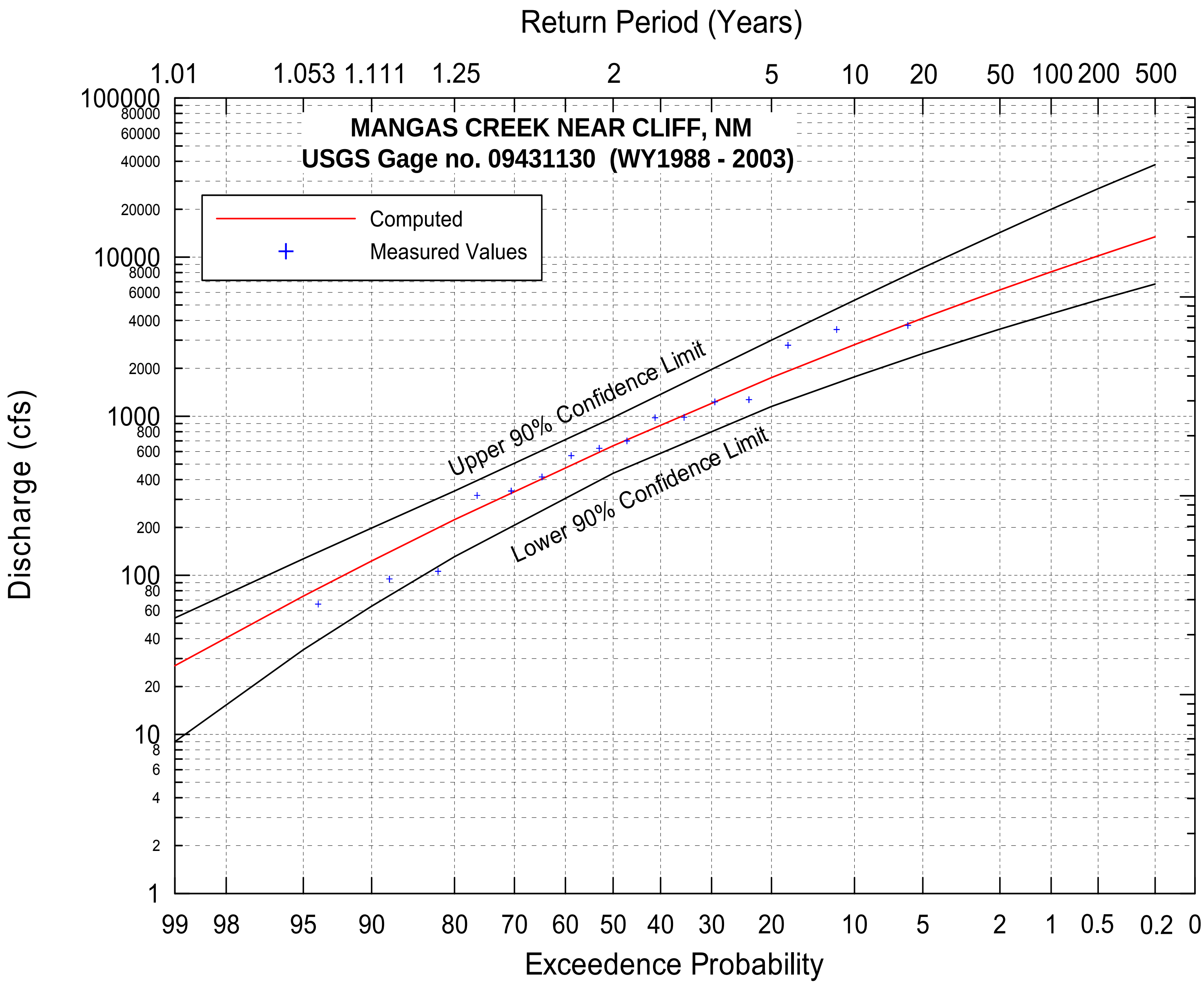


Figure 4.7. Flood-frequency curve for USGS Mangas Creek near Cliff, NM (9431130) gage, WY1988-WY2003.

Virden gage. The trends were consistent for the 1931-2000 period and 1941-2000 period. Also, there were increasing trends in peak flow, daily maximum flows at the Gila River near Gila gage for the periods 1931-2000, 1941-2000 and 1951-2000. These positive trends are opposite those found for the Rio Puerco by Molnar and Ramirez (2001). No significant trends were identified for flood discharge volumes at any of the gages.

4.2. Flow-duration Analysis

Flow-duration curves were developed for all of the gages with a mean daily flow record (Table 4.1). The flow-duration curves for the Gila River near Gila, Gila River near Redrock and Gila River near Virden gages, and for Mogollon Creek are shown on **Figure 4.8**. Summary statistics for the 4 gages are provided in **Table 4.4**. On the Gila River, 90 percent of the time, flows are equal to or exceed 38 cfs at the upstream gage and equal or exceed 22 cfs at the downstream gage as a result of existing flow diversions. Fifty percent of the time flows are equal to or exceed 74 cfs at the upstream gage and 90 cfs at the downstream gage due to flow accretion in the downstream direction. Similarly, the 10-percent exceedence flows increase from 302 cfs at the upstream gage to 431 cfs at the downstream gage.

Table 4.4. Flow-duration statistics for the Upper Gila River gages.

Exceedence Probability	Discharge (cfs)			
	9430500	9431500	9432000	9430600
	Gila River near Gila	Gila River near Redrock	Gila River near Virden	Mogollon Creek
90	38	29	22	0.2
50	74	92	90	6
10	302	438	431	77

4.3. Representative Annual Hydrographs

For the purposes of evaluating the geomorphic impacts of CUFA diversions, the annual hydrographs for the mainstem Upper Gila River gages were sorted into three representative classes: dry, typical and wet. The basis for the classification was the number of days that bed material mobilization occurred in the year (refer to details in Chapter 6). Years with 0 days of bed material mobilization were assigned to dry years. If there were between 1 and 4 days of bed material mobilization the year was assigned to a typical class, and if the number of days of bed material mobilization was five or more, the year was assigned to a wet class. Representative years for dry, typical and wet years are 1989, 1998 and 1993, respectively.

For the Gila River near Gila gage the annual hydrographs for 1989, 1998 and 1993 clearly show the differences in water year types (**Figure 4.9**). The annual hydrographs show the winter runoff events as well as the spring snowmelt and the monsoonal flows in the fall. Annual hydrographs for the representative water year types for the Gila River near Redrock (**Figure 4.10**) and Gila River near Virden (**Figure 4.11**) show the same patterns.

4.4. Diversion Scenarios

The NMISC provided daily diversion data for the Gila River near Gila gage for two minimum bypass scenarios; 73- and 150-cfs bypass. The diversion data covered the period from October

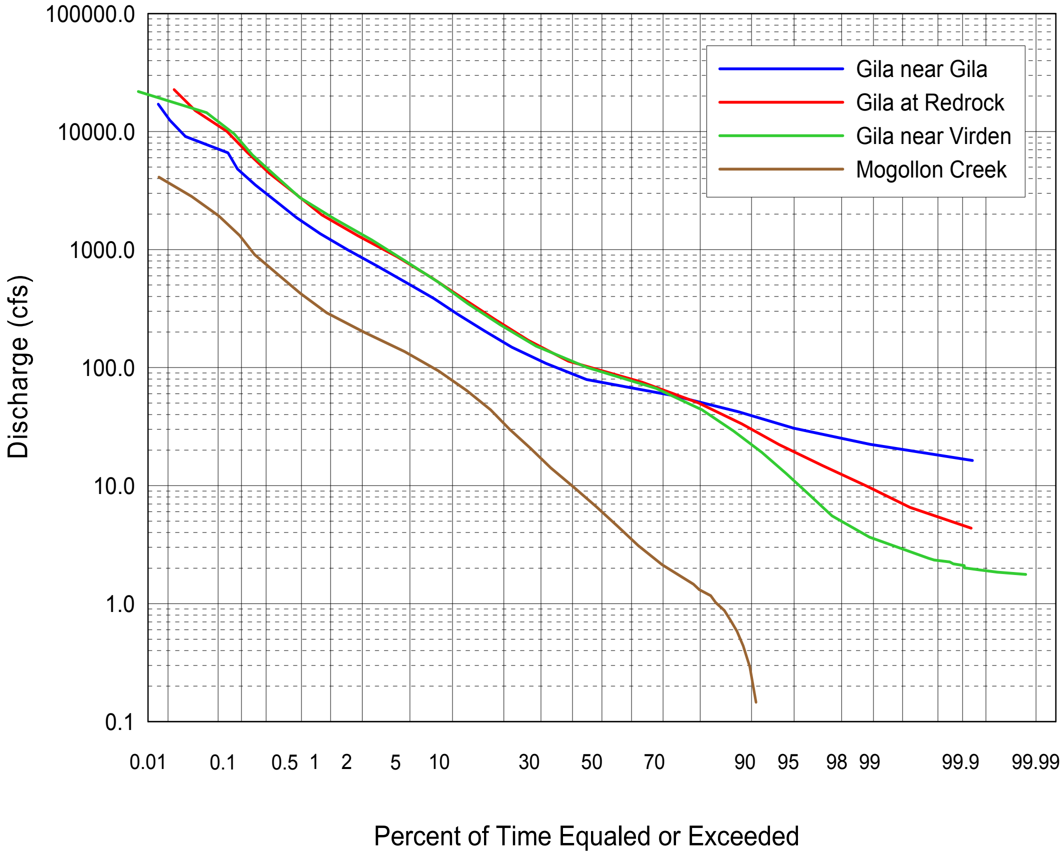


Figure 4.8. Flow-duration curves for Gila River near Gila, Gila River near Redrock, Gila River near Virden and Mogollon Creek gages.

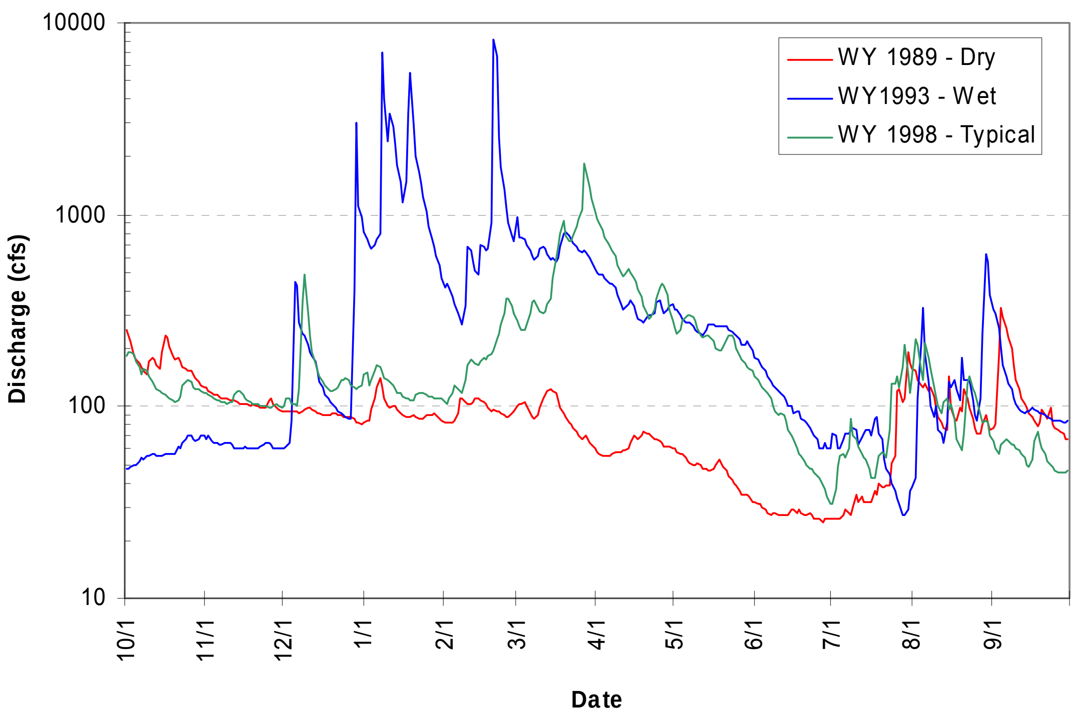


Figure 4.9. Annual hydrographs for dry, typical and wet years for the Gila River near Gila gage.

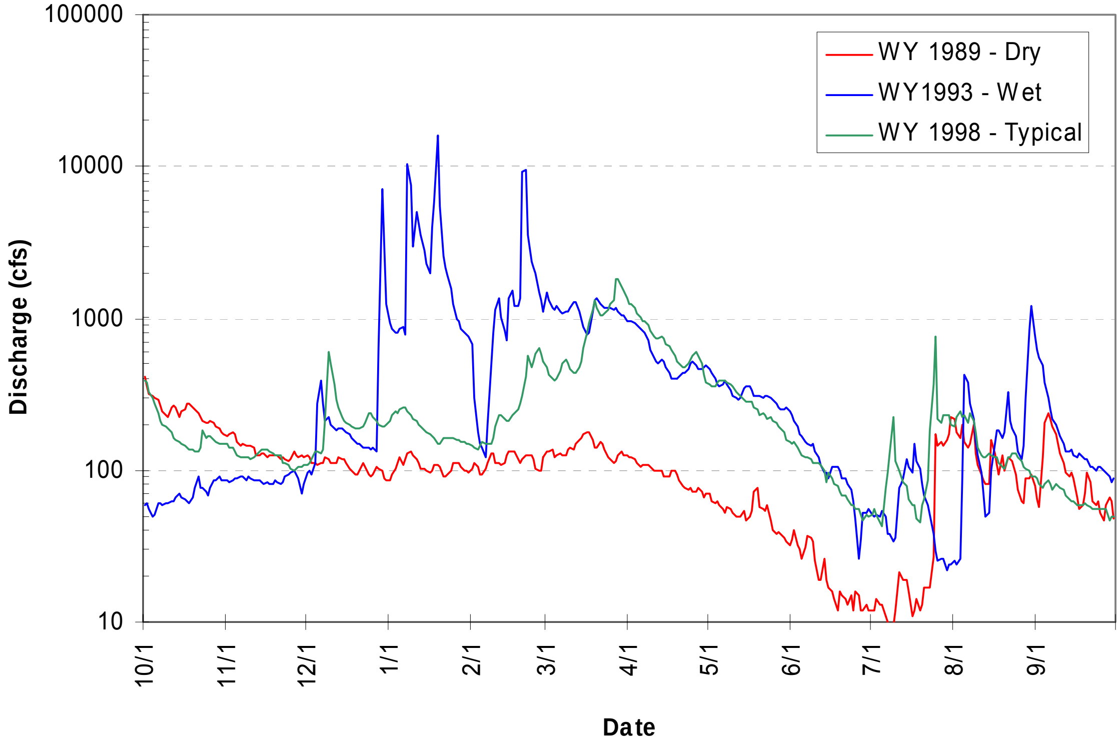


Figure 4.10. Annual hydrographs for dry, typical and wet years for the Gila River near Redrock gage.

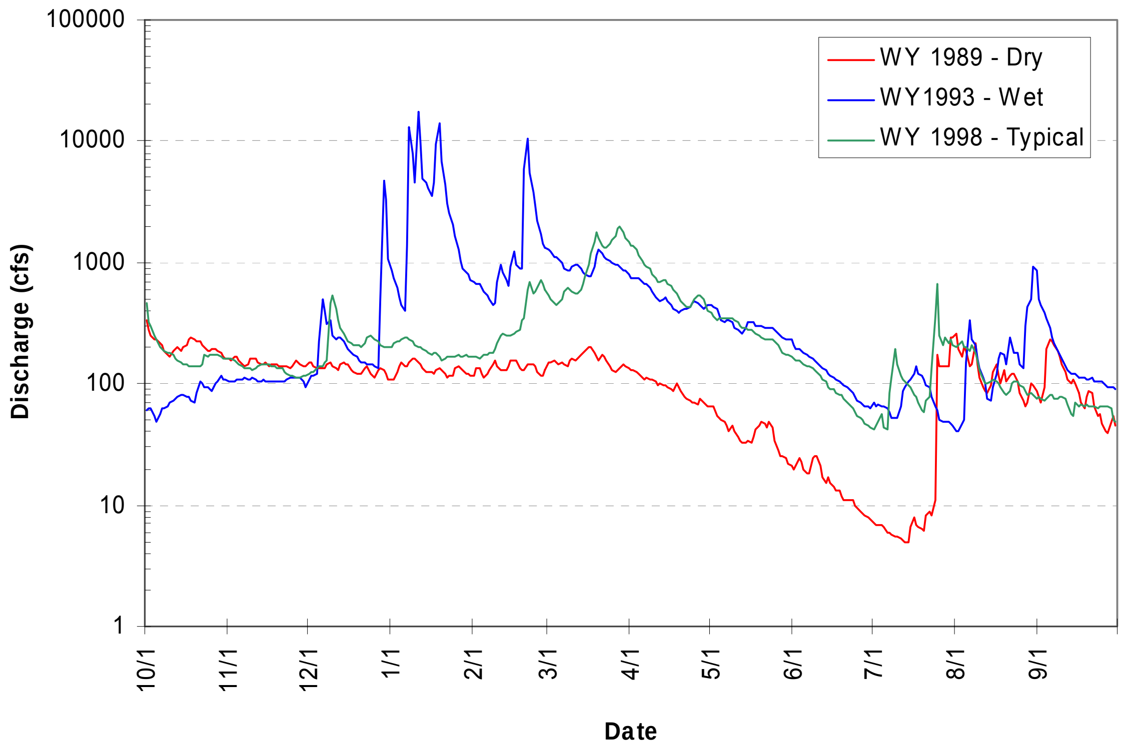


Figure 4.11. Annual hydrographs for dry, typical and wet years for the Gila River near Virden gage.

1, 1936, to December 31, 1978, and from January 1, 1981, to September 30, 2001. To evaluate the impacts of the diversions on the geomorphology of the river, annual hydrographs for the three representative year types with the diversions applied were developed for the Gila River near Gila gage. For the representative dry year (1989), application of the two diversion scenarios results in diversion of 7,225 AF for the 73-cfs minimum bypass scenario, and 1,266 AF for the 150-cfs minimum bypass scenario (**Figure 4.12**). For the representative typical year (1998), application of the two diversion scenarios results in diversion of 12,946 AF for the 73-cfs minimum bypass scenario, and 22,037 AF for the 150-cfs minimum bypass scenario (**Figure 4.13**). For the representative wet year (1993), application of the two diversion scenarios results in diversion of 1,718 AF for the 73 cfs minimum bypass scenario, and 7,636 AF for the 150-cfs minimum bypass scenario (**Figure 4.14**).

Annual hydrographs for the three representative year types with the same diversions applied were developed for the Gila River near Redrock gage (**Figures 4.15 through 4.17**) and the Gila River near Virden gage (**Figures 4.18 through 4.20**) so that the effects of the diversions on sediment transport and hence geomorphic processes could be evaluated (Chapter 6). Diversion of the same flows at the downstream gages occasionally results in the bypass flows at these gages being less than the minima, but since no algorithm for diversion was provided, it was not possible to adjust the flows. However, the differences resulting from this issue are very unlikely to be geomorphically significant.

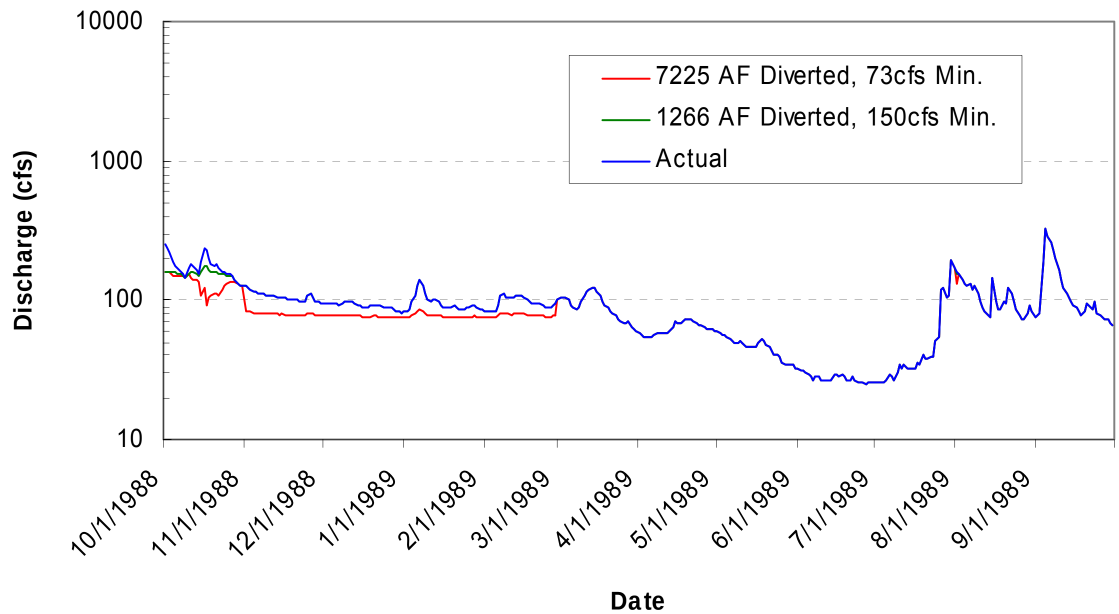


Figure 4.12. 1989 hydrographs (representative dry year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Gila gage.

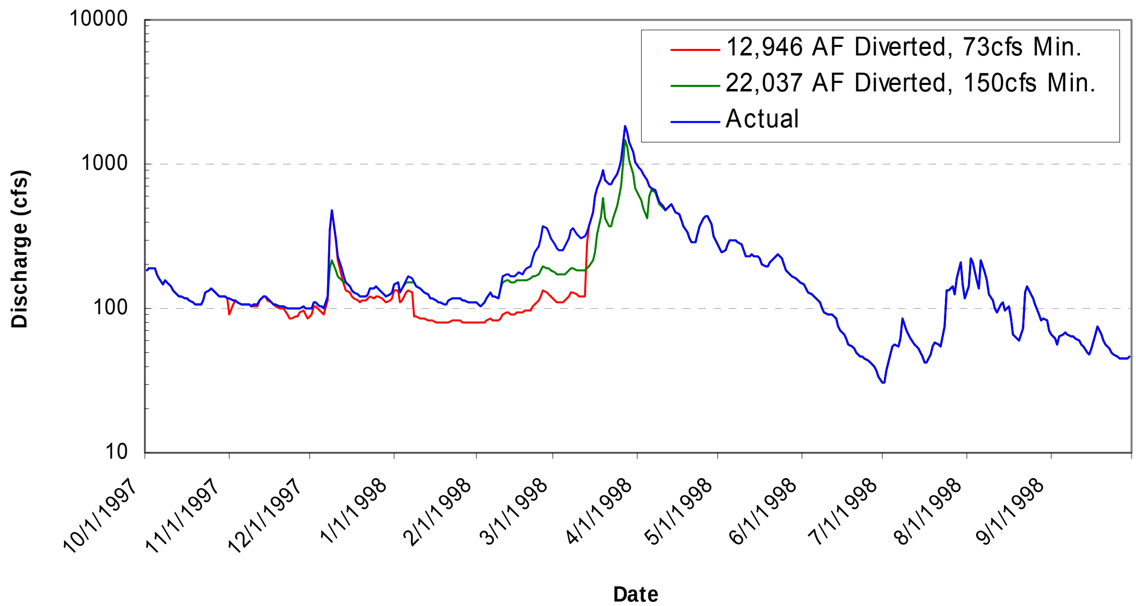


Figure 4.13. 1998 hydrographs (representative typical year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Gila gage.

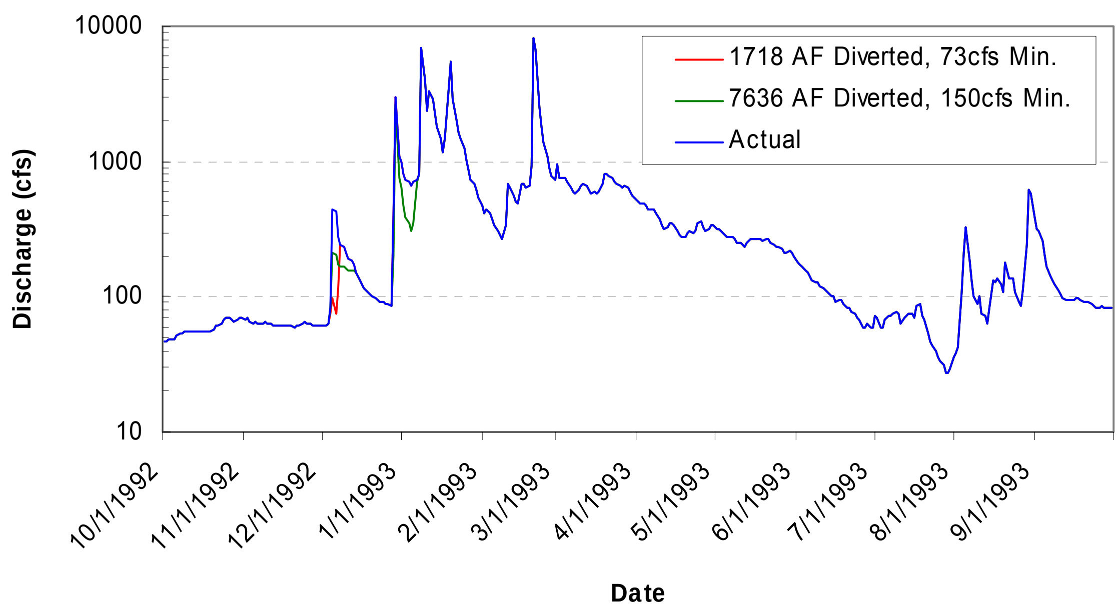


Figure 4.14. 1989 hydrographs (representative wet year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Gila gage.

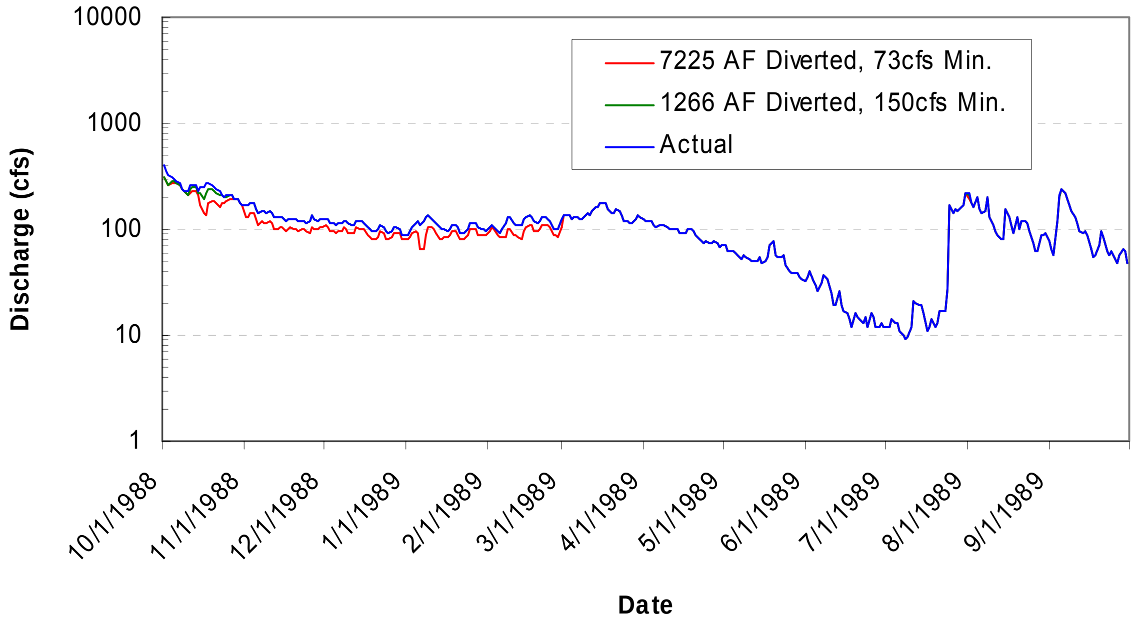


Figure 4.15. 1989 hydrographs (representative dry year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Redrock gage.

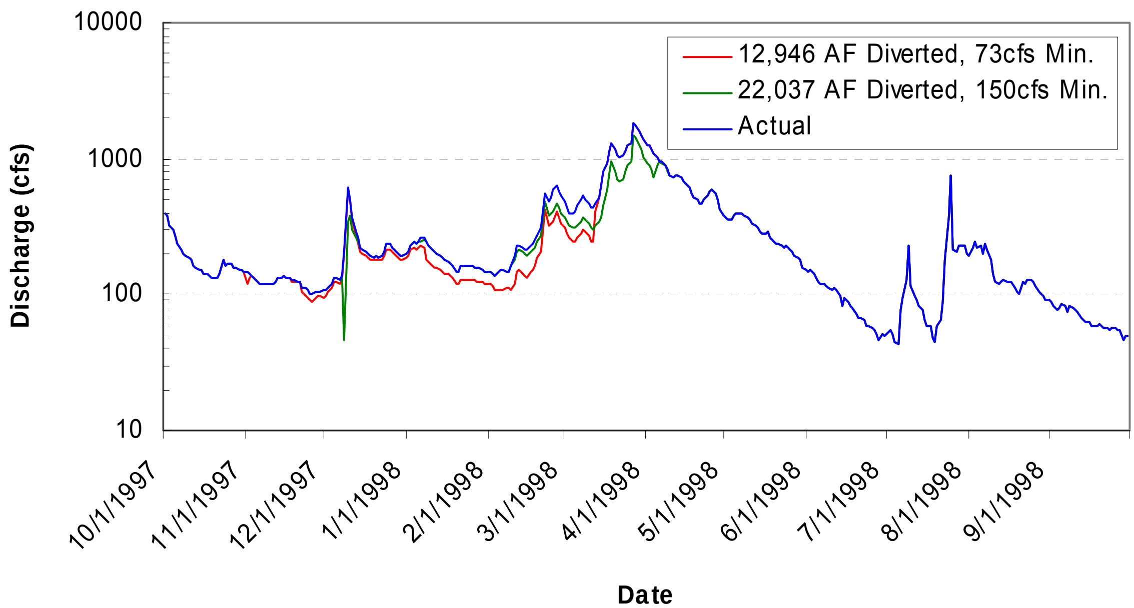


Figure 4.16. 1998 hydrographs (representative typical year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Redrock gage.

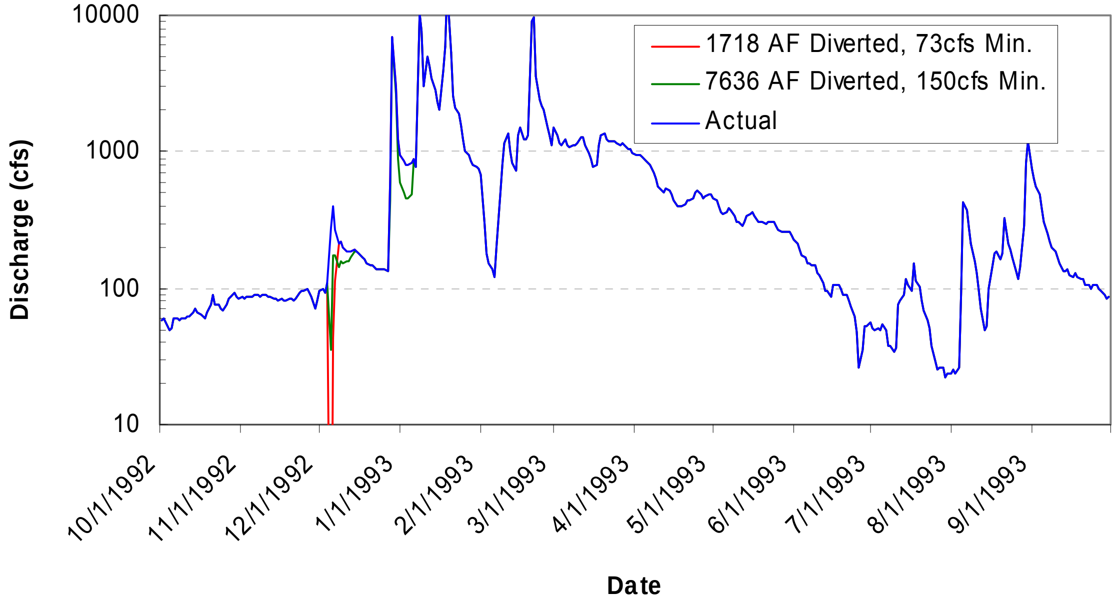


Figure 4.17. 1989 hydrographs (representative wet year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Redrock gage.

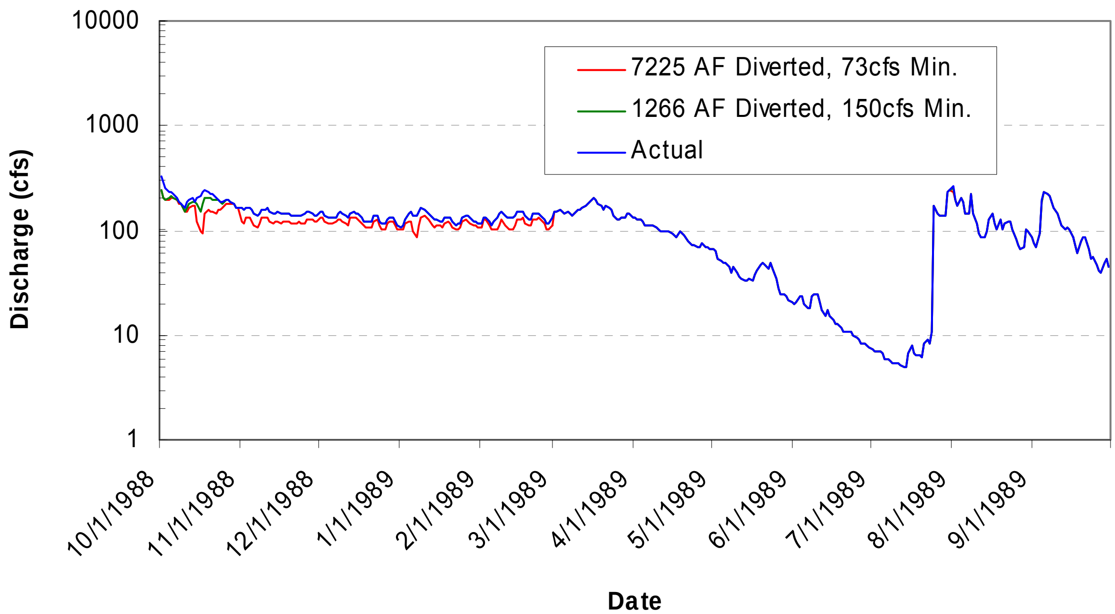


Figure 4.18. 1989 hydrographs (representative dry year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Virden gage.

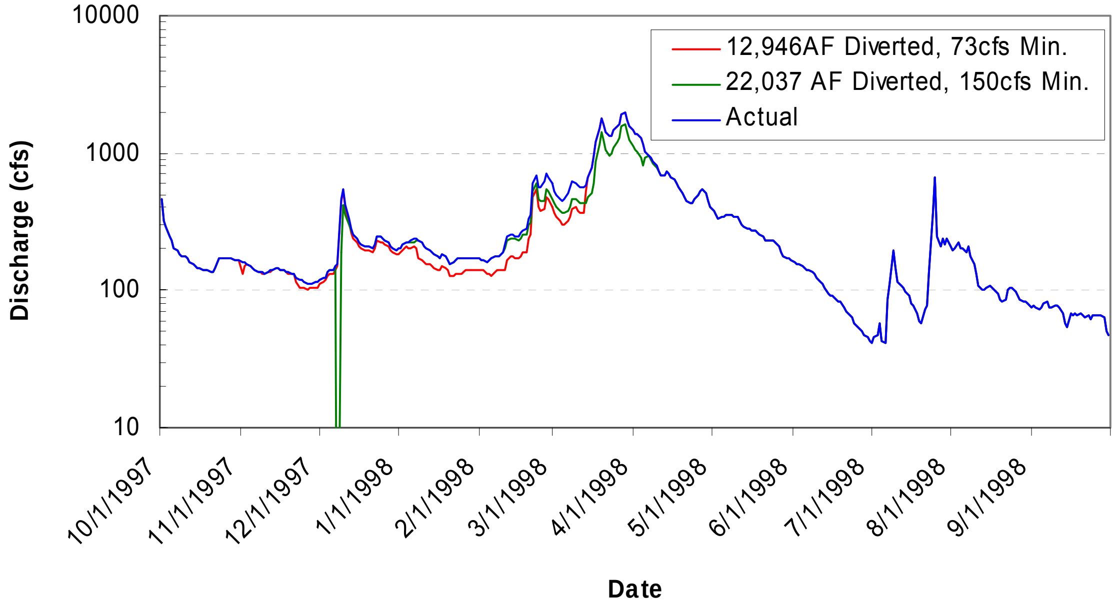


Figure 4.19. 1998 hydrographs (representative typical year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Virden gage.

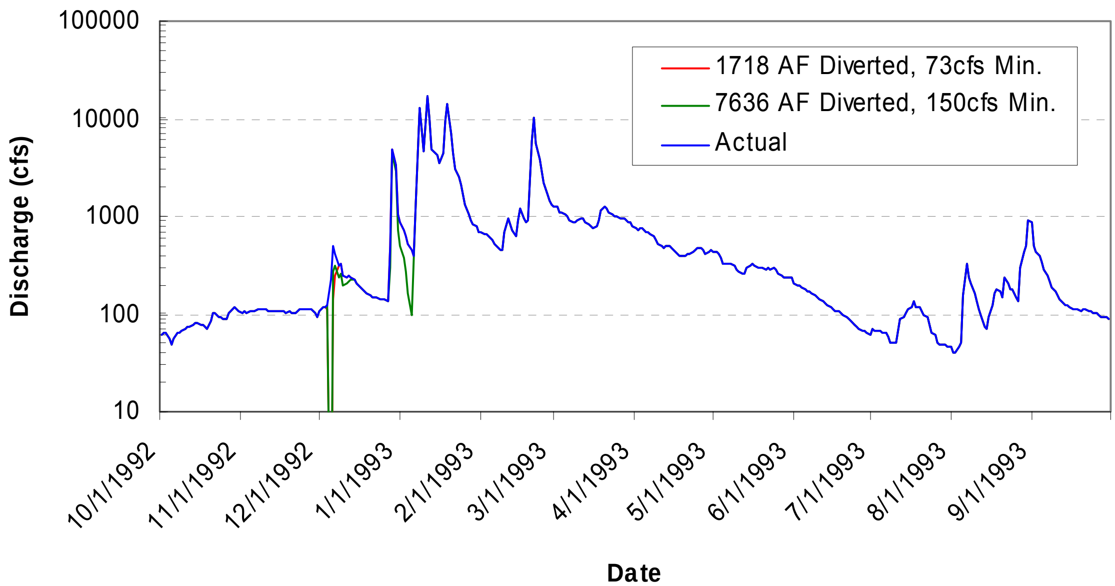


Figure 4.20. 1989 hydrographs (representative wet year) for existing conditions and with 73- and 150-cfs minimum bypass requirements for the Gila River near Virden gage.

5. HYDRAULICS

Hydraulic models were developed for all of the sites to quantify the hydraulic characteristics (velocity, depth, water-surface elevation) for a range of flows. Output from the hydraulic models was used to quantify the hydraulic parameters for in-channel habitat assessment purposes and to quantify sediment transport processes at each site. Inundation frequency and duration for various channel margin features (floodplain and terraces) that provide riparian habitat were also assessed with the model output. The hydraulic analyses were conducted with the U.S. Army Corps of Engineers one-dimensional HEC-RAS step-backwater program, Version 3.1.3 (USACE, 2005).

The individual site hydraulic models were developed from the surveyed cross sections and longitudinal profiles. The cross sections were located in the field to encompass the hydraulic controls in the surveyed reach over the full range of modeled flows. HEC-RAS accounts for energy losses that result from roughness along the channel bed and banks with a roughness coefficient, Manning's *n*. Manning's *n*-values were assigned to the channel and the overbank areas based on field estimations and by use of standard references (Barnes, 1967; Hicks and Mason, 1991). At the Turkey Creek site, *n*-values ranged from 0.035 for the finer in-channel bed materials to 0.1 for dense willows on the channel margins. At the TNC site *n*-values ranged from in-channel 0.035 to densely vegetated overbanks at 0.12. At the Birds site in-channel *n*-values were 0.03 and the highest overbank values was 0.1. At the Box site the in-channel *n*-value with mobile bedforms was 0.035, and the very dense, woody debris jams in the overbanks were assigned *n*-values of 0.3. At the Virden site, the in-channel *n*-value was 0.035 and the highest assigned overbank value was 0.1 where the vegetation was thickest. A normal-depth downstream boundary condition with the existing channel bed slope was used for all of the sites. The models were run with a range of flows from a 5-cfs baseflow to the peak of the 500-year flow.

5.1. Turkey Creek Site

The Turkey Creek Site HEC-RAS model was developed from the 11 cross sections surveyed in February 2006 (Figure 3.1). The model was calibrated to the measured discharge (60 cfs) at the time of the survey. Thalweg, and bank profiles and the water-surface profiles of a range of flows between 5 and 28,200 cfs (50-year peak flow recurrence interval) are shown on **Figure 5.1**. **Table 5.1** summarizes the reach-averaged hydraulic parameters for the range of flows modeled (5 to 87,100 cfs). At the 2-year flow (1,930 cfs), the average channel velocity is about 5 feet per second (fps), hydraulic depth is about 4 feet, and the channel top width is about 98 feet. At the 2005 peak flow (19,900 cfs), which is the most geomorphically effective flow at the site since 1997, the average velocity was about 9 fps, the hydraulic depth was about 12 feet and the channel width was about 103 feet. Effective width-, channel velocity- and hydraulic depth-discharge rating curves for each of the cross sections at the site that can be used to evaluate the in-channel hydraulic characteristics at the various habitat units (riffles, runs, pools, glides are provided in **Appendix B**.

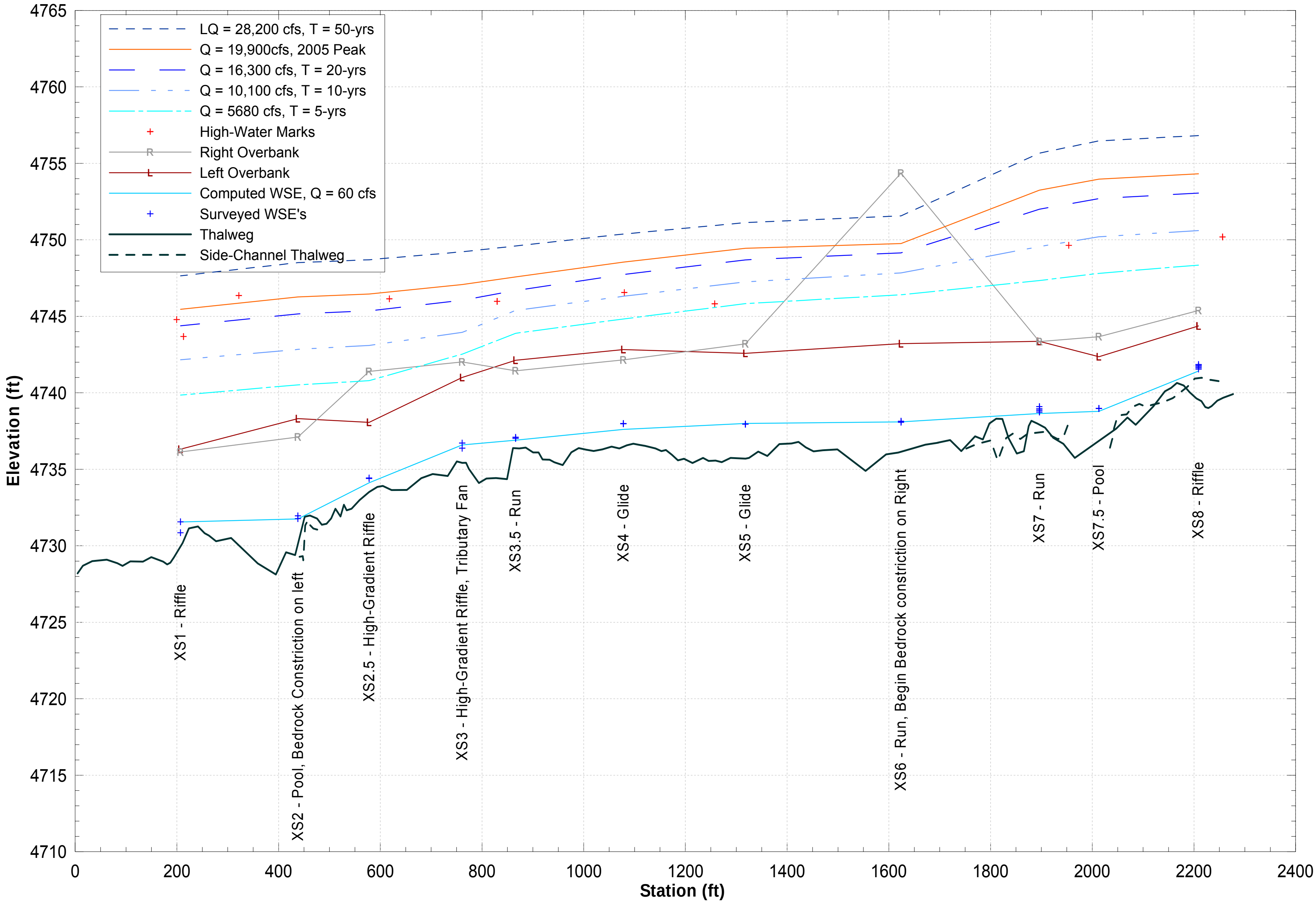


Figure 5.1. Thalweg, top-of-bank and water-surface profiles for the Turkey Creek site.

Table 5.1. Reach-averaged hydraulics for the Turkey Creek site.						
Profile	Q Total (cfs)	Q Channel (cfs)	Velocity Channel (ft/s)	Hydraulic Depth C (ft)	Top Width Channel (ft)	Energy Gradeline Slope (ft/ft)
Base	5	5	1.21	0.57	23.14	0.01937
25 cfs	25	25	1.72	0.81	34.87	0.01208
80pct Exc.	49	49	2.01	0.99	40.07	0.01063
Calibration	60	60	2.10	1.04	42.48	0.01007
50pct Exc.	74	74	2.19	1.11	45.76	0.01225
1.01-yr	115	115	2.47	1.27	51.76	0.01209
1.053-yr	257	257	3.04	1.81	57.93	0.00800
1.111-yr	397	397	3.49	2.17	62.45	0.00736
1.25-yr	679	679	3.92	2.76	71.77	0.00642
1.5-yr	951	949	4.22	3.16	79.45	0.00587
1.75-yr	1,340	1,304	4.54	3.57	90.11	0.00565
2-yr	1,930	1,802	5.02	4.06	97.62	0.00574
3-yr	2,717	2,405	5.46	4.78	100.57	0.00533
4-yr	3,910	3,224	5.97	5.64	101.66	0.00468
5-yr	5,680	4,261	6.44	6.75	102.33	0.00409
10-yr	10,100	6,439	7.49	8.65	102.49	0.00396
20-yr	16,300	8,819	8.29	10.62	102.53	0.00367
2005 Peak	19,900	10,098	8.67	11.63	102.55	0.00363
50-yr	28,200	12,898	9.34	13.77	102.61	0.00344
100-yr	40,800	16,992	10.20	16.59	102.69	0.00327
200-yr	57,400	22,233	11.14	19.88	102.70	0.00314
500-yr	87,100	31,398	12.54	24.99	102.70	0.00303

5.2. TNC Site

The TNC Site HEC-RAS model was developed from the eight cross sections surveyed in February 2006 (Figure 3.5). The model was calibrated to the measured discharge (22 cfs) at the time of the survey. Thalweg, and bank profiles and the water-surface profiles of a range of flows between 5 and 28,200 cfs (50-year peak flow recurrence interval) are shown on **Figure 5.2**. **Table 5.2** summarizes the reach-averaged hydraulic parameters for the range of flows modeled (5 to 87,100 cfs). At the 2-year flow (1,930 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 2 feet, and the channel top width is about 191 feet. At the 2005 peak flow (19,900 cfs), which is the most geomorphically effective flow at the site since 1997, the average velocity was about 8 fps, the hydraulic depth was about 7 feet and the channel width was about 228 feet. Effective width-, channel velocity- and hydraulic depth-discharge rating curves for each of the cross sections at the site that can be used to evaluate the in-channel hydraulic characteristics at the various habitat units (riffles, runs, pools, glides are provided in **Appendix B**.

5.3. Birds Site

The Birds Site HEC-RAS model was developed from the 10 cross sections surveyed in February 2006 (Figure 3.8). The model was calibrated to the measured discharge (60 cfs) at the time of the survey. Thalweg, and bank profiles and the water-surface profiles of a range of

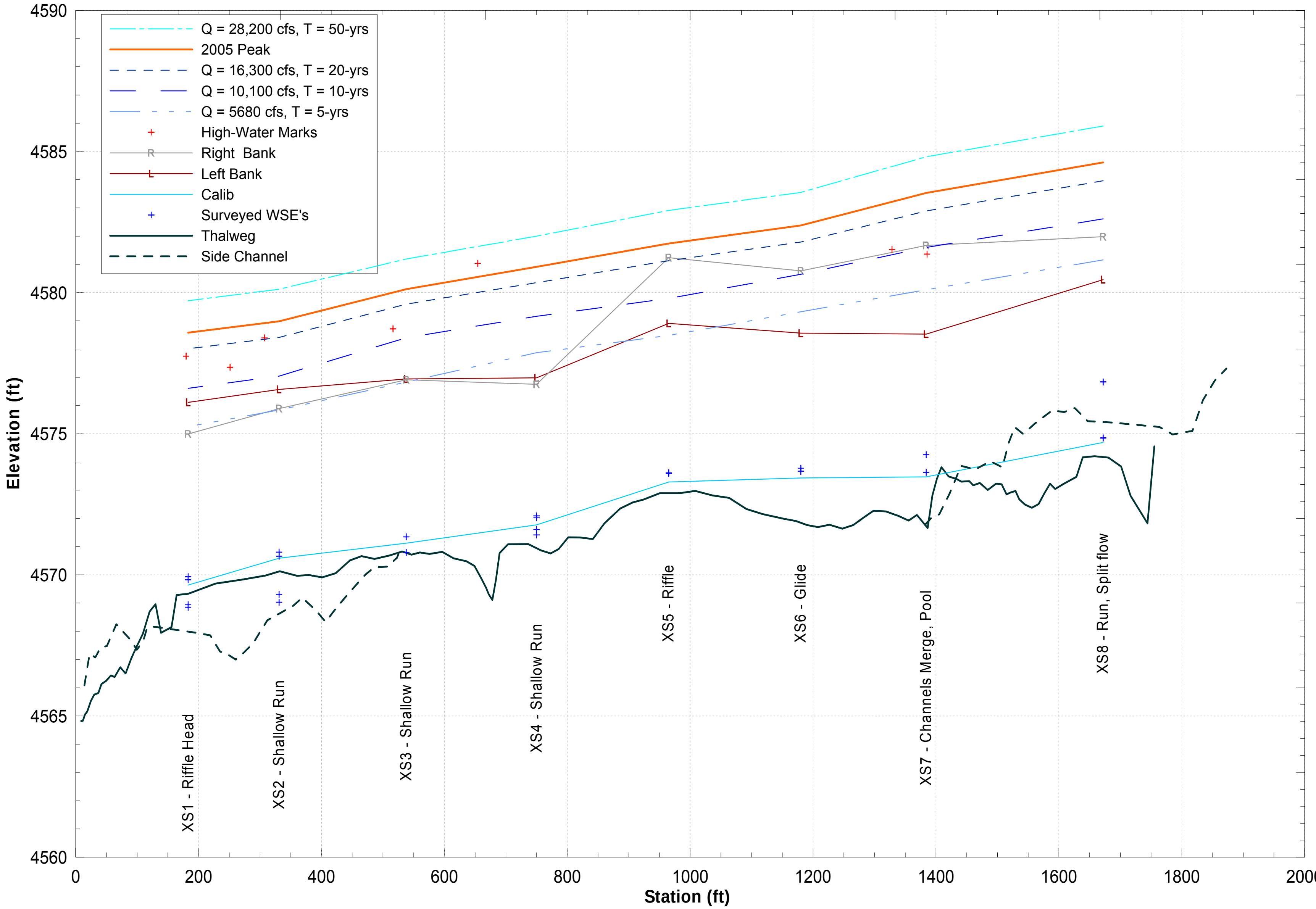


Figure 5.2. Thalweg, top-of-bank and water-surface profiles for the TNC site.

Table 5.2. Reach-averaged hydraulics for the TNC site.						
Profile	Q Total (cfs)	Q Channel (cfs)	Velocity Channel (ft/s)	Hydraulic Depth C (ft)	Top Width Channel (ft)	Energy Gradeline Slope (ft/ft)
Base	5	5	1.07	0.34	39.70	0.01654
Calibration	22	22	1.60	0.50	55.74	0.01055
80pct Exc.	49	49	1.91	0.67	67.61	0.00752
50pct Exc.	74	74	2.11	0.68	74.15	0.01169
1.01-yr	115	115	2.14	0.83	83.94	0.00783
1.053-yr	257	257	3.00	1.08	92.92	0.00805
1.111-yr	397	397	3.34	1.34	101.96	0.00680
1.25-yr	679	679	3.58	1.66	123.72	0.00449
1.5-yr	951	951	3.92	1.87	141.36	0.00424
1.75-yr	1340	1340	4.28	2.05	159.97	0.00419
2-yr	1930	1930	4.63	2.33	191.06	0.00414
3-yr	2717	2669	4.97	2.82	200.19	0.00405
4-yr	3910	3806	5.38	3.44	214.58	0.00395
5-yr	5680	5416	5.90	4.28	222.53	0.00367
10-yr	10100	8423	6.88	5.57	227.30	0.00360
20-yr	16300	11709	7.72	6.83	228.08	0.00360
2005 Peak	19900	13514	8.18	7.41	228.42	0.00368
50-yr	28200	17455	9.08	8.58	228.42	0.00382
100-yr	40800	23098	10.21	10.05	228.42	0.00399
200-yr	57400	30193	11.43	11.70	228.42	0.00416
500-yr	87100	42300	13.17	14.18	228.42	0.00435

flows between 5 and 28,200 cfs (25-year peak flow recurrence interval) are shown on **Figure 5.3**. **Table 5.3** summarizes the reach-averaged hydraulic parameters for the range of flows modeled (5 to 72,900 cfs). At the 2-year flow (5,930 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 7 feet, and the channel top width is about 151 feet. At the 2005 peak flow (22,900 cfs), which is the most geomorphically effective flow at the site since 1997, the average velocity was about 8 fps, the hydraulic depth was about 10 feet and the channel width was about 151 feet. Effective width-, channel velocity- and hydraulic depth-discharge rating curves for each of the cross sections at the site that can be used to evaluate the in-channel hydraulic characteristics at the various habitat units (riffles, runs, pools, glides are provided in **Appendix B**.

5.4. Box Site

The Box Site HEC-RAS model was developed from the 12 cross sections surveyed in February 2006 (Figure 3.11). The model was calibrated to the measured discharge (60 cfs) at the time of the survey. Thalweg, and bank profiles and the water-surface profiles of a range of flows between 5 and 22,900 cfs (15-year peak flow recurrence interval) are shown on **Figure 5.4**. **Table 5.4** summarizes the reach-averaged hydraulic parameters for the range of flows modeled (5 to 72,800 cfs). At the 2-year flow (5,190 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 7 feet, and the channel top width is about 108 feet. At the 2005 peak flow (22,900 cfs), which is the most geomorphically effective flow at the site since 1997, the average velocity was about 6 fps, the hydraulic depth was about 12 feet and the channel width

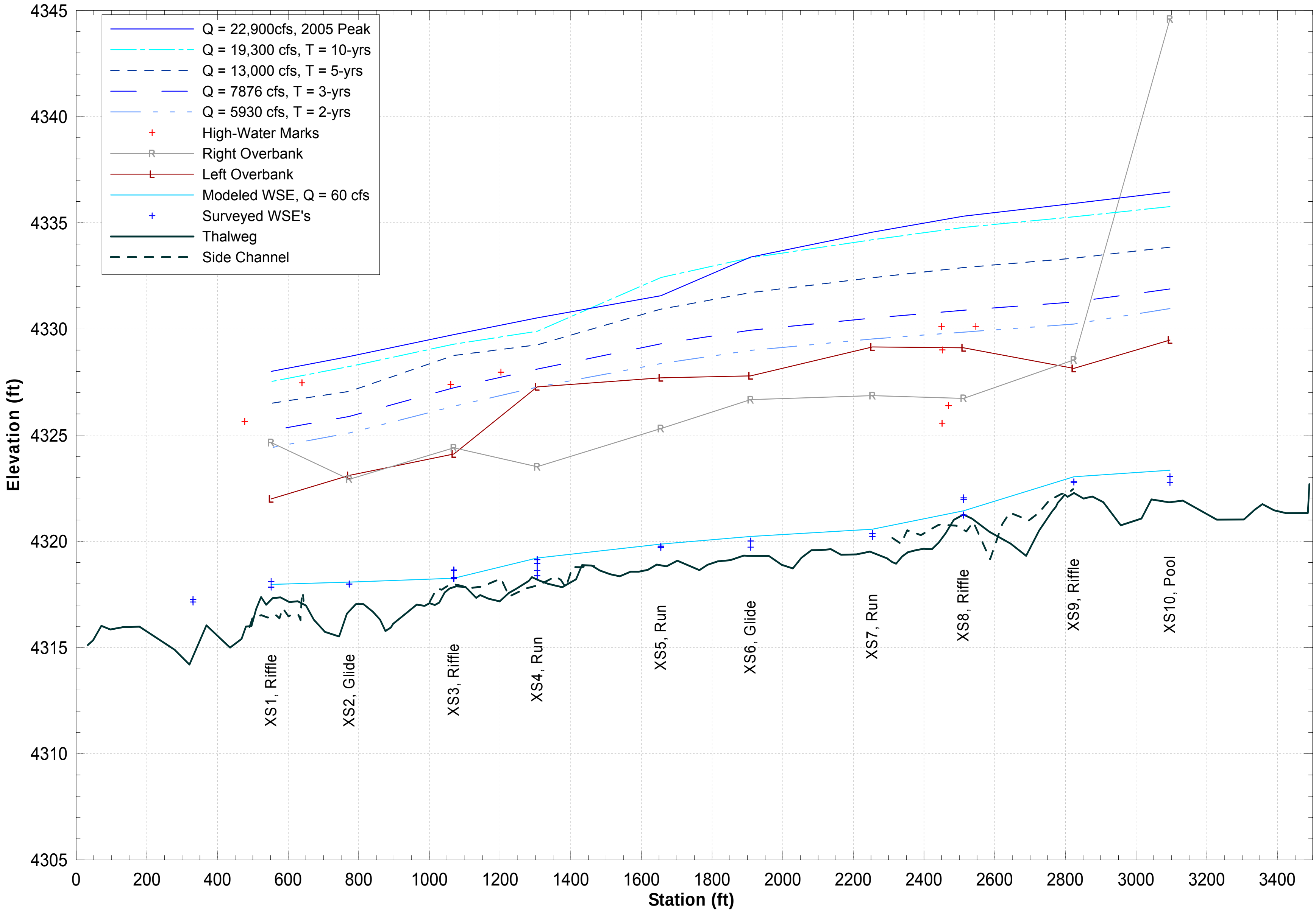


Figure 5.3. Thalweg, top-of-bank and water-surface profiles for the Birds site.

Table 5.3. Reach-averaged hydraulics for the Birds site.						
Profile	Q Total (cfs)	Q Channel (cfs)	Velocity Channel (ft/s)	Hydraulic Depth C (ft)	Top Width Channel (ft)	Energy Gradeline Slope (ft/ft)
Base	5	5	1.06	0.36	32.49	0.01436
90pct Exc.	30	30	1.41	0.57	51.61	0.00800
Calibration	60	60	1.64	0.74	63.56	0.00663
30pct Exc.	150	60	1.63	0.77	62.83	0.00691
20pct Exc.	230	230	2.22	1.35	82.85	0.00266
13pct Exc.	350	350	2.53	1.65	88.01	0.00247
1.01-yr	530	530	2.84	1.99	98.84	0.00245
1.053-yr	1120	1120	3.46	2.84	120.53	0.00254
1.111-yr	1640	1640	3.82	3.53	127.81	0.00251
1.25-yr	2580	2548	4.07	4.56	143.96	0.00255
1.5-yr	3265	3159	4.38	5.09	147.81	0.00270
1.75-yr	4434	4154	4.87	5.91	150.32	0.00283
2-yr	5930	5149	5.32	6.67	150.89	0.00286
3-yr	7876	6308	5.86	7.38	151.00	0.00302
4-yr	10300	7497	6.33	8.05	151.11	0.00309
5-yr	13000	8641	6.74	8.65	151.20	0.00314
10-yr	19300	10976	7.51	9.75	151.39	0.00328
2005 Peak	22900	12194	7.87	10.27	151.48	0.00335
20-yr	26500	13365	8.21	10.76	151.56	0.00341
50-yr	37400	16703	9.08	12.03	151.78	0.00358
100-yr	46900	19445	9.74	12.99	151.95	0.00371
200-yr	57300	22319	10.38	13.93	152.10	0.00384
500-yr	72900	26484	11.23	15.19	152.31	0.00401

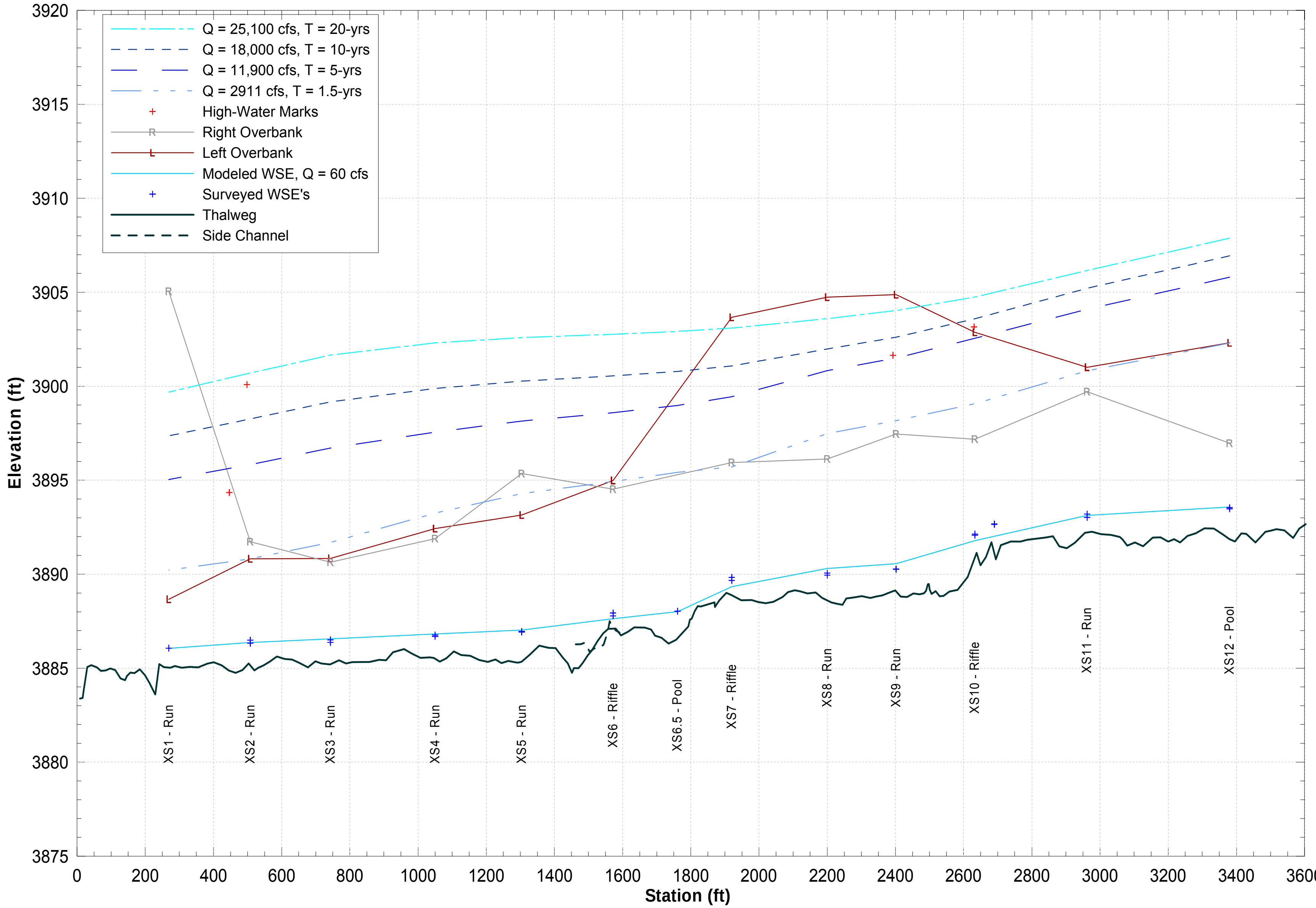


Figure 5.4. Thalweg, top-of-bank and water-surface profiles for the Box site.

Table 5.4. Reach-averaged hydraulics for the Box site.						
Profile	Q Total (cfs)	Q Channel (cfs)	Velocity Channel (ft/s)	Hydraulic Depth C (ft)	Top Width Channel (ft)	Energy Gradeline Slope (ft/ft)
Base	5	5	0.86	0.32	28.50	0.00876
90pct Exc.	22	22	1.36	0.58	38.82	0.00711
Calibration	60	60	1.82	0.91	44.71	0.00535
30pct Exc.	145	145	2.21	1.45	51.64	0.00444
20pct Exc.	220	220	2.47	1.80	55.73	0.00410
13pct Exc.	335	335	2.77	2.20	61.53	0.00421
1.01-yr	409	409	2.83	2.37	66.76	0.00347
1.053-yr	896	890	3.48	3.38	81.59	0.00378
1.111-yr	1340	1305	3.86	3.95	92.54	0.00406
1.25-yr	2160	1976	4.39	4.69	101.96	0.00432
1.5-yr	2911	2513	4.76	5.31	105.72	0.00443
1.75-yr	3904	3109	5.11	6.00	107.18	0.00441
2-yr	5190	3743	5.41	6.69	108.11	0.00423
3-yr	6885	4418	5.67	7.37	109.36	0.00396
4-yr	9054	5140	5.88	8.15	109.81	0.00368
5-yr	11900	5887	5.99	9.04	110.20	0.00336
10-yr	18000	7155	6.03	10.77	110.66	0.00279
2005 Peak	22900	7984	5.96	12.05	111.18	0.00239
20-yr	25100	8322	5.92	12.60	111.44	0.00224
50-yr	36100	9945	5.73	15.40	111.72	0.00161
100-yr	45700	11318	5.60	17.75	111.72	0.00126
200-yr	56600	12921	5.54	20.31	111.72	0.00102
500-yr	72800	15387	5.58	23.90	111.72	0.00082

was about 111 feet. Reduced velocities and increased flow depths at higher flows are the result of backwater conditions caused by the downstream bedrock contraction at the head of the Lower Box canyon. Effective width-, channel velocity- and hydraulic depth-discharge rating curves for each of the cross sections at the site that can be used to evaluate the in-channel hydraulic characteristics at the various habitat units (riffles, runs, pools, glides are provided in **Appendix B**.

5.5. Virden Bridge Site

The Virden Bridge Site HEC-RAS model was developed from the 11 cross sections surveyed in February 2006 (Figure 3.14). The model was calibrated to the measured discharge (40 cfs) at the time of the survey. Thalweg, and bank profiles and the water-surface profiles of a range of flows between 5 and 22,900 cfs (15-year peak flow recurrence interval) are shown on **Figure 5.5**. **Table 5.5** summarizes the reach-averaged hydraulic parameters for the range of flows modeled (5 to 87,100 cfs). At the 2-year flow (5,190 cfs), the average channel velocity is about 6 fps, hydraulic depth is about 5 feet, and the channel top width is about 158 feet. At the estimated 2005 peak flow (22,900 cfs), which is the most geomorphically-effective flow at the site since 1997, the average velocity was about 9 fps, the hydraulic depth was about 12 feet and the channel width was about 103 feet. Effective width-, channel velocity- and hydraulic depth-discharge rating curves for each of the cross sections at the site that can be used to evaluate the in-channel hydraulic characteristics at the various habitat units (riffles, runs, pools, glides are provided in **Appendix B**.

Table 5.5. Reach-averaged hydraulics for the Virden Bridge site.

Profile	Q Total (cfs)	Q Channel (cfs)	Velocity Channel (ft/s)	Hydraulic Depth C (ft)	Top Width Channel (ft)	Energy Gradeline Slope (ft/ft)
Base	5	5	0.99	0.43	28.21	0.01237
90pct Exc.	22	22	1.44	0.57	49.99	0.00987
Calibration	40	40	1.72	0.69	57.33	0.00939
30pct Exc.	145	145	2.48	1.17	70.02	0.00654
20pct Exc.	220	220	2.48	1.31	83.63	0.00411
13pct Exc.	335	335	2.66	1.51	94.52	0.00290
1.01-yr	409	409	2.77	1.57	104.40	0.00279
1.053-yr	896	894	3.43	2.14	128.72	0.00264
1.111-yr	1340	1330	3.85	2.55	141.83	0.00268
1.25-yr	2160	2110	4.50	3.32	147.65	0.00268
1.5-yr	2911	2776	4.93	3.89	151.05	0.00265
1.75-yr	3904	3622	5.37	4.54	154.96	0.00263
2-yr	5190	4677	5.85	5.29	157.56	0.00263
3-yr	6885	5988	6.38	6.14	159.25	0.00265
4-yr	9054	7565	6.96	7.07	159.64	0.00266
5-yr	11900	9505	7.62	8.11	159.64	0.00267
10-yr	18000	13272	8.70	9.90	159.64	0.00268
20-yr	25100	17150	9.69	11.46	159.64	0.00277
50-yr	36100	22720	10.98	13.38	159.64	0.00292
100-yr	45700	27327	11.93	14.81	159.64	0.00303
200-yr	56600	32384	12.86	16.26	159.64	0.00312
500-yr	72800	39663	14.06	18.21	159.64	0.00323

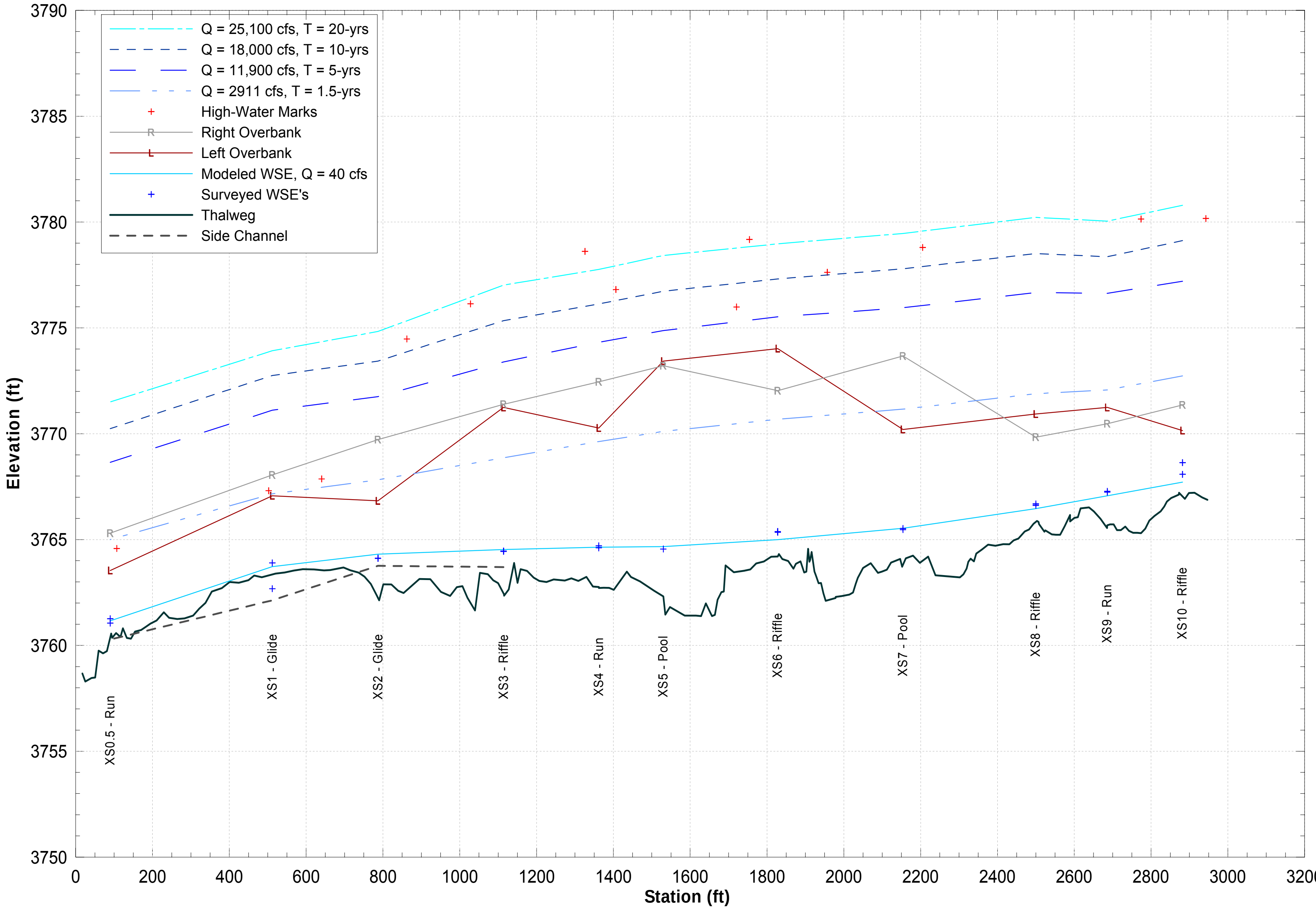


Figure 5.5. Thalweg, top-of-bank and water-surface profiles for the Virden Bridge site.

6. SEDIMENT TRANSPORT

The HEC-RAS hydraulic model output for each site was also used to determine shear stresses for the range of modeled flows. Shear stress, in conjunction with the sediment gradations (Chapter 3), was used to evaluate the flows required to mobilize the coarse bed material at the Turkey Creek, TNC, Birds and Virden sites. Because of the sand bed at the Box site, no incipient-motion analysis was carried out. Output from the hydraulic models was also used to compute the volume of sediment transported on an annual basis for the period of record for the three Gila River gages and to determine the effective discharge at each site.

6.1. Incipient-Motion Analysis

An incipient-motion analysis (evaluation of flows required to move the surface bed material) was performed by evaluating the effective shear stress on the channel bed in relation to the amount of shear stress that is required to move the surface particles. The shear stress required for bed mobilization was estimated using the Shields (1936) relation, given by:

$$\tau_C = \tau_{*C}(\gamma_S - \gamma)D_{50} \tag{6.1}$$

where τ_c = critical shear stress for particle motion,
τ_{*c} = dimensionless critical shear stress (often referred to as the Shields parameter),
γ_s = unit weight of sediment (~165 lb/ft^3),
γ = unit weight of water (62.4 lb/ft^3), and
D_{50} = median particle size of the bed material.

In gravel- and cobble-bed streams, when the critical shear stress for the median particle size is exceeded, the bed is mobilized and all sizes up to about five times the median size can be transported by the flow (Parker et al., 1982; Andrews, 1984).

Reported values for the Shields parameter range from 0.03 (Neill, 1968; Andrews, 1984) to 0.06 (Shields, 1936). A value of 0.047 is commonly used in engineering practice, based on the point at which the Meyer-Peter, Müller (MPM) bed-load equation indicates no transport (MPM, 1948). More recent evaluations of the MPM data and other data (Parker et al., 1982; Andrews, 1984) indicates that true incipient motion occurs at a value of about 0.03 in gravel- and cobble-bed streams. Neill (1968) concluded that a dimensionless shear value of 0.03 corresponds to true incipient motion of the bed-material matrix while 0.047 corresponds to a low, but measurable transport rate. A value of 0.03 was used in this analysis.

In performing an incipient-motion analysis, the bed shear stress due to grain resistance (τ') is used rather than the total shear stress, because it is a better descriptor of the near-bed hydraulic conditions that are responsible for sediment movement. The grain shear stress is computed from the following relation:

$$\tau' = \gamma Y' S \tag{6.2}$$

where Y' = the portion of the total hydraulic stress associated with grain resistance (Einstein, 1950), and
S = the energy slope at the cross section.

The value of Y' is computed by iteratively solving the semilogarithmic velocity profile equation:

$$\frac{V}{V_*'} = 5.75 + 6.25 \log\left(\frac{Y'}{K_S}\right) \tag{6.3}$$

where V = mean velocity at the cross section,
K_s = characteristic roughness of the bed, and
V_*' = shear velocity due to grain resistance given by:

$$V_*' = \sqrt{gY'S} \tag{6.4}$$

The characteristic roughness height of the bed (K_s) was assumed to be 3.5 D_{84} (Hey, 1979). Normalized grain shear stress (ϕ') is the ratio of the grain sheer stress (τ') to the critical shear stress for particle mobilization (τ_c). When ϕ' is equal to 1 the bed material begins to mobilize (point of incipient motion), and substantial sediment transport occurs when ϕ'>1.5 (Harvey et al., 1993; Mussetter et al., 2001).

Incipient-motion (ϕ' = 1) and sediment-transport (ϕ'>1.5) analyses were conducted for each of the cross sections at the sites and an appropriate sediment gradation was applied to each of the cross sections. The results of the individual cross section analyses at each site were then reviewed to select reach-averaged values for each site. **Table 6.1** summarizes the results of the incipient motion and sediment-transport analyses for the 4 sites.

Table 6.1. Summary of sediment-transport results.

Variable	Turkey Creek	TNC	Birds	Box	Virden Bridge
Representative D_{50} (mm)	49	61	47	1.3	57
Representative D_{84} (mm)	101	111	85	2.8	100
Reach Average Incipient Motion (ϕ' = 1) (cfs)	2,500	1,300	2,500	NA	1,200
Reach Average Significant Transport (ϕ' >1.5) (cfs)	4,000	3,500	5,500	NA	3,000

On the basis of the results of the shear stress-based incipient-motion and significant sediment-transport computations, it can be argued that flow diversions at flows less than critical (ϕ' = 1) at each of the sites will have no geomorphic effect, since morphogenetic flows by definition must be able to mobilize the channel boundary sediments. Additionally, it can be argued that diversion of flows above those required for significant sediment transport ((ϕ'>1.5) at each of the sites will have the most effect on geomorphic processes. Because of its physical setting and location upstream of the Cliff-Gila Valley, it is highly unlikely that flows will be diverted at the Turkey Creek site. Based on the above reasoning, at the TNC site diversion of flows below 1,300 cfs will have little or no geomorphic impacts, and diversion of flows above 3,500 cfs will have the most impacts. At the Birds site, diversion of flows below 2,500 cfs will have little impact, while diversion of flows above 5,500 cfs will have the most impact. The differences in values between the two sites are due primarily to the differences in their slopes, with the TNC site being about 1.5 times steeper. At the Virden Bridge site, diversion of flows below 1,200 cfs will have little geomorphic impact, while diversion of flows above 3,000 cfs will have the most impact.

6.2. Effective Discharge

The concept of effective discharge, as initially advanced by Wolman and Miller (1960), related the frequency and magnitude of various discharges to their ability to do geomorphic work by transporting sediment. They concluded that events of moderate magnitude and frequency transported the most sediment over the long-term, and that these flows were the most effective in forming and maintaining the planform and geometry of the channel. Andrews (1980) defined the effective discharge as "*the increment of discharge that transports the largest fraction of the annual sediment load over a period of years.*"

Alluvial rivers adjust their shape in response to flows that transport sediment, and numerous authors have attempted to relate the effective discharge to the concepts of dominant discharge, channel-forming discharge and bankfull discharge, and it is often assumed that these discharges are roughly equivalent and correspond to approximately the mean annual flood peak (Benson and Thomas, 1966; Pickup, 1976; Pickup and Werner, 1976; Andrews, 1980, 1986; Nolan et al., 1987; Andrews and Nankervis, 1985). Baker (1977) and Wolman and Gerson (1978), however, concluded that in more arid environments, less frequent, higher magnitude flood events are the most important with respect to sediment transport, and the interrelationships of these concepts are not universally accepted (Biedenharn et al., 2000). Regardless of the scientific debate on the interrelationships, quantification of the range of flows that transport the most sediment provides useful information to assess the current state of adjustment of the channel, and to evaluate the potential effects of decreased discharge. Although various investigators have used only the suspended-sediment load and the total sediment load to compute the effective discharge, the bed-material load should generally be used when evaluating the linkage between sediment loads and channel size because it is the bed-material load that has the most influence on the form of the channel (Schumm, 1963; Biedenharn et al., 2000).

Bed-material rating curves were developed for each of the sites using the sediment gradations shown in Table 6.1 and the reach-averaged hydraulics (**Figures 6.1 through 6.5)**. For the coarse-grained sites, Turkey Creek, TNC, Birds and Virden Bridge, the Parker surface gradation equation (Parker, 1990) was used to compute sediment transport. At the Box site, where the bed material is composed of sand-sized material, the Yang sand equation (Yang, 1973) was used. Reversal of the rating curve at flows above about 7,000 cfs is due to backwater created by the downstream contraction at higher flows.

The effective discharge for each site was computed by dividing the range of flows during the period of record at the appropriate gage into 25 logarithmic classes, and then computing the total quantity of bed-material load transported by the flows within each class (Biedenharn et al., 2000). The results of the effective discharge computations for each of the sites are shown in **Figures 6.6 through 6.10**. The discharge shown on the abscissa of each figure is the average discharge of the flow interval. Figure 6.9 shows the results of the effective discharge calculation for the Box site where the bed material is composed of sand. This site provides an example of the expected pattern for an alluvial river, where the modal value is about the mean annual peak flow (1,500 to 2000 cfs) (Andrews, 1980; Biedenharn et al., 2000). At the Turkey Creek site (Figure 6.6), the modal value is about 4,000 cfs (4-year recurrence interval), and this reflects the forced morphology of the site (Baker, 1977; Montgomery and Buffington, 1997). At the TNC site (Figure 6.7), the modal value is about 9,000 cfs (~10-year recurrence interval), and this is related to the coarseness of the bed material. At the Birds and Virden Bridge sites (Figure 6.8,

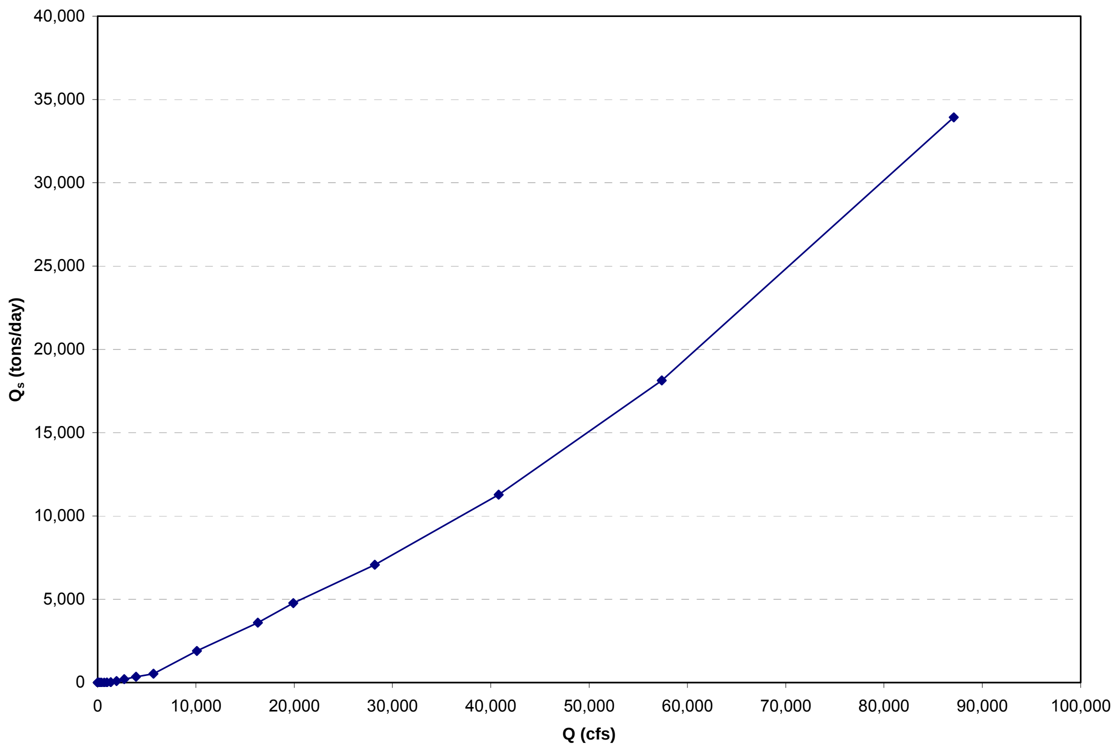


Figure 6.1. Bed-material rating curve for the Turkey Creek site.

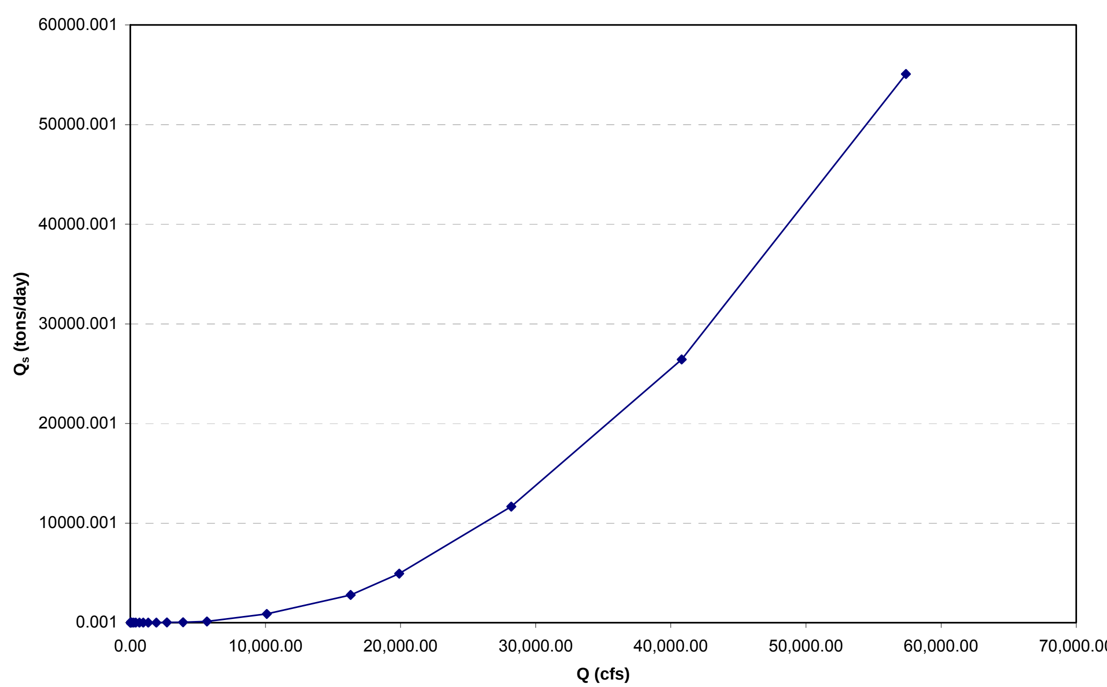


Figure 6.2. Bed-material rating curve for the TNC site.

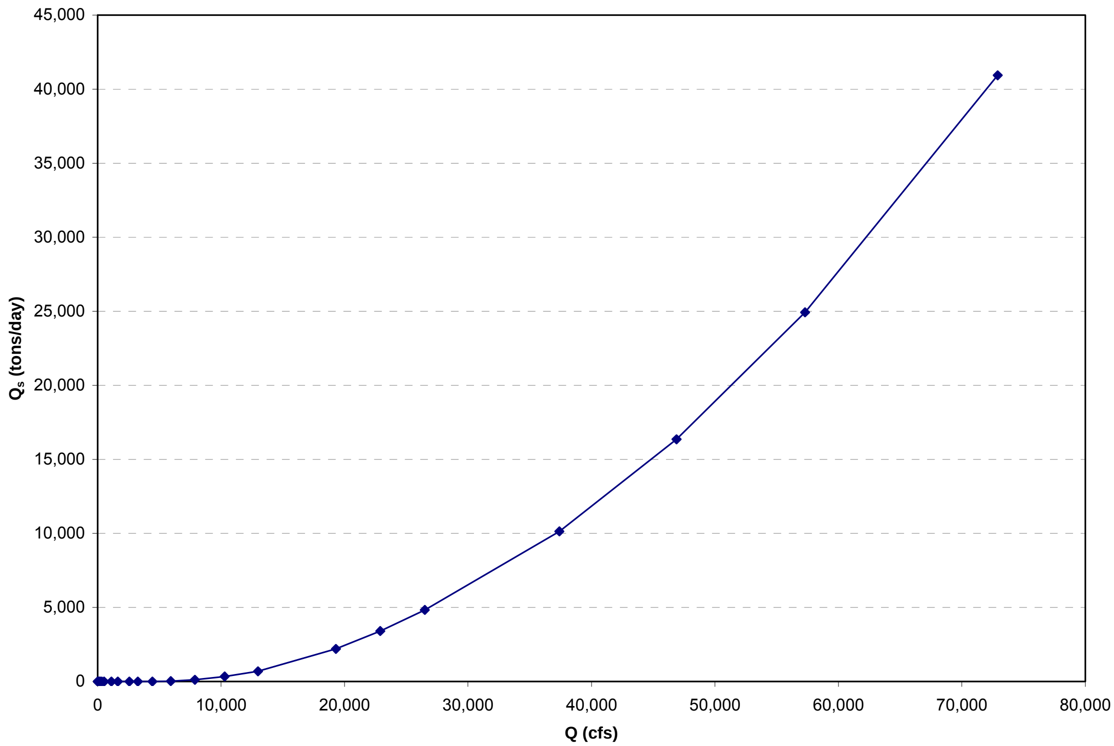


Figure 6.3. Bed-material rating curve for the Birds site.

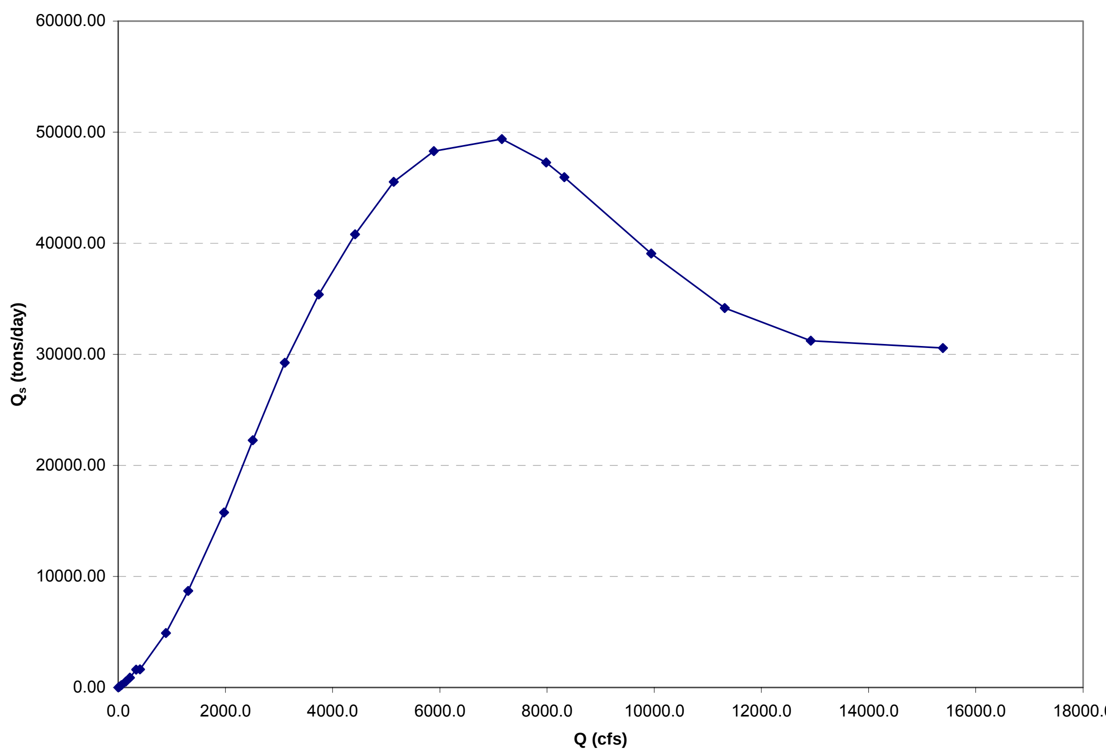


Figure 6.4. Bed-material rating curve for the Box site.

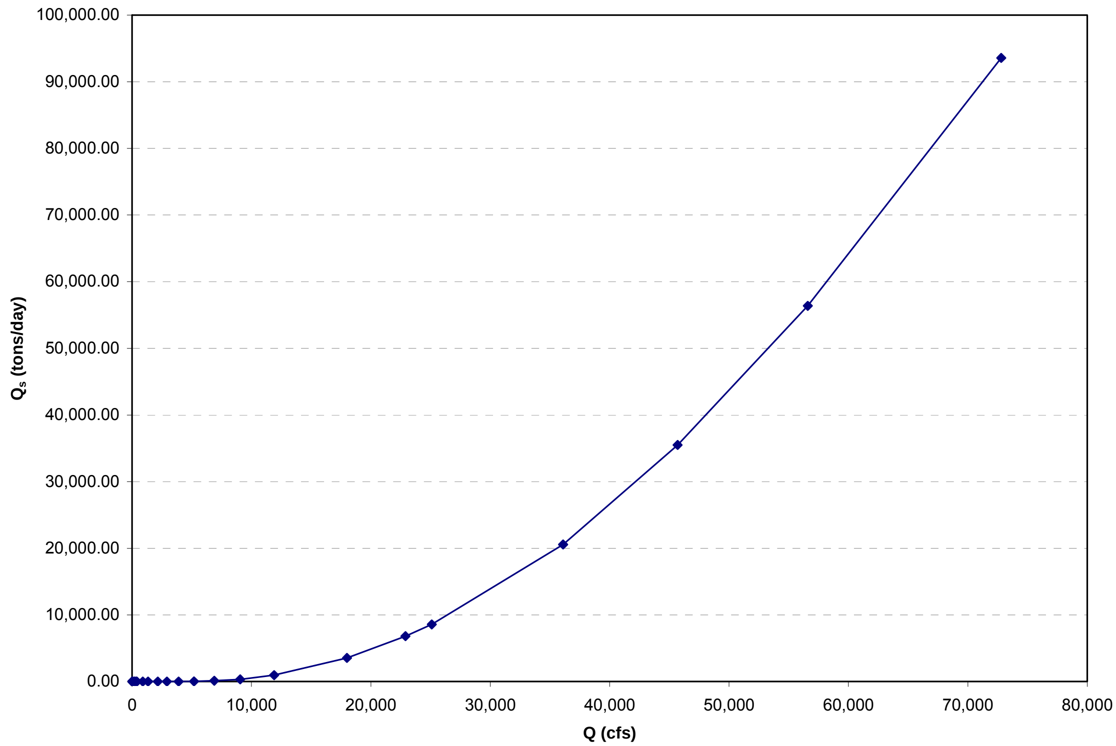


Figure 6.5. Bed-material rating curve for the Virden Bridge site.

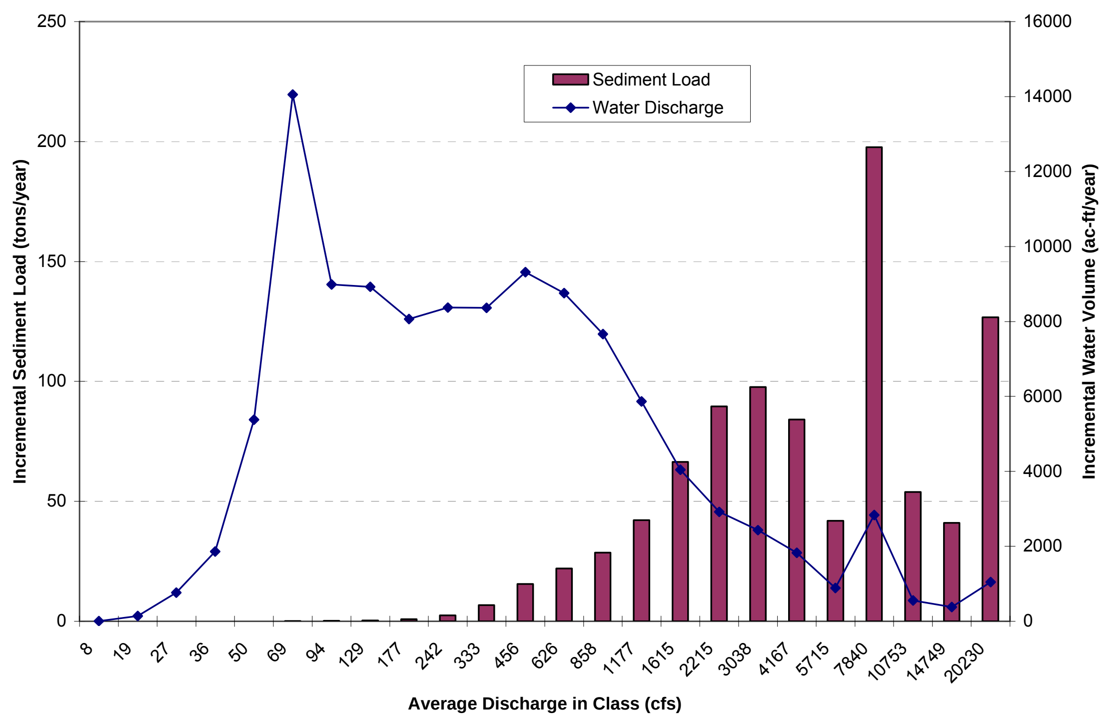


Figure 6.6. Effective discharge plot for the Turkey Creek site.

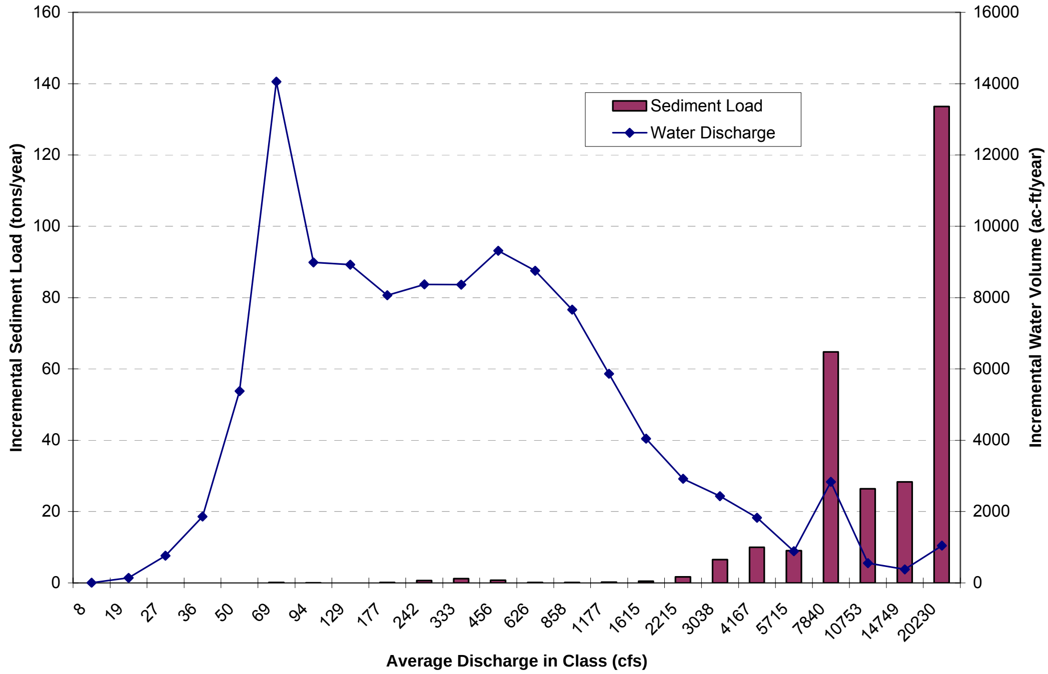


Figure 6.7. Effective discharge plot for the TNC site.

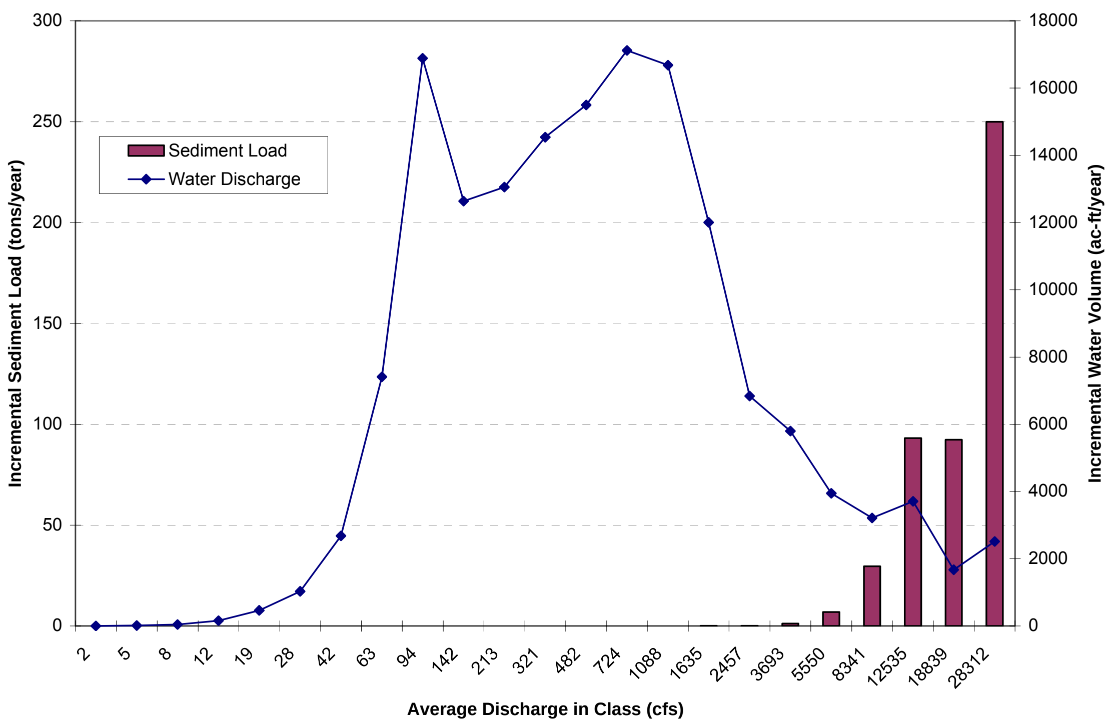


Figure 6.8. Effective discharge plot for the Birds site.

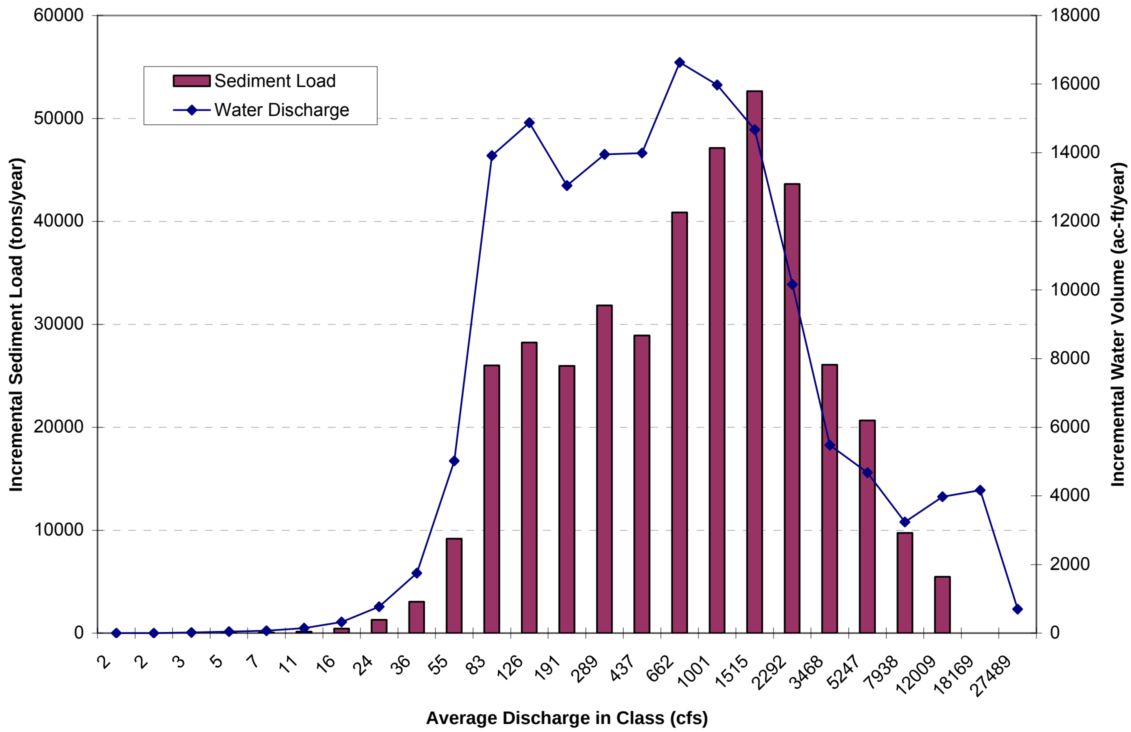


Figure 6.9. Effective discharge for the Box site.

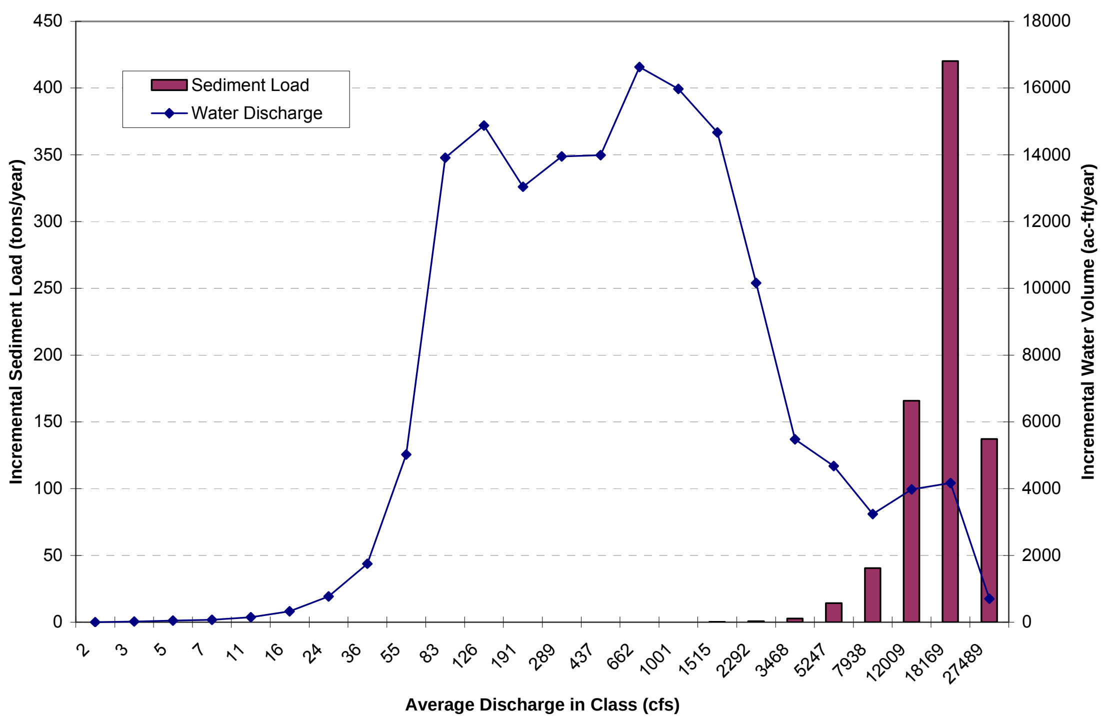


Figure 6.10. Effective discharge for the Virden Bridge site.

6.10), the effective discharge value is also skewed to the higher flows (~18,000 cfs) and the higher recurrence intervals (10-year recurrence interval). Displacement of the effective discharge towards the higher, less frequent flows is a typical characteristic of dryland rivers (Baker, 1977; Graf, 1983b; Neff, 1967; Harvey and Mussetter, 2005).

Clearly, the effective discharge computations show that changes in the flow regime will have an impact of the Box site where the bed material is composed of sand (Figure 6.9), and may increase the time required to return the channel bed to a gravel-cobble pool-riffle morphology. At the remainder of the sites, where the bed materials are coarser, the effective discharge will only be affected if there are significant diversions at the higher flows. Based on the diversion estimates provided by NMISC, the maximum diversion is estimated to be 350 cfs, and therefore, unless the diversions occur in the range of the incipient motion and significant sediment transport thresholds, there should be no significant geomorphic impacts.

6.3. Sediment Transport

The annual frequency of bed material mobilization at the TNC site for the period of record at the Gila River near Gila gage was used to classify each year within the record into either, inactive (0 days of bed material mobilization), average (1 to 4 days of bed material mobilization) and active (5 or more days of bed-material mobilization). Based on these classification criteria, 45 percent of the years are inactive, 26 percent are average and 29 percent are active (**Figure 6.11**). Diversion of flows under the 73- and 150-cfs minimum bypass scenarios causes an increase in the percentage of inactive years to 50 and 52 percent, respectively. Concurrently, the percentage of average years are reduced by the diversions to about 24 percent and the percentage of active years are decreased to 27 and 26 percent, respectively, by the diversions.

Table 6.2 provides a summary of the effects of diversion on the average daily transport rate based on the integration of the bed-material rating curves (Figures 6.1 through 6.5) with the mean daily flows for the three different year classes at each of the sites.

At the Turkey Creek site, the largest effects of the diversions on a percentage basis occur in the inactive years (-32 and -22 percent) because of the very low transport rates. However, because of the very limited effect on total sediment transport, the changes are unlikely to be significant geomorphically. Diversion effects in the average years are between 16 and 14 percent, but because of the forced morphology of the site, the changes are unlikely to be geomorphically significant. In active water years, the diversion changes are less, because of the greater volume of transport.

At the TNC site, diversions during the inactive years have no real effect because the flows do not exceed the critical discharge for bed-material mobilization. The greatest effect of the diversions, on a percentage basis, occurs in the average years, but the total volume of transport is very low, and thus, the diversions are unlikely to have significant morphological effects on the channel. In active water years, the diversion changes are about 6 percent. Similarly, at the Birds site, in inactive years there is little impact of diversion on sediment transport, and the highest percentage effects occurs in the average years (-8 to -11 percent), but again the transport rates are low and therefore there are unlikely to be significant geomorphic impacts. In the active year types the diversions will reduce the transport rate by about 3 percent, and this is not likely to be significant.

In contrast, at the Box site, where the current bed material is sand sized, diversions have similar effects, regardless of the year types because there are no threshold discharges required for

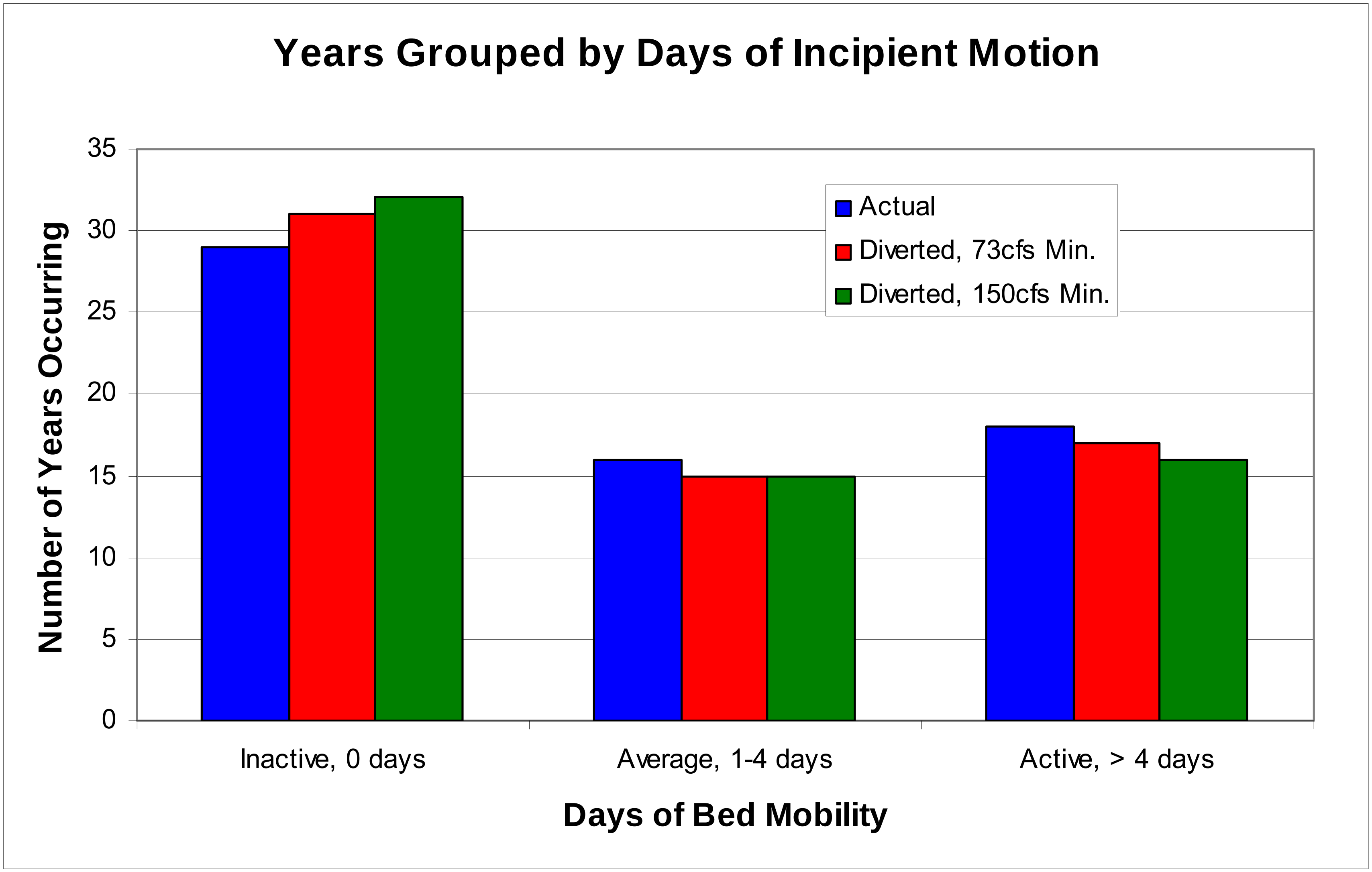


Figure 6.11. Histograms showing the number of years in the period of record at the Gila River near Gila gage that bed material was mobilized at the TNC site and the effects of the two diversion scenarios on the frequency of mobilization.

sediment mobilization. Changes range from about 7 to 11 percent. From a geomorphic perspective, the diversions will slow the rate of removal of the sand-sized sediments from the bed of the channel, provided that the upstream source of sand-sized material is not high. If there is a continued supply of sand from upstream, the diversions will have little effect.

Table 6.2. Summary of effects of diversion on sediment transport.

Site/Year Type	Average Transport Rate (t/day)	Percent Change in Average Transport Rate	
		Diversion Scenario	
		150 cfs	73 cfs
Turkey Creek			
Inactive	0.32	-32	-22
Average	5.3	-16	-14
Active	16.2	-7	-6
TNC			
Inactive	0	0	0
Average	0.43	-13	-8
Active	2.3	-6	-6
Birds			
Inactive	0.06	-5	-3
Average	0.47	-11	-8
Active	4.15	-3	-3
Box			
Inactive	548	-9	-7
Average	1385	-11	-12
Active	2897	-11	-10
Virden			
Inactive	0	0	0
Average	0.002	-43	-35
Active	3.1	-4	-4

At the Virden site, there will be no impacts of diversion in the inactive years. Because of the extremely low transport rates in the average year type, the diversions will show a high change percentage, but in reality these changes will be insignificant geomorphically. Minor changes will also occur in the active year type, and these are not likely to be significant geomorphically.

In summary, the sediment-transport computations show that the largest impacts will occur in the average year type (about 25 percent of the years) when flow diversions can have an affect on the sediment mobilization thresholds. In the inactive year type (about 50 percent of the years) there is little possibility of a significant geomorphic impact from diversion of the flows. In the active year type (about 25 percent of the years), the impact of diversions is minimized because of the relative size of the maximum diversion rate (350 cfs) to the river flows. As shown by the review of the published literature (Chapter 2), most of the sediment transport, and hence geomorphic change, occurs during large, infrequent floods, when it is unlikely that diversions will be occurring.

7. INUNDATION FREQUENCY AND DURATION

The capacity of the channel governs the frequency and duration of inundation of the channel margin areas that support the riparian vegetation community along the Gila River. In contrast to low gradient alluvial streams in more humid regions where the channel capacity is about the mean annual flood (1.5-year recurrence interval) (Leopold et al., 1964), the channel in dryland rivers tends to be compound and can convey a range of flows from baseflow to large floods, in-bank (Graf, 1988; Harvey and Mussetter, 2005). Floodplains are poorly defined between bounding un-paired terraces, and large, infrequent floods tend to have a strong influence on channel geometry that in turn confines subsequent lower magnitude flows (Graf, 1988). Therefore, delineation of contiguous channel margin surfaces that support the riparian community along the study sites on the Gila River is difficult and requires a measure of interpretation.

In general, the ground cover across the surveyed cross sections at each site was classified as follows for the purposes of defining overbank Manning's *n*-values:

- bare ground
- bare ground with shrubs
- sparse grasses and shrubs
- willows
- mixed willows and young cottonwoods
- older cottonwoods and sycamores
- mature upland vegetation

Based on the field survey data, the boundaries of the different vegetation types were plotted on the site cross sections, and these were related to the water-surface elevations for the range of modeled flows (**Appendix C**).

7.1. Turkey Creek Site

Based on the output from the HEC-RAS hydraulic model of the site, field notes and photographs, and the plotted cross sections (Appendix C), floodplain and terrace surfaces were identified at the Turkey Creek site (**Figure 7.1**). The floodplain elevation is approximated by the 2-year recurrence interval flood peak (1,930 cfs) water-surface elevation, which has a duration of about 2 days per year based on the mean daily flow duration curve for the Gila River near Gila gage (Figure 4.8). The terrace that intermittently bounds the floodplain at the Turkey Creek site is inundated by the 20-year recurrence interval flow (16,300 cfs), and for the period of record the duration of inundation is less than 0.1 days per year. High-water marks from the 2005 flood correlated well with the terrace elevation.

At the Turkey Creek site, willows were generally restricted to the channel banks in an elevation zone between baseflow and the water-surface elevation for a flow of about 2,000 cfs, which is the approximate 2-year recurrence interval flood peak. The mixed willow young cottonwood group of plants were similarly distributed, but extended onto the floodplain. Older cottonwoods were in general located at elevations above the 2-year water-surface elevation on the floodplain. Upland plant species (junipers) and large sycamores were located on the terraces at elevations that are rarely inundated and are correlated with the 20-year recurrence interval flow (16,300 cfs).

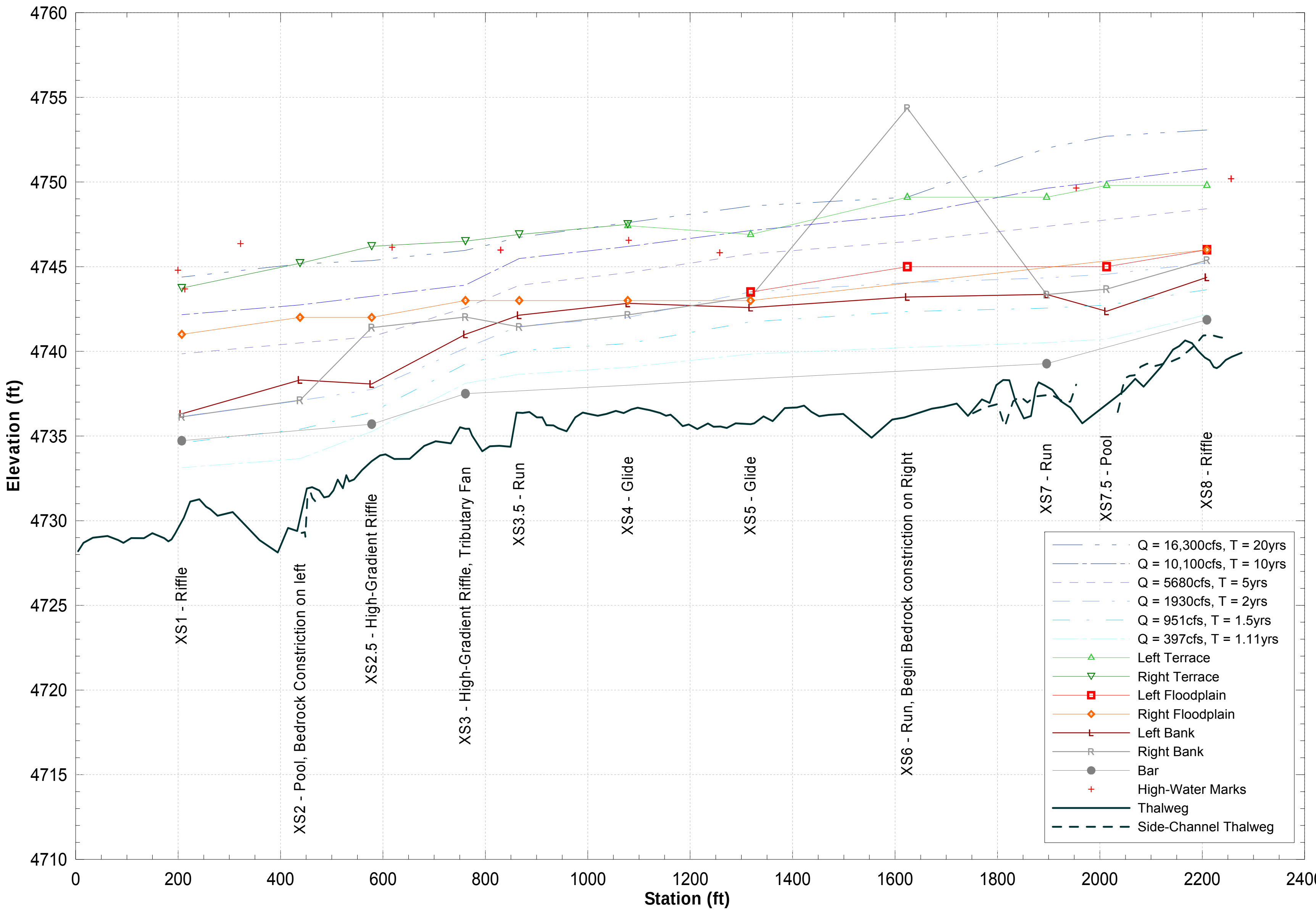


Figure 7.1. Thalweg, geomorphic surface and water-surface profiles for the Turkey Creek site.

7.2. TNC Site

Based on the output from the HEC-RAS hydraulic model of the site, field notes and photographs, and the plotted cross sections (Appendix C), floodplain and terrace surfaces were identified at the TNC site (**Figure 7.2**). The floodplain elevation is approximated by the 5-year recurrence interval flood peak (5,860 cfs) water-surface elevation which has a duration of about 0.5 days per year based on the mean daily flow duration curve for the Gila River near Gila gage (Figure 4.8). The high in-channel capacity could be due to two causes. The channel bed may have degraded somewhat during the 2005 flood as a result of channel shortening, and there is little doubt that the channel widened as well. The terrace that forms the boundary along the west side of the channel in the upper part of the site is correlated with the 20-year recurrence interval flow (16,300 cfs) water-surface elevation. High-water marks from the 2005 flood did not correlate well with the terrace elevations, possibly because they were set before the channel avulsion occurred.

At the TNC site, the distribution of willows was limited and they were generally restricted to the channel banks in an elevation zone between baseflow and the water-surface elevation for a flow of about 2,000 cfs, which is the approximate 2-year recurrence interval flood peak. Younger cottonwoods were distributed on the floodplain surface that is correlated with the 5-year recurrence interval flood, which has a duration of about half a day per year on average. Older cottonwoods were in general located on the terrace at an elevation that is rarely inundated (<0.1 days per year) and that is correlated with the 20-year recurrence interval flow (16,300 cfs).

7.3. Birds Site

Based on the output from the HEC-RAS hydraulic model of the site, field notes and photographs, and the plotted cross sections (Appendix C), floodplain and terrace surfaces were identified at the TNC site (**Figure 7.3**). The floodplain elevation is approximated by the 2-year recurrence interval flood peak (5,930 cfs) water-surface elevation which has a duration of about 1 day per year based on the mean daily flow-duration curve for the Gila River near Redrock gage (Figure 4.8). The continuous terrace located on the east side of the channel is correlated with the 5-year recurrence interval flood peak (13,000 cfs) water-surface elevation, and was overtopped by the 2005 flood.

At the Birds site, the willows were generally restricted to the channel banks in an elevation zone between baseflow and the water-surface elevation for a flow of about 5,930 cfs, which is the approximate 2-year recurrence interval flood peak with a duration of inundation of about 1 day per year. Younger cottonwoods were in general located on the floodplain, while the older cottonwoods and sycamores were located on the terrace that is inundated for less than 0.1 days per year.

7.4. Box Site

Based on the output from the HEC-RAS hydraulic model of the site, field notes and photographs, and the plotted cross sections (Appendix C), floodplain and terrace surfaces were identified at the Box site (**Figure 7.4**). The floodplain elevation is approximated by the 1.5-year recurrence interval flood peak (2,911 cfs) water-surface elevation which has a duration of about 1 day per year based on the mean daily flow-duration curve for the Gila River near Virden gage (Figure 4.8). A low terrace located on the left (east) side of the channel is correlated with the 5-year recurrence interval flow (11,900 cfs) that has a duration of 0.4 days per year. A higher elevation terrace is located along the right (west) side of the channel and appears to be

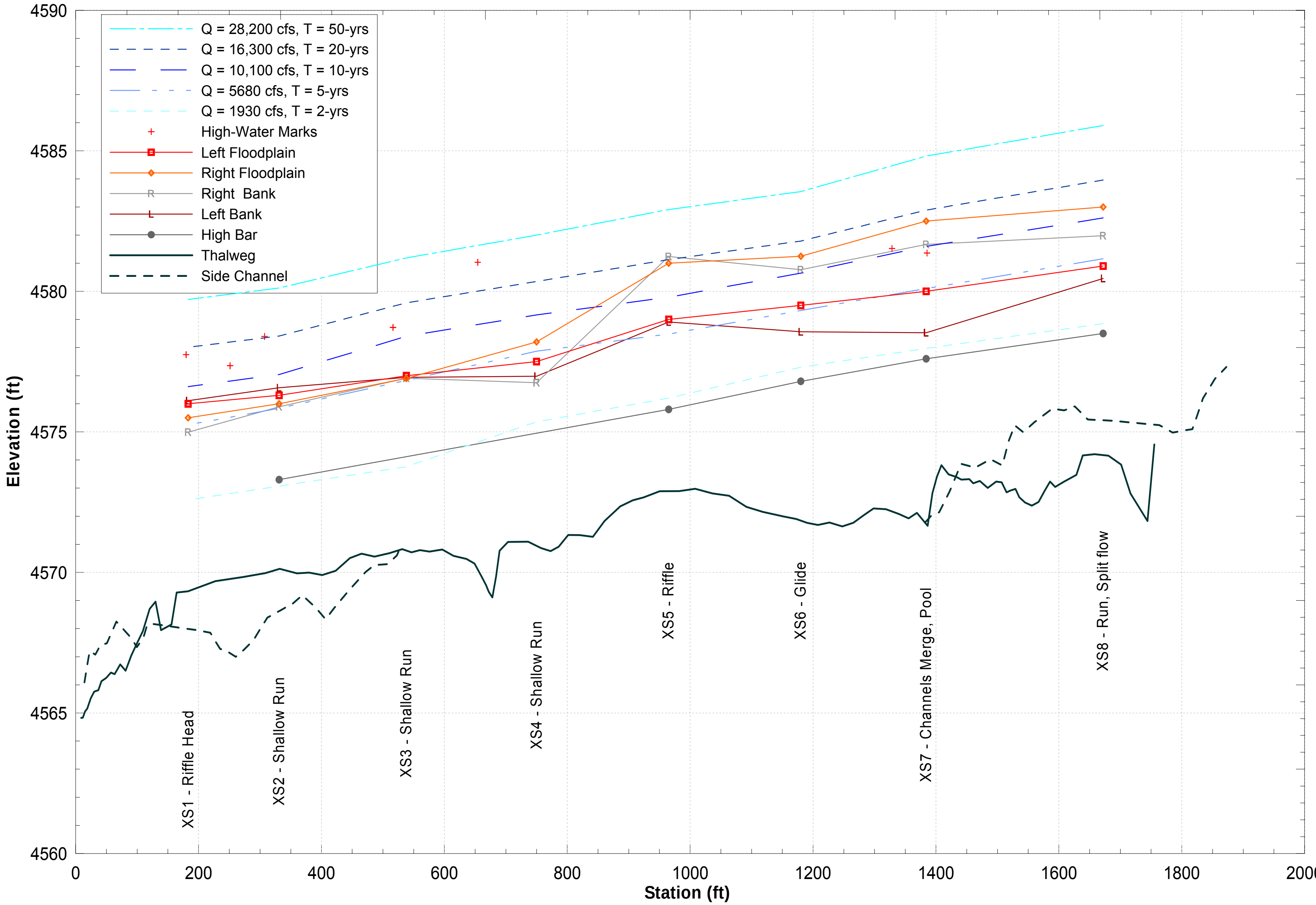


Figure 7.2. Thalweg, geomorphic surface and water-surface profiles for the TNC site.

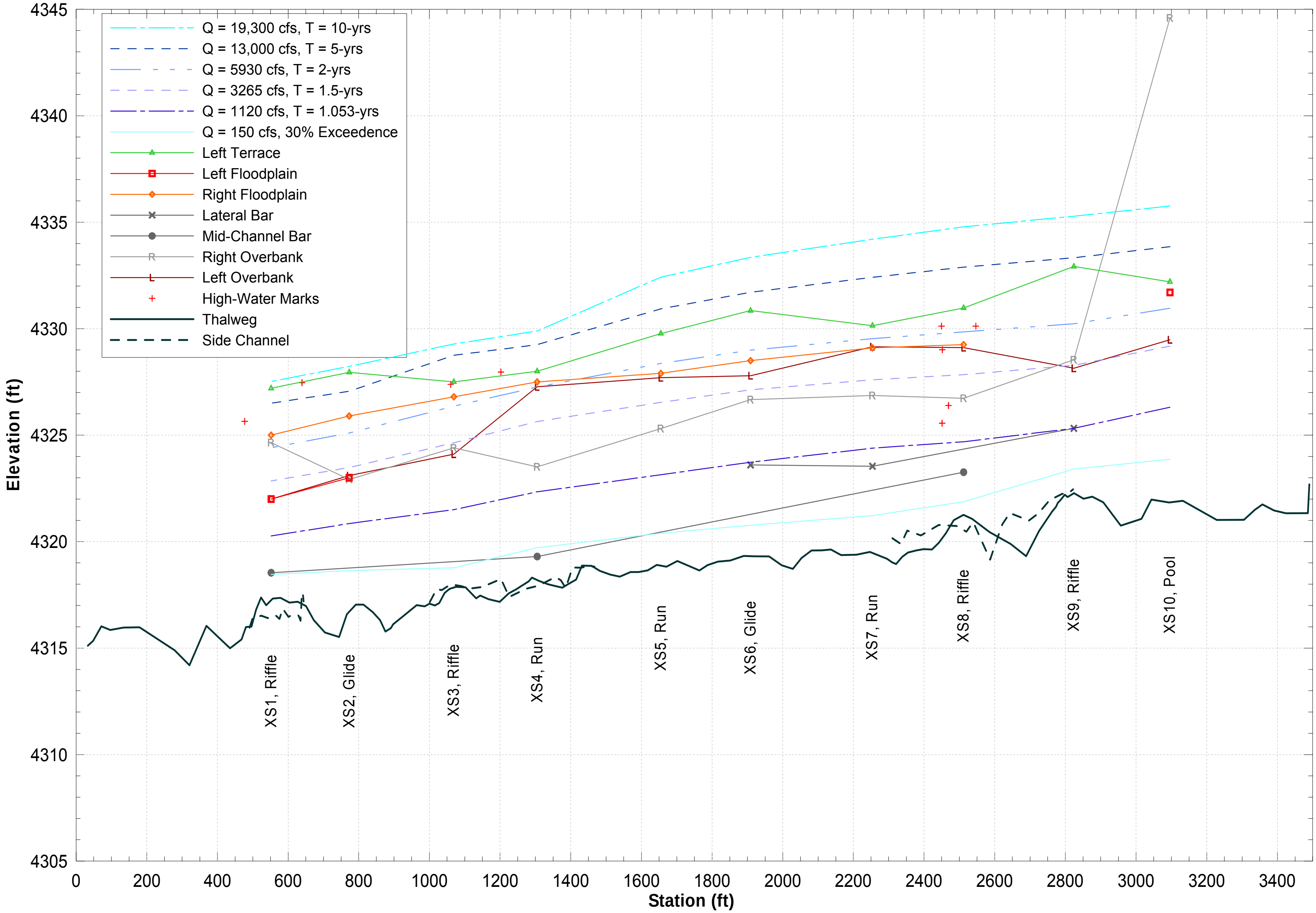


Figure 7.3. Thalweg, geomorphic surface and water-surface profiles for the Birds site.

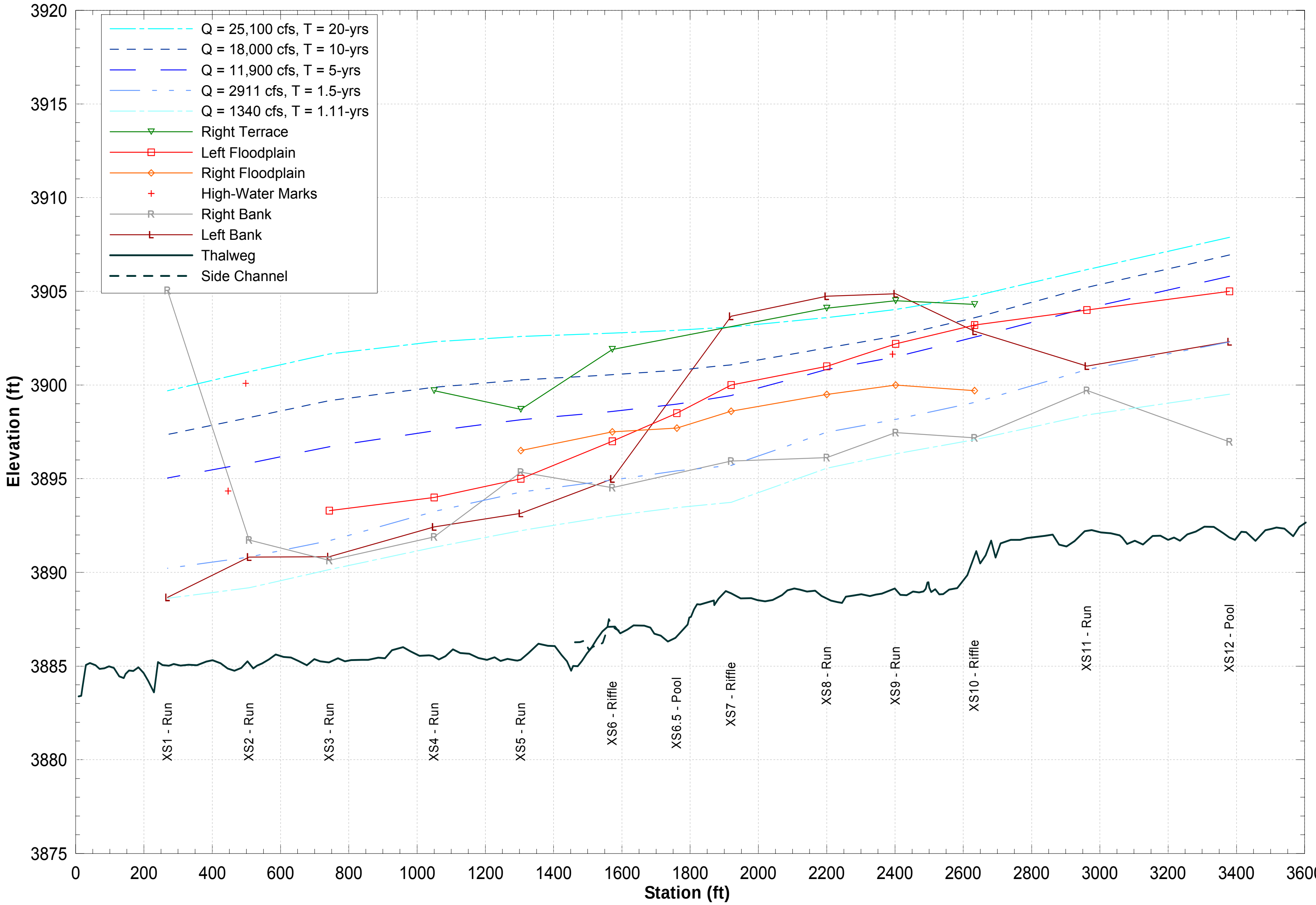


Figure 7.4. Thalweg, geomorphic surface and water-surface profiles for the Box site.

correlated with the 20-year recurrence interval flood (25,100 cfs) that has a duration of less than 0.1 days per year.

At the Box site, the willows were generally restricted to the lower channel banks in an elevation zone between baseflow and the water-surface elevation for a flow of about 2,911 cfs, which is the approximate 1.5-year recurrence interval flood peak with a duration of inundation of about 2 days per year. Younger cottonwoods were in general located at an elevation that correlates with the lower terrace (11,900 cfs) with a duration of inundation of about 0.4 days per year, while the older cottonwoods and sycamores were located on the higher terrace (25,100 cfs) that is inundated for less than 0.1 days per year. Upland species were also located on the higher terrace.

7.5. Virden Bridge Site

Based on the output from the HEC-RAS hydraulic model of the site, field notes and photographs, and the plotted cross sections (Appendix C), floodplain and terrace surfaces were identified at the Virden Bridge site (**Figure 7.5**). The floodplain elevation is approximated by the 2-year recurrence interval flood peak (5,190 cfs) water-surface elevation which has a duration of about 1 day per year based on the mean daily flow-duration curve for the Gila River near Virden gage (Figure 4.8). A continuous terrace is located along the left (east) side of the river in the upper portion of the site, and the elevation is correlated with the 5-year recurrence interval flow (11,900 cfs) which has a duration of about 0.4 days per year. A higher elevation continuous terrace is present on the right (west) side of the river in the lower portion of the site, and it is correlated with the 10-year recurrence interval flow (18,000 cfs) which has a duration of less than 0.1 days per year. Both of the terraces were overtopped during the 2005 flood.

At the Virden Bridge site, the willows were generally restricted to the lower portion of the site on the channel banks in an elevation zone between baseflow and the water-surface elevation for a flow of about 5,190 cfs, which is the approximate 2-year recurrence interval flood peak with a duration of inundation of about 1 day per year. In the upper portion of the site, it appears as though the willows were removed by the 2005 flood. Willows were also observed on the terrace along the right bank, but this may be due to irrigation of the fields beyond the levee. Younger cottonwoods were in general located at an elevation that correlates with the lower terrace (11,900 cfs) with a duration of inundation of about 0.4 days per year, while the older cottonwoods were located on the higher terrace (18,000 cfs) that is inundated for less than 0.1 days per year.

7.6. Summary

At the five study sites on the Gila River, the willows are located primarily on the banks of the channel up to an elevation that correlates with the 1.5- to 2-year recurrence interval floods that have a duration of between 1 and 2 days per year. Younger cottonwoods tend to be located on floodplain and lower terrace surfaces that correlate with the 2- to 5-year recurrence interval floods that have a duration of inundation between 1 and 0.5 days per year. Older cottonwoods and sycamores tend to be located on terrace surfaces that correlate with the 10- to 20-year recurrence interval floods that have a duration of inundation of less than 0.1 days per year. Upland plant species also tend to be located on the higher terraces. Diversion of a maximum of 350 cfs is unlikely to have a significant effect on water surface elevations nor durations of inundation for any of the geomorphic surfaces.

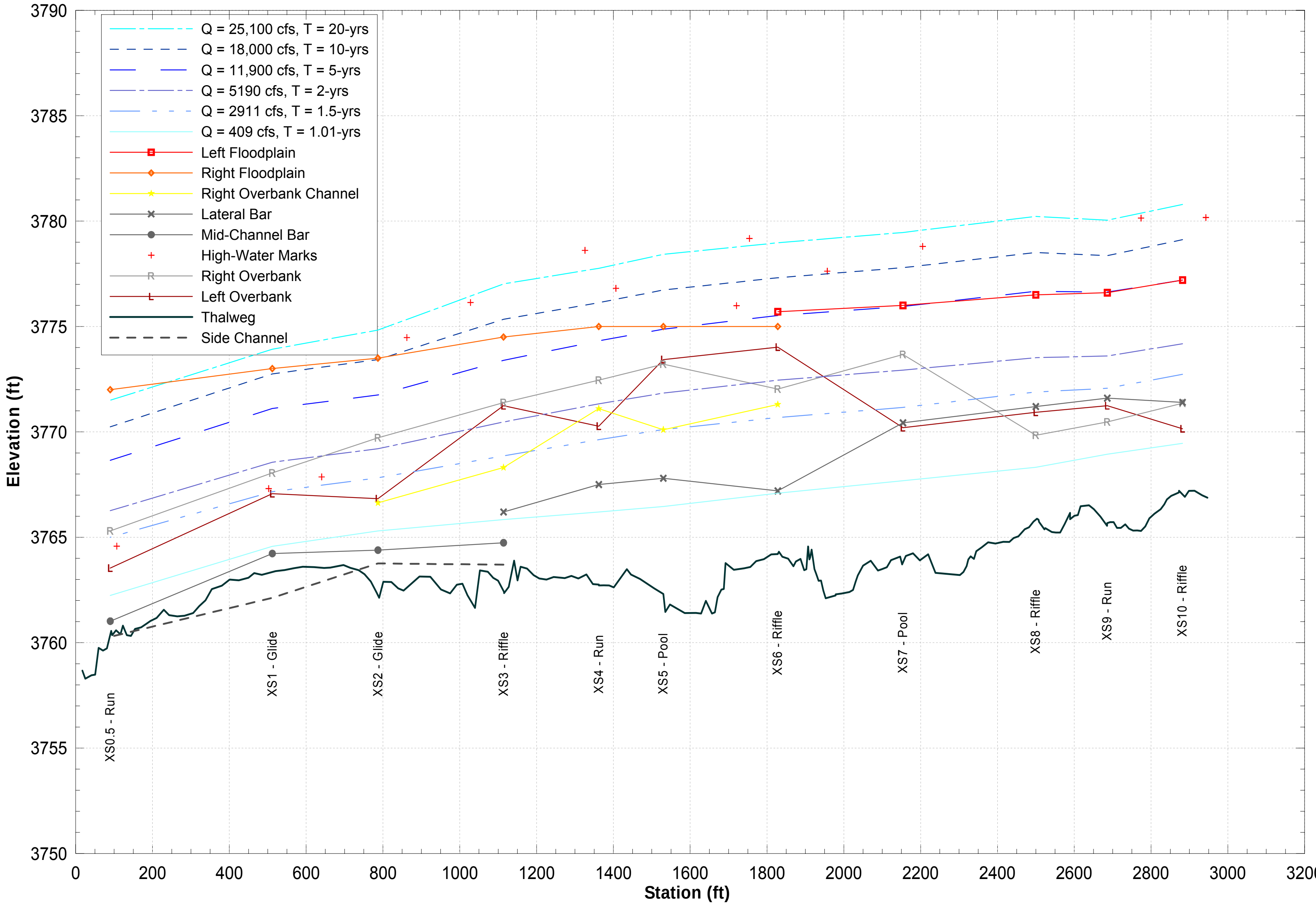


Figure 7.5. Thalweg, geomorphic surface and water-surface profiles for the Virden site.

8. SUMMARY AND CONCLUSIONS

This investigation of the Upper Gila River Basin in New Mexico was conducted by Mussetter Engineering, Inc. for the New Mexico Interstate Stream Commission to provide a basis for determining the geomorphic impacts on the Gila River, if any, due to annual diversion of up to 14,000 AF of additional water as a result of implementation of the Consumptive Use and Forbearance Agreement (CUFA) in the 2004 Arizona Water Settlement Act. Geomorphic changes to the Gila River have the potential to adversely affect the physical habitat for a number of species listed under the Endangered Species Act, primarily, spikedace, loach minnow and the southwest willow flycatcher.

8.1. Summary

The primary objectives of this investigation of the geomorphology, hydrology, hydraulics and sediment-transport characteristics of the Upper Gila River at five locations between the downstream boundary of the Gila Wilderness Area and the Arizona-New Mexico State Line (Figure 1.1) were to evaluate the existing dynamics of the river in the context of its dryland setting and then to identify the geomorphic impacts, if any, of two depletion scenarios (73- and 150-cfs bypass flows with a maximum diversion of 350 cfs) provided by the NMISC. An understanding of the geomorphological characteristics of the Gila River and their relation to the current flow regime provides a sound basis from which to evaluate potential changes to the physical system caused by additional flow diversions, and thus impacts on the habitats for the listed species.

8.1.1. Literature Review

An extensive review of the dryland rivers literature, as well as the literature specific to the Gila River within and downstream of New Mexico, was conducted to establish the geomorphologic context of the reach of interest between the downstream boundary of the Gila Wilderness Area and the New Mexico-Arizona State line (Chapter 2). In many ways, dryland rivers are very different from lower gradient, perennial flow, humid area rivers from which much of the geomorphic concepts regarding channel response to changes in hydrology and sediment supply were developed. Graf (1983b) has argued that dryland channels are not equilibrium forms, and that as a result, it is not possible to define a dominant discharge (Graf, 2002). Larger and more infrequent flows are more geomorphically effective (Baker, 1977) and dryland rivers often transport 60 percent of their sediment loads in 10-year or larger events (Neff, 1967). Compound or braided channels with poorly defined floodplains between bounding terraces make identification of bankfull capacity very difficult and large, infrequent floods tend to have a strong influence on channel geometry that in turn confines subsequent lower magnitude flows (Graf, 2002). Local tributary contribution of sediments causes great variation in the distribution of particle sizes that comprise the beds of dryland rivers (Rhoads, 1986). The documentation of Gila River response to infrequent, large floods of long duration, both within and downstream of New Mexico, supports the conclusion that dryland rivers are very susceptible to lateral erosion. In general, dryland channel change is dominated by widening that occurs during infrequent floods of long duration and by post-flood narrowing which occurs between the floods (Friedman and Lee, 2002).

8.1.2. Study Sites

Based on a reconnaissance investigation in December 2005, five sites that were considered to be representative of geomorphic conditions in the Upper Gila Basin, and that were also accessible, were selected for study (Figure 1.1, Chapter 3). The study sites, listed from upstream to downstream were:

6. Turkey Creek Site, located in the lower reaches of the Upper Box canyon, about 3 miles upstream of the Gila River near Gila USGS gage (No. 09430500),
7. Nature Conservancy Site (TNC), located in the Gila-Cliff Valley about 5 miles downstream of the Gila River near Gila USGS gage (No. 09430500),
8. Gila Bird Research Area (Birds) Site, located about 18 miles downstream of the Gila River near Gila USGS gage (No. 09430500) at the downstream end of the Gila-Cliff Valley,
9. Box Site, located at the downstream end of the Redrock Valley and immediately upstream of the Gila River below Blue Creek, near Virden USGS gage (No. 09432000), and
10. Virden Bridge Site, located immediately downstream of the NM Highway 92 Bridge in the Virden Valley.

The Turkey Creek site is a geologically-constrained site where the characteristics of the Gila River are forced by non-fluvial factors. Although extensive coarse and fine grained alluvial deposits are present throughout the site, the geomorphic characteristics of the site are primarily controlled by the locations of outcrops of hydrothermally altered volcanic bedrock that define the overall geometry of the bend in the canyon. Alluvial terraces, vegetated by large riparian (cottonwoods and sycamores) and upland (juniper) tree species are discontinuously present on both sides of the river. Tributaries deliver both coarse and fine sediment to the channel, and the coarser boulders transported by debris flows create coarse grained riffles and relatively deep pools in the channel. Between the bedrock and boulder-dominated reaches, the channel morphology is pool-riffle.

The TNC site is located within the Gila-Cliff alluvial valley downstream of the confluence with Mogollon Creek. A man-made levee that has been breached by historical flood flows farther upstream forms the left (east) boundary of the site, and the remains of a man-made levee that was breached and eroded upstream during the 2005 flood forms the right (west) boundary of the site. A channel avulsion during the 2005 flood led to the formation of a bifurcated channel at the head of the site. The east branch upstream of the site was the former channel of the Gila River, but currently the former channel location is occupied by a large pond, the origin of which is unclear. The west branch upstream of the site was formed by erosion during the 2005 flood and traverses an area of mature cottonwood trees. The location of the channel within the site did not change significantly during the 2005 flood, but there was erosion along the east bank, and mainly deposition along the west bank. The overall channel morphology at the site can be characterized as pool-riffle, with a portion of the reach, exhibiting less well-defined plane-bed morphology.

The Birds site is located towards the downstream end of the Gila-Cliff alluvial valley between the confluences of Moonfull Canyon on the west and Ira Canyon on the east side of the valley, and just upstream of the Middle Box canyon. Except for an outcrop of volcanic bedrock in the west valley wall at the upstream end of the site, the site is composed of alluvial sediments distributed in the channel, floodplain and bounding terraces. The channel morphology is primarily pool-riffle, but 2005 flood-related sediment deposition in the reach has created a number of finer-grained mid-channel bars that create relatively long pools at lower flows.

The Box site is located immediately upstream of the Lower Box canyon at the downstream end of the Redrock Valley. The site is composed of alluvial sediments located in channel, floodplain and terraces that have been deposited over time in response to the backwater created during floods by the bedrock contraction at the head of the Lower Box canyon. The basic channel morphology at the site is pool-riffle with the riffles being composed of cobble-boulder-sized materials. However, the pool-riffle spacing greatly exceeds the expected 5 to 7 times channel width norm (Leopold et al., 1964; Richards, 1982), primarily because the 2005 flood caused in excess of 3 feet of sand and fine gravel deposition within the channel and the deposition masks the normal-pool riffle spacing. At the time of the survey, the bed of the channel between the riffles was composed of migrating sand-wave mesoforms spaced at approximately one channel width intervals.

The Virden site is located immediately downstream of the New Mexico Highway 92 Bridge across the Gila River. The site is composed of alluvial sediments located in the channel, floodplain and bounding terraces. An alluvial fan and the hillslope form the east boundary of the site, and the west boundary is formed by a man-made levee that was built on a terrace. During the 2005 flood, there was some erosion of the west bank in the upstream part of the site, but the overall location of the channel within the site did not change. The basic channel morphology at the site is pool-riffle, but flow expansion and loss of sediment-transport capacity in the lower part of the site during the 2005 flood caused in-channel deposition of finer sand and gravels and a low-flow braided channel morphology.

8.1.3. Hydrology

Rains from fall and winter storm systems cause the major floods in the Gila River Basin (Bureau of Reclamation, 2004b). The rainfall events are caused by cold frontal systems colliding with warm, moist air or tropical storms. Extreme flood-producing storms are widespread and cover the majority of the Upper Gila River Basin. The largest floods are produced by rainfall or rain on snow events. Within the period of record, large floods (≥15,000 cfs) have occurred in water years 1941, 1979, 1984, 1985, 1995, 1997, and 2005 (Figure 4.1).

The hydrological characteristics of the Upper Gila River Basin (Chapter 4) were evaluated by analyzing the peak streamflow and mean daily flow records from the USGS Gila River mainstem gages (Gila River near Gila, Gila River at Redrock, Gila River below Blue Creek, Near Virden) and the peak streamflow flow records from the USGS gages on the major tributaries (Mogollon Creek Near Cliff, New Mexico, Duck Creek at Cliff, New Mexico, Mangas Creek Near Cliff, New Mexico) (Table 4.1). Flood-frequency curves were developed for all of the mainstem and tributary gages, and the 1- through 500-year recurrence interval flows for the individual gages are summarized in Tables 4.2 and 4.3, respectively. The 2-year recurrence interval flood increases from about 1,930 cfs at the upstream Gila River gage to about 5,190 cfs at the downstream gage. Similarly, 100-year recurrence interval flood increase from about 40,800 cfs at the upstream gage to about 45,700 cfs at the downstream gage. Based on the flood frequency curves, the 2005 flood event was about a 25-year recurrence interval flood. The flow-duration curves, developed from the mean daily flow record for the Gila River near Gila, Gila River near Redrock and Gila River near Virden gages, and for Mogollon Creek are shown on Figure 4.8. Summary statistics for the four gages are provided in Table 4.4. On the Gila River, 90 percent of the time, flows are equal to or exceed 38 cfs at the upstream gage and equal or exceed 22 cfs at the downstream gage as a result of existing flow diversions. Fifty percent of the time flows are equal to or exceed 74 cfs at the upstream gage and 90 cfs at the downstream gage due to flow accretion in the downstream direction. Similarly, the 10-percent exceedence flows increase from 302 cfs at the upstream gage to 431 cfs at the downstream gage.

For the purposes of evaluating the geomorphic impacts of CUFA diversions, the annual hydrographs for the Upper Gila River gages were sorted into three representative classes: dry, typical and wet. The basis for the classification was the number of days that bed material mobilization occurred in the year. Years with 0 days of bed-material mobilization were assigned to dry years. If there were between 1 and 4 days of bed-material mobilization the year was assigned to a typical class, and if the number of days of bed-material mobilization was five or more, the year was assigned to a wet class. Representative years for dry, typical and wet years are 1989, 1998 and 1993, respectively (Figures 4.9 through 4.11).

To evaluate the impacts of the diversions on sediment transport and thus the geomorphology of the river, annual hydrographs for the three representative year types with the two diversion scenarios applied were developed for the Gila River near Gila gage. For the representative dry year (1989), application of the two diversion scenarios results in diversion of 7,225 AF for the 73-cfs minimum bypass scenario, and 1,266 AF for the 150-cfs minimum bypass scenario (Figure 4.12). For the representative typical year (1998), application of the two diversion scenarios results in diversion of 12,946 AF for the 73-cfs minimum bypass scenario, and 22,037 AF for the 150-cfs minimum bypass scenario (Figure 4.13). For the representative wet year (1993), application of the two diversion scenarios results in diversion of 1,718 AF for the 73-cfs minimum bypass scenario, and 7,636 AF for the 150-cfs minimum bypass scenario (Figure 4.14). Annual hydrographs for the three representative year types with the same diversions applied were developed for the Gila River near Redrock gage (Figures 4.15 through 4.17) and the Gila River near Virden gage (Figures 4.18 through 4.20).

8.1.4. Hydraulics

Hydraulic models were developed for all of the sites to quantify the hydraulic characteristics (velocity, depth, water-surface elevation) for a range of flows (Chapter 5). Output from the hydraulic models was used to quantify the hydraulic parameters for in-channel habitat assessment purposes and to quantify sediment-transport processes at each site. Inundation frequency and duration for various channel margin features (floodplain and terraces) that provide riparian habitat were also assessed with the model output. The hydraulic analyses were conducted with the U.S. Army Corps of Engineers one-dimensional HEC-RAS step-backwater program, Version 3.1.3 (USACE, 2005). The models were calibrated to the flows at the time of the site topographic surveys in February 2006).

Reach-averaged hydraulic parameters were summarized for each of the sites in Tables 5.1 through 5.5. At the Turkey Creek site, for the 2-year flow (1,930 cfs), the average channel velocity is about 5 feet per second (fps), hydraulic depth is about 4 feet, and the channel top width is about 98 feet. At the TNC site, for the 2-year flow (1,930 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 2 feet, and the channel top width is about 191 feet. At the Birds site, for the 2-year flow (5,930 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 7 feet, and the channel top width is about 151 feet. At the Box site, for the 2-year flow (5,190 cfs), the average channel velocity is about 5 fps, hydraulic depth is about 7 feet, and the channel top width is about 108 feet, and at the Virden Bridge site, for the 2-year flow (5,190 cfs), the average channel velocity is about 6 fps, hydraulic depth is about 5 feet, and the channel top width is about 158 feet.

8.1.5. Sediment Transport

The HEC-RAS hydraulic model output for each site was also used to determine shear stresses for the range of modeled flows. Shear stress, in conjunction with the sediment gradations (Chapter 3), was used to evaluate the flows required to mobilize the coarse bed material at the Turkey Creek, TNC, Birds and Virden sites. Because of the sand bed at the Box site, no incipient-motion analysis was carried out. Output from the hydraulic models was also used to compute the volume of sediment transported on an annual basis for the period of record for the three Gila River gages for with- and without diversion conditions, and to determine the effective discharge at each site (Chapter 6).

Table 6.1 provides a summary of the shear stress-based incipient-motion and sediment-transport results for the four coarse-grained bed-material sites. The Turkey Creek site has a representative median (D_{50}) bed-material size of 49 mm, and D_{84} value of 101 mm, and critical discharges for bed mobilization and significant sediment transport of 2,500 and 4,000 cfs, respectively. The TNC site has representative D_{50} and D_{84} bed-material sizes of 61 and 111 mm, respectively, and critical discharges for bed mobilization and significant sediment transport of 1,300 and 3,500 cfs, respectively. The Birds site has representative D_{50} and D_{84} bed-material sizes of 47 and 85 mm, respectively, and critical discharges for bed mobilization and significant sediment transport of 2,500 and 5,500 cfs, respectively. The Virden Bridge site has representative D_{50} and D_{84} bed-material sizes of 57 and 100 mm, respectively, and critical discharges for bed mobilization and significant sediment transport of 1,200 and 3,000 cfs, respectively. On the basis of the results of the shear stress-based incipient-motion and significant sediment-transport computations flow diversions at flows less than critical for bed-material mobilization at each of the sites will have no geomorphic effect, since morphogenetic flows by definition must be able to mobilize the channel boundary sediments. Additionally, it can be argued that the diversion of flows above those required for significant sediment transport at each of the sites will have the most effect on geomorphic processes.

Effective discharge computations show that changes in the flow regime resulting from the proposed diversions will have an impact at the Box site where the bed material is composed of sand (Figure 6.9), and may increase the time required to return the channel bed to a gravel-cobble pool-riffle morphology. At the remainder of the sites, where the bed materials are coarser, the effective discharge is, as expected, skewed towards the higher magnitude, less frequent flows, and will therefore, only be affected if there are significant diversions at the higher flows (Figures 6.6, 6.7, 6.8, 6.10). Based on the diversion estimates provided by NMISC, the maximum diversion is estimated to be 350 cfs, and therefore, unless the diversions occur in the range of the incipient-motion and significant sediment-transport thresholds, there should be no significant geomorphic impacts.

The annual frequency of bed-material mobilization at the TNC site for the period of record at the Gila River near Gila gage was used to classify each year within the record into either, inactive (0 days of bed-material mobilization), average (1 to 4 days of bed-material mobilization) and active (5 or more days of bed-material mobilization). The sediment-transport computations (Table 6.2) show that the largest impacts of flow diversion will occur in the average year type (about 25 percent of the years) when flow diversions can have an effect on the sediment mobilization thresholds. In the inactive year type (about 50 percent of the years) there is little possibility of a significant geomorphic impact from diversion of the flows. In the active year type (about 25 percent of the years), the impact of diversions is minimized because of the relative size of the maximum diversion rate (350 cfs) to the river flows. As shown by the review of the published literature (Chapter 2), most of the sediment transport, and hence geomorphic change, occurs during large, infrequent floods, when it is unlikely that diversions will be occurring.

8.1.6. Inundation Frequency and Duration

The capacity of the channel governs the frequency and duration of inundation of the channel margin areas that support the riparian vegetation community along the Gila River. The channel in dryland rivers tends to be compound and can convey a range of flows from baseflow to large floods, in-bank (Graf, 1988; Harvey and Mussetter, 2005). Floodplains are poorly defined between bounding un-paired terraces, and large, infrequent floods tend to have a strong influence on channel geometry that in turn confines subsequent lower magnitude flows (Graf, 1988). Therefore, as expected, delineation of contiguous channel margin surfaces that support the riparian community along the study sites on the Gila River was difficult, and required a measure of interpretation at each of the sites.

At the five study sites, the willows are located primarily on the banks of the channel up to an elevation that correlates with the 1.5- to 2-year recurrence interval floods that have a duration of between 1 and 2 days per year. Younger cottonwoods tend to be located on floodplain and lower terrace surfaces that correlate with the 2- to 5-year recurrence interval floods that have a duration of inundation between 1 and 0.5 days per year. Older cottonwoods and sycamores tend to be located on terrace surfaces that correlate with the 10- to 20-year recurrence interval floods that have a duration of inundation of less than 0.1 days per year. Upland plant species also tend to be located on the higher terraces. Diversion of a maximum of 350 cfs is unlikely to have a significant effect on water-surface elevations nor on durations of inundation for any of the geomorphic surfaces.

8.2. Conclusions

Based on the results of the analyses that were conducted in this investigation of the geomorphic characteristics and dynamics of the five representative sites in the Upper Gila River Basin, the following can be concluded:

9. The primary determinant of the channel morphology in the alluvial reaches of the upper Gila River is the occurrence of infrequent, large magnitude floods (≥15,000 cfs) of long duration (1941, 1979, 1984, 1985, 1995, 1997, and 2005) that cause lateral erosion and widening of the channel. Between large floods, channel narrowing occurs. Man-made features such as diversions, bank protection and levees have local effects only.

10. On the basis of the annual frequency of bed-material mobilization, the hydrologic record in the upper Gila Basin can be divided into dry, typical and wet years, with representative years being, 1989, 1998 and 1993, respectively. Dry (inactive) years occur about 50 percent of the time, and typical (average) and wet (active) years each occur about 25 percent of the time.

11. Sediment-transport computations show that the greatest impacts of the flow diversions will occur in the typical or average year types, when flow diversions can have an impact on sediment mobilization thresholds.

12. Bed-material mobilization thresholds for the Turkey Creek, TNC, Birds and Virden Bridge sites, where the bed materials are composed of gravels and cobbles, are 2,500, 1,300, 2,500, and 1,200 cfs, respectively. Diversion of flows below these threshold values will have no geomorphic impacts.

13. Effective discharge calculations for all the sites except the Box site show that the maximum diversion rate of 350 cfs is unlikely to have a significant effect on sediment transport volumes during infrequent flows when the bulk of the sediment is being transported.

14. The effective discharge calculations show that diversion of flows is likely to increase the time it takes for the sand-bed Box site to recover to gravel-cobble bed material and an associated pool-riffle morphology.

15. Although the morphological characteristics of the upper Gila River sites are very complex, hydro-geo-botanical correlations can be made. Willows are located primarily on the banks of the channel up to an elevation that correlates with the 1.5- to 2-year recurrence interval floods that have durations of between 1 and 2 days per year. Younger cottonwoods tend to be located on floodplain and lower terrace surfaces that correlate with the 2- to 5-year recurrence interval floods that have durations of inundation between 1 and 0.5 days per year. Older cottonwoods and sycamores tend to be located on terrace surfaces that correlate with the 10- to 20-year recurrence interval floods that have durations of inundation of less than 0.1 days per year.

16. Diversion of a maximum of 350 cfs is unlikely to have a significant effect on water-surface elevations nor durations of inundation for any of the geomorphic surfaces.

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APPENDIX A
Site Photographs

Figure A.1. View upstream of Gila River at Turkey Creek site showing bedrock control of the site, overbank chute channels and terraces supporting the larger cottonwoods.

Figure A.2. View upstream of Gila River at Turkey Creek site showing bedrock control, boulder riffle and recent debris fan at mouth of Brock Canyon.

Figure A.3. View downstream of contraction of Gila River caused by recent debris flows in Brock Canyon. Note ponding upstream of the contraction.

Figure A.4. Large boulders delivered to the Gila River by debris flows in Brock Canyon. Boulder lag deposits form coarse grained riffles in the channel of the Gila River.

Figure A.5. View downstream of Gila River at Turkey Creek site showing typical pool-riffle morphology. The boulders in the riffle are derived from the local tributaries.

Figure A.6. View upstream of Gila River at Turkey Creek site showing a deep pool located upstream of a cobble-gravel riffle.

Figure A.7. Surface sediments on the Brock Canyon debris fan (D_{50}=44 mm) that were delivered to the Gila River in 2005.

Figure A.8. Close up view of gravels and cobbles that comprise the riffle at Cross Section 4 at the Turkey Creek site at WC 2 (D_{50} = 80 mm).

Figure A.9. View downstream of gravel bar deposited in the 2005 flood in the vicinity of Cross Section 7 at the Turkey Creek site. The surface gradation was determined by WC 3 (D_{50} = 36 mm).

Figure A.10. Subsurface sediments on the Brock Canyon fan at the Turkey Creek site. The D_{50} is 5.2 mm and the sand content is about 35 percent.

Figure A.11. View upstream of the Gila River at the TNC site showing the split flow at the head of the reach caused by the 2005 flood.

Figure A.12. View upstream of the channel formed as a result of a channel avulsion during the 2005 flood at the TNC site. Note the large number of cottonwood trees in the channel due to channel erosion.

Figure A.13. View downstream of the TNC site showing erosion of the left bank and deposition of the right bank that occurred in the 2005 flood.

Figure A.14. View downstream of the Gila River at the TNC site showing the pool-riffle channel morphology.

Figure A.15. View upstream of the Gila River showing the wide channel section in the middle of the TNC site where widening occurred during the 2005 flood and the consequent plane-bed morphology.

Figure A.16. View upstream of bank-attached bar on the right bank of the Gila River at the TNC site that was formed in the 2005 flood. The location of sample TNC 2 is at the two sample bags.

Figure A.17. Close up view of sediments (TNC 2) that form the bank-attached bar between Cross Sections 5 and 6 at the TNC site (D_{50} = 6.4 mm).

Figure A.18. View downstream of the Gila River at the Birds site showing the pool-rifle morphology of the site.

Figure A.19. View upstream of mid-channel bars and braided channel morphology in the lower portion of the Birds site. Bars were deposited during the 2005 flood.

Figure A.20. View upstream of long pool formed upstream of the mid-channel bars in the lower reach of the Birds site.

Figure A.21. View upstream of overbank channels scoured during the 2005 flood at the Birds site.

Figure A.22. View downstream of dense willow growth along both banks of the Gila River at the Birds site.

Figure A.23. Close up view of mid-channel bar sample S2 at Cross Section 3 at the Birds site. The D_{50} is 4 mm and the sand content is about 45 percent.

Figure A.24. View downstream of bank-attached bar at Cross Section 5 at the Birds site. The D_{50} of the surface sediments is 47 mm (WC3).

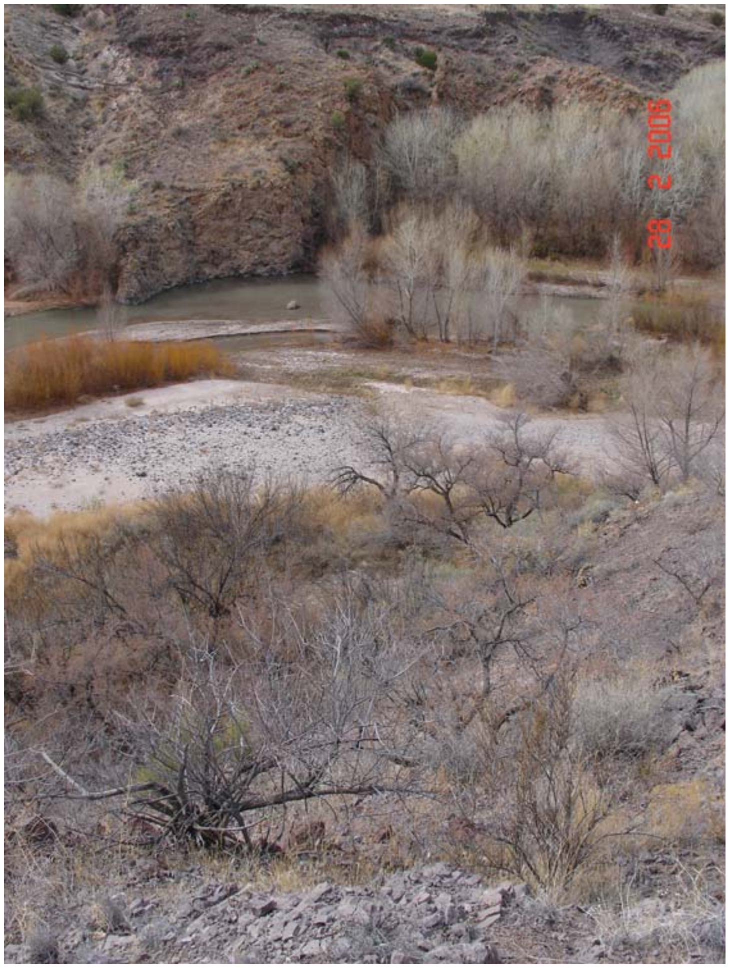


Figure A.25. View west of bedrock contraction at the downstream end of the Box site, which is the upstream end of the Lower Box canyon reach.

Figure A.26. View upstream of the Box site showing the 2005 flood overbank flow paths as well as the location of the perennial channel in the center of the photograph that is bounded by the dense willow growth.

Figure A.27. View upstream of the Gila River in the Box site at a flow of 60 cfs. Note the very dense willow growth on both banks. At the time of the field survey the bed of the river was sand.

Figure A.28. View downstream of the boulder riffle at Cross Section 6 at the Box Site. The D_{50} of the riffle sediments is 157 mm. Note the sand deposits in the riffle amongst the boulders.

Figure A.29. Close up view of sand bed material at Cross Section 1 at the Box site. The D_{50} is 1 mm and the sand content is about 70 percent.

Figure A.30. View downstream from the Highway 92 Bridge of the Gila River at the Virden site. Channel is bounded by floodplain and terraces.

Figure A.31. View downstream of the Gila River at the Virden site showing the hillslope that forms the left bank in the lower part of the reach and a mid-channel bar formed in the 2005 flood.

Figure A.32. View downstream of the Gila River at the Virden site showing bank erosion and an overbank flow path during the 2005 flood.

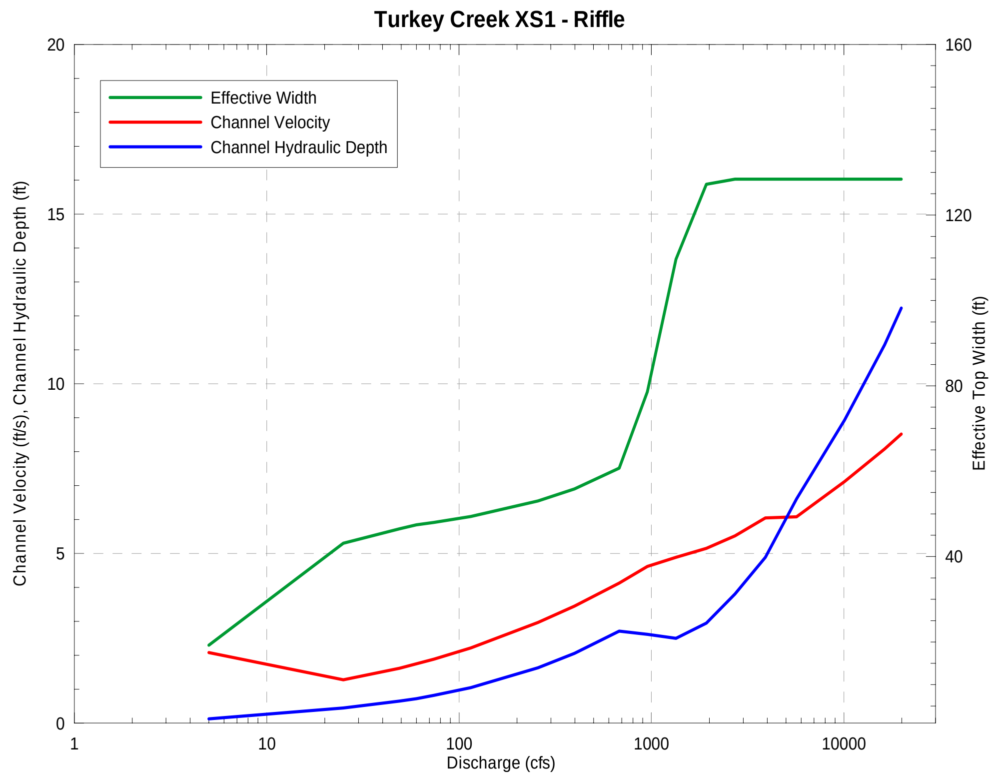
Figure A.33. View upstream of the Gila River at the Virden site showing the pool-riffle morphology of the channel.

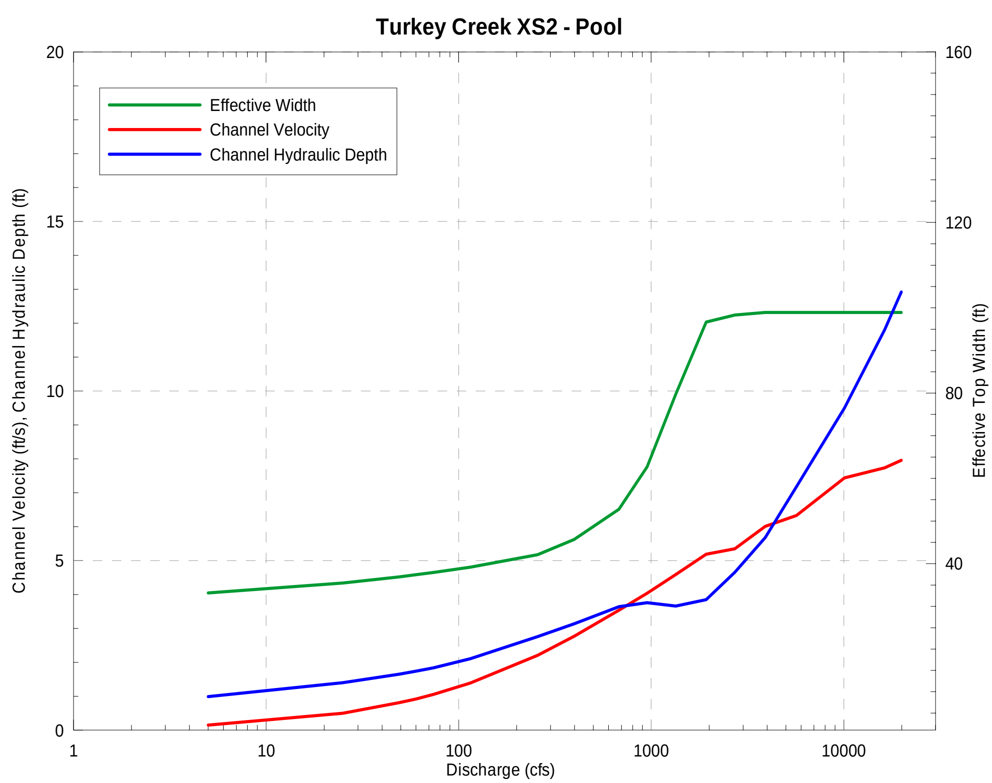
Figure A.34. Close up view of sediments deposited in the mid-channel bar at Cross Section 4 (V1) at the Virden site. The D_{50} is 1 mm and the sand content is about 55 percent.

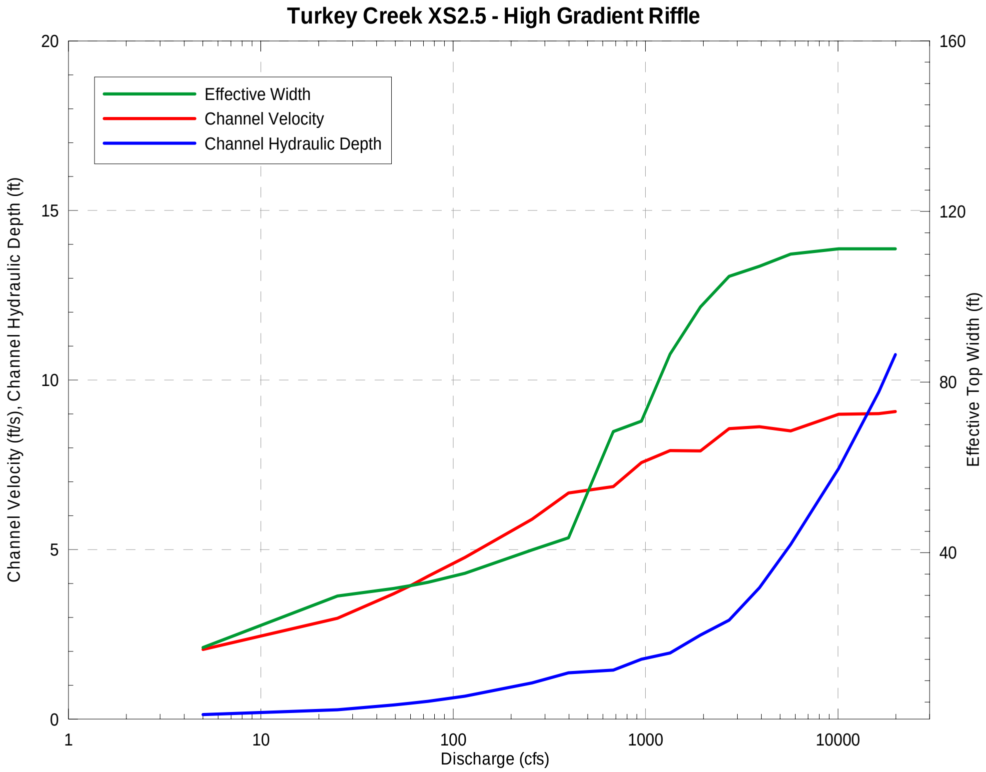
Figure A.35. Close up view of the bank-attached bar sediments (V2) at Cross Section 8 at the Virden site. The D_{50} is 4 mm and the sand content is about 33 percent.

APPENDIX B

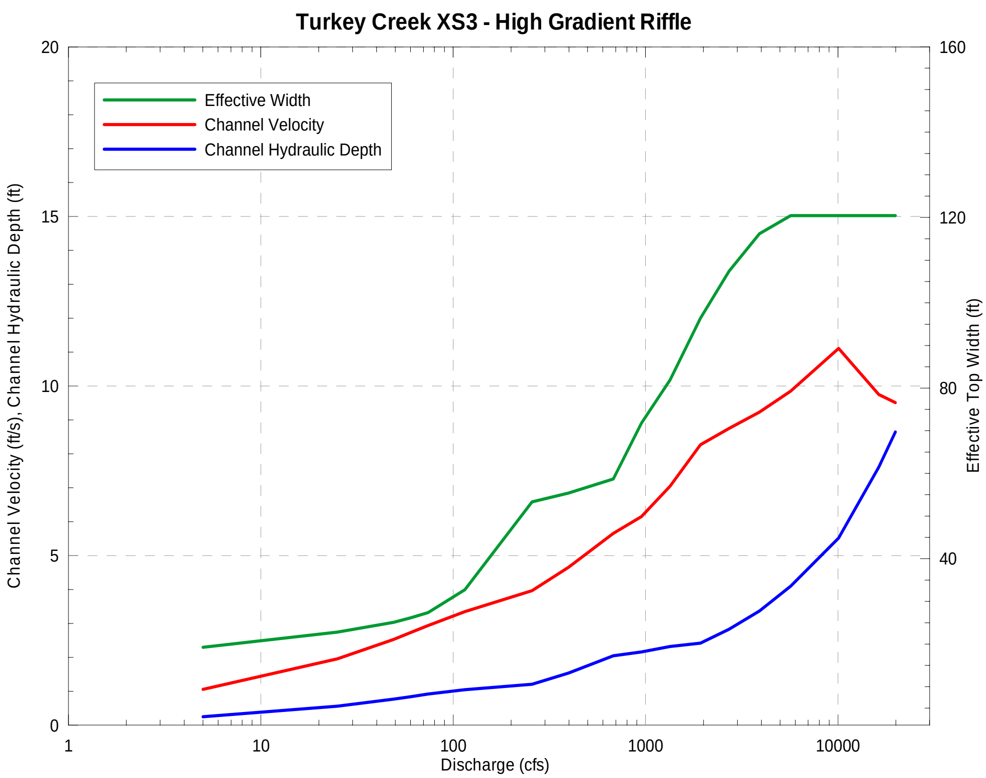
Hydraulic Rating Curves for Individual Cross Sections at the Turkey Creek, TNC, Birds, Box, and Virden Sites


Turkey Creek XS1 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000

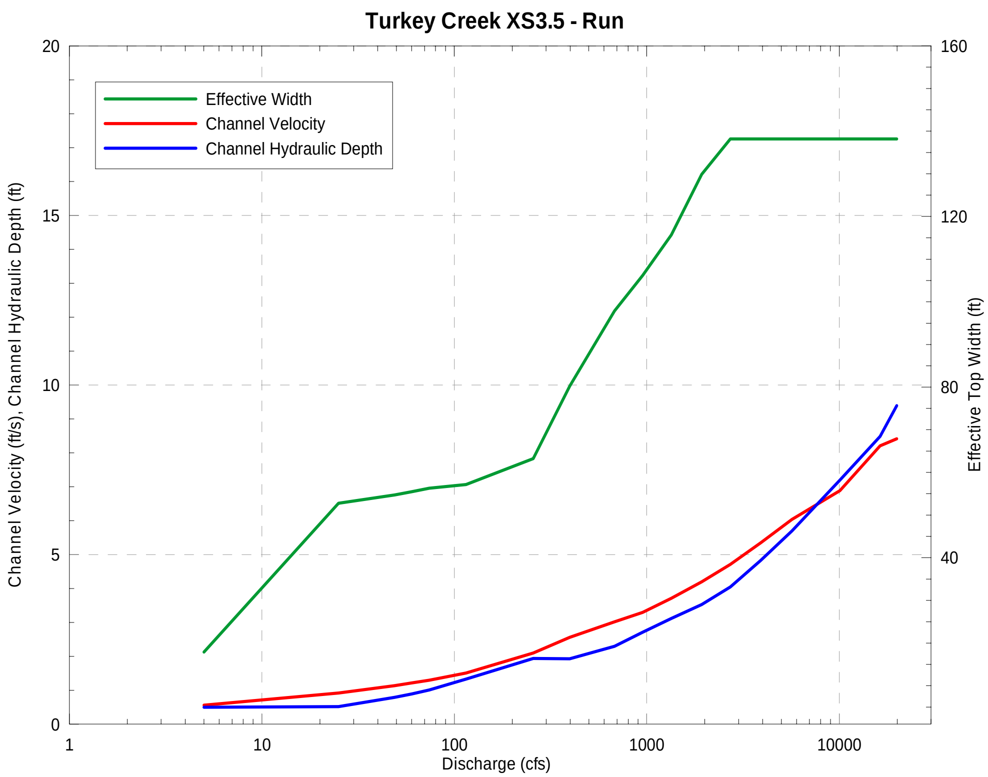

Turkey Creek XS2 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000



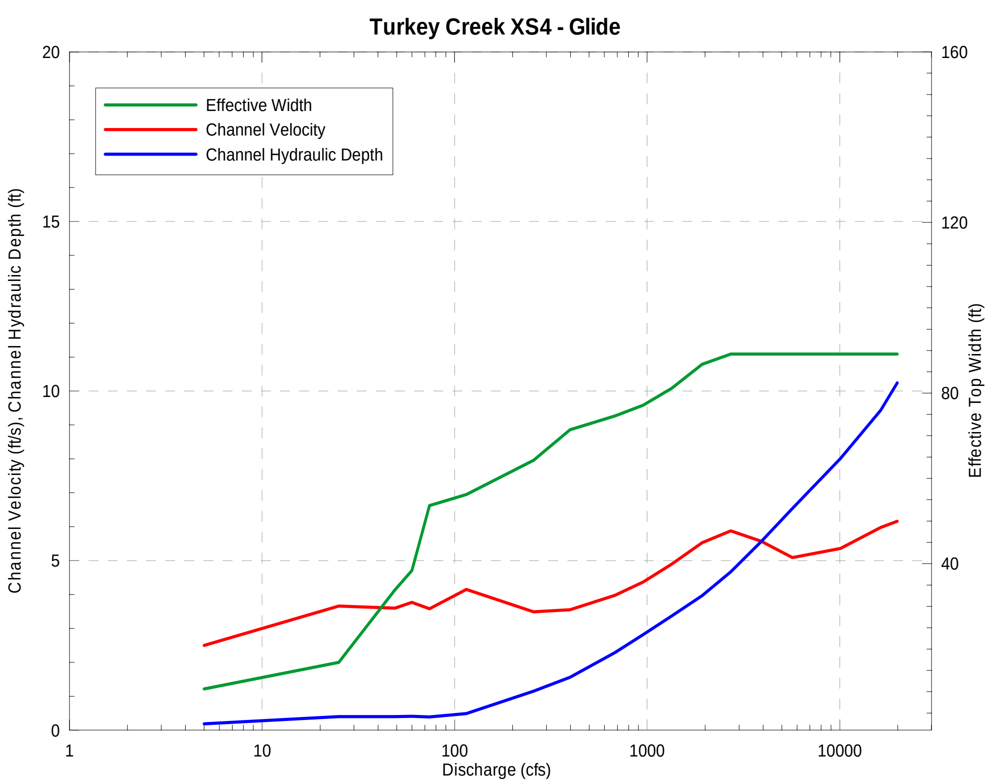
Turkey Creek XS2.5 - High Gradient Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000



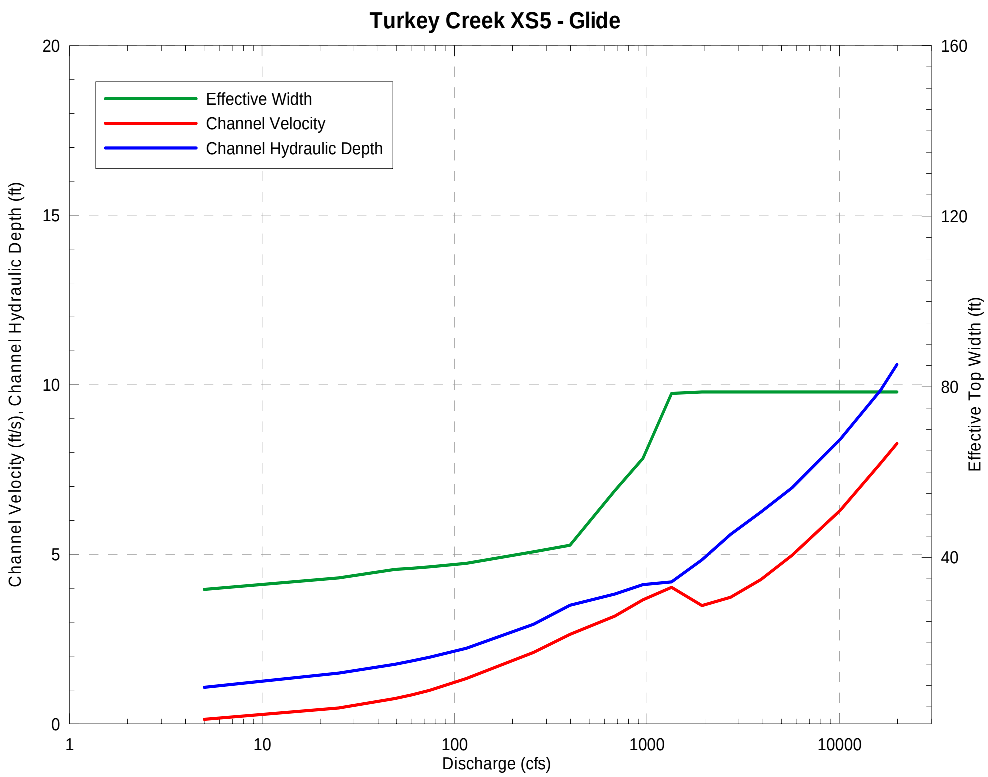
Turkey Creek XS3 - High Gradient Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000

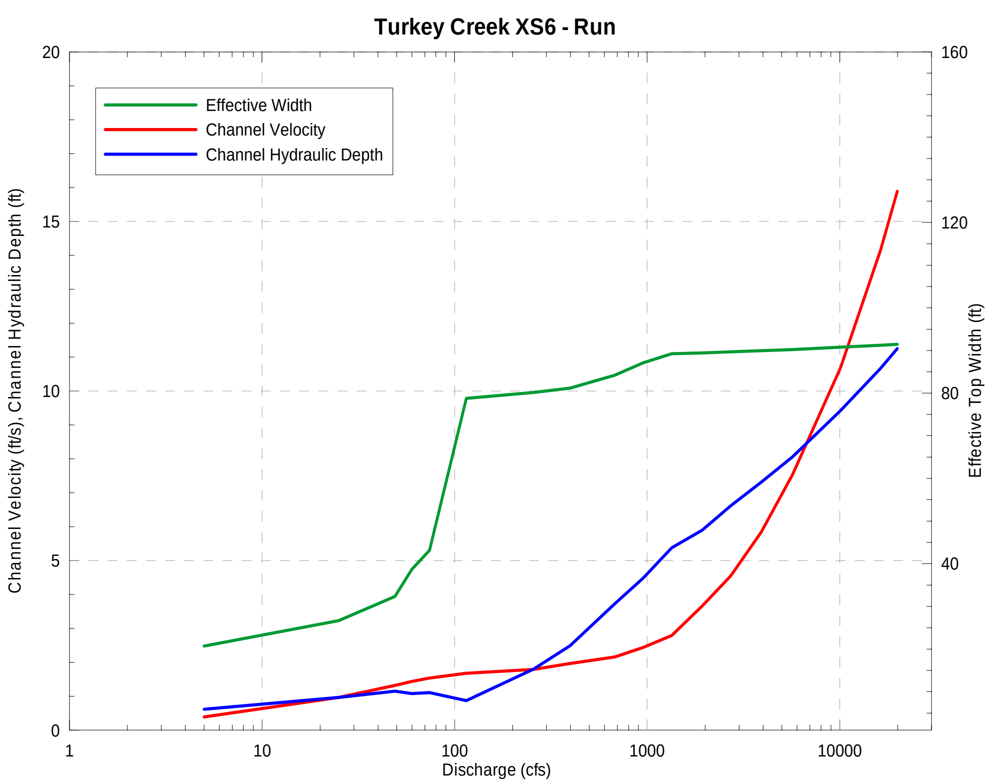


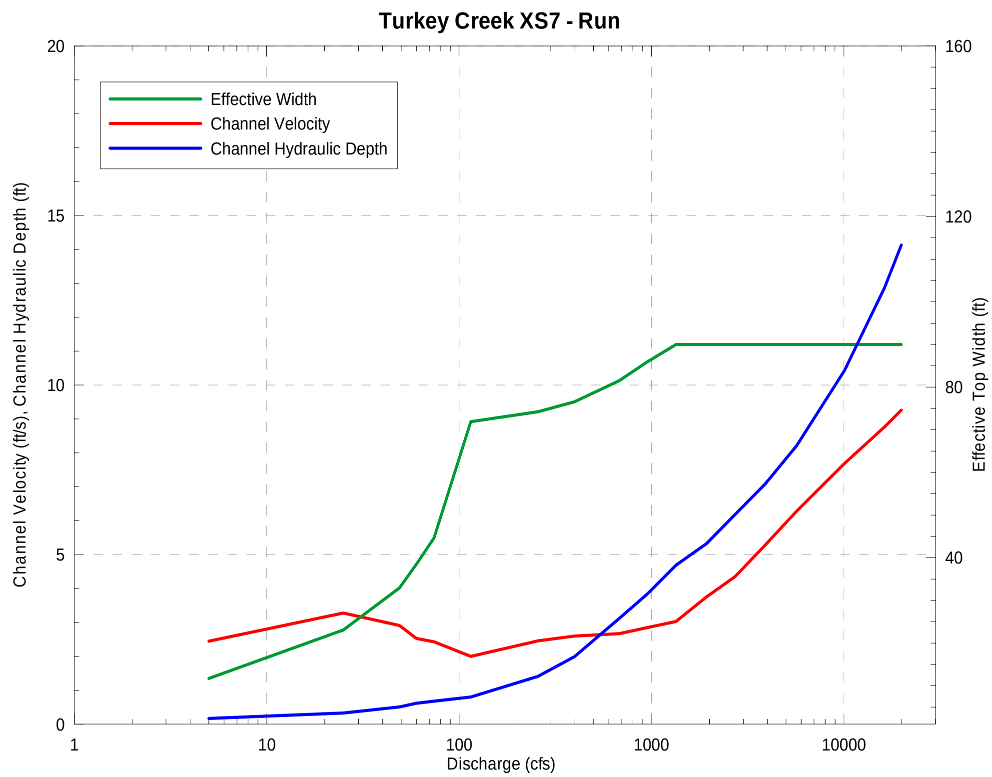
Turkey Creek XS3.5 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000

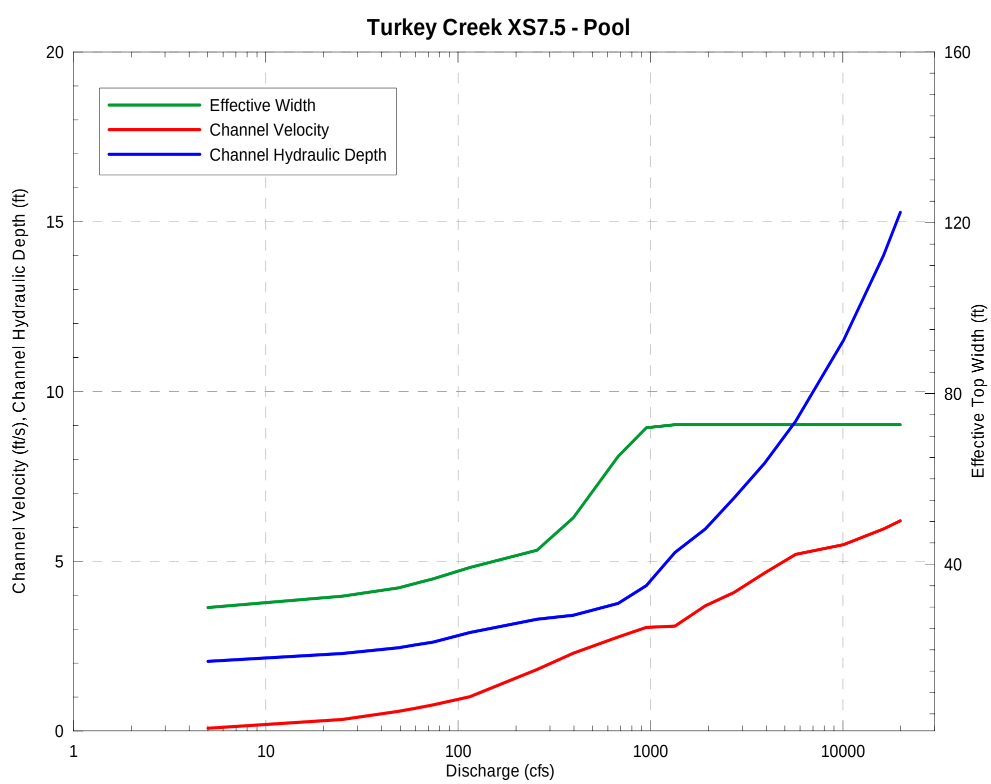


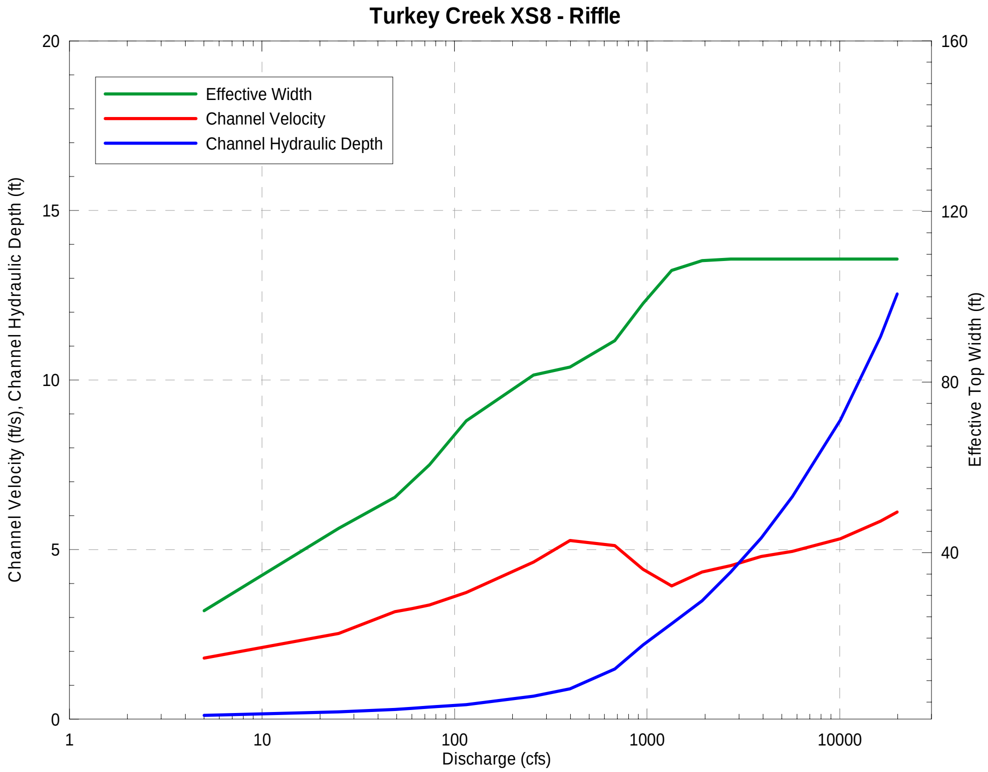
Turkey Creek XS4 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000

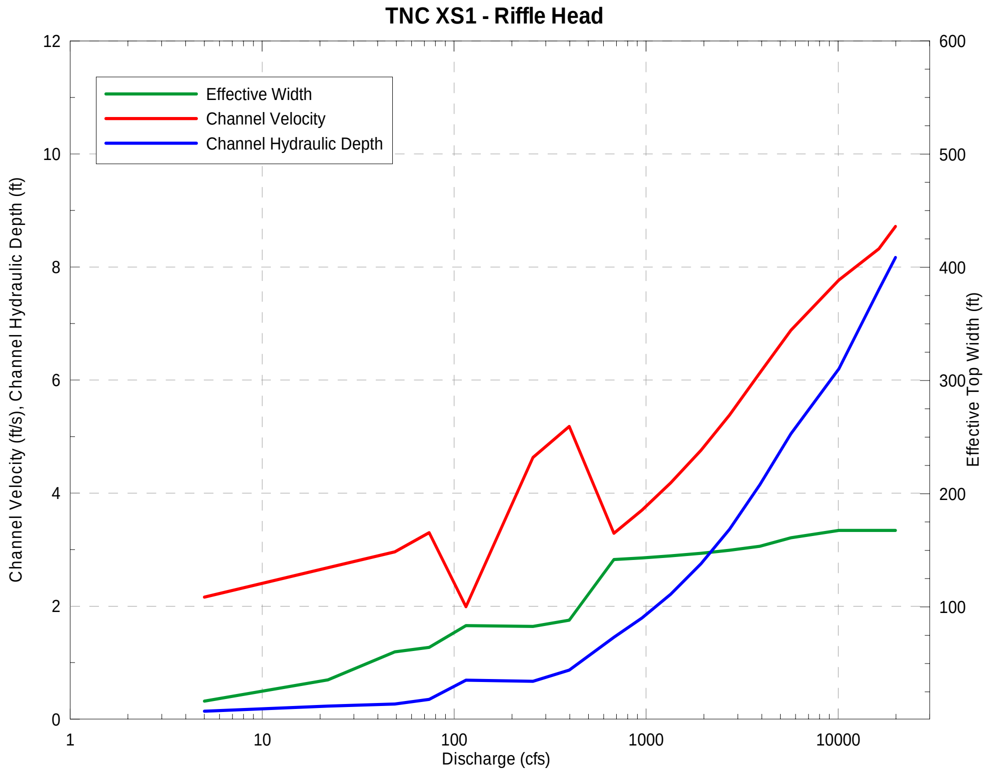

Turkey Creek XS5 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000


Turkey Creek XS6 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
5
10
15
20
40
80
120
160
1
10
100
1000
10000


Turkey Creek XS7 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
20
15
10
5
0
160
120
80
40
1
10
100
1000
10000


Turkey Creek XS7.5 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
20
15
10
5
0
160
120
80
40
1
10
100
1000
10000


Turkey Creek XS8 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
20
15
10
5
0
160
120
80
40
1
10
100
1000
10000


TNC XS1 - Riffle Head
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
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4
6
8
10
12
100
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400
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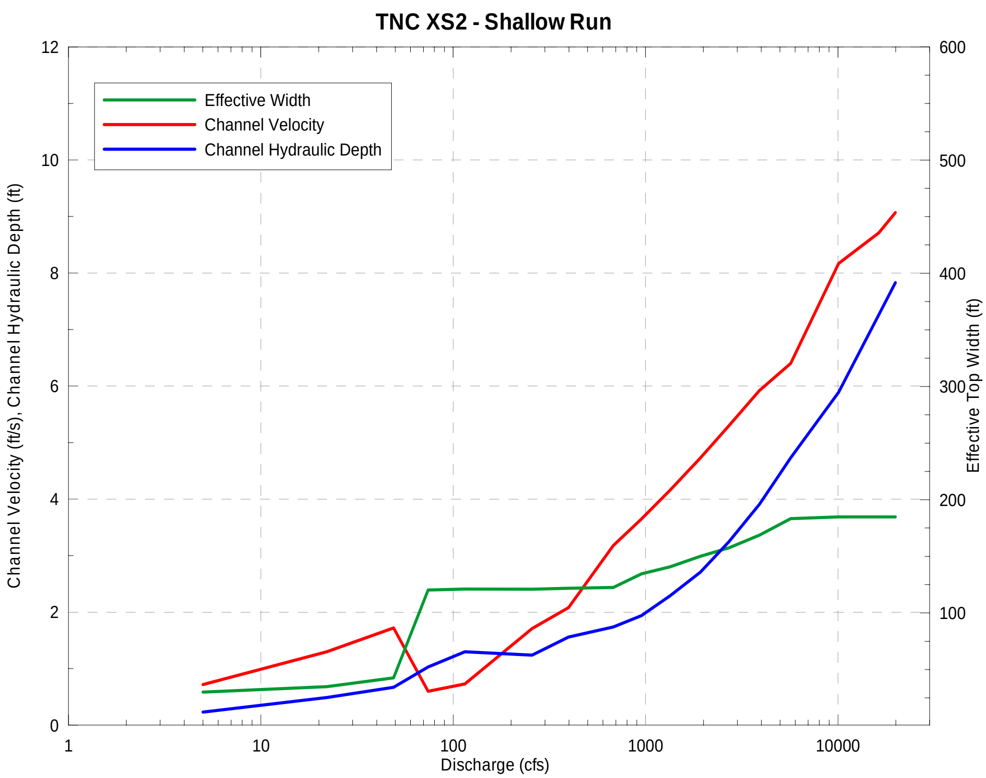
1
10
100
1000
10000


TNC XS2 - Shallow Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
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12
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1000
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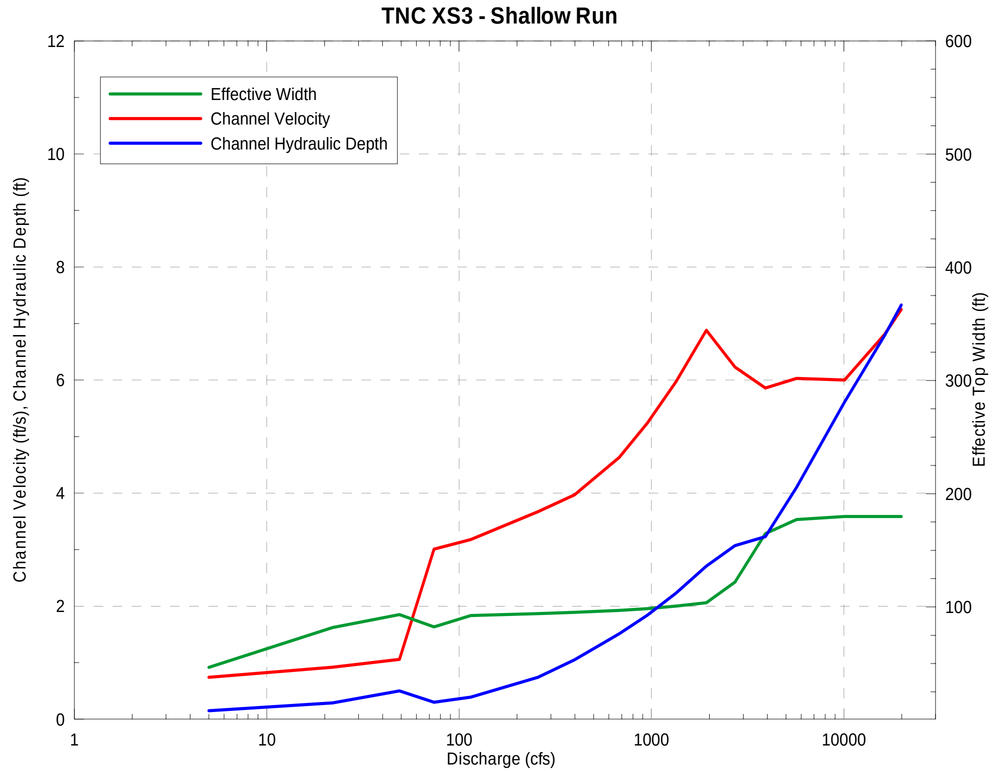
TNC XS3 - Shallow Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
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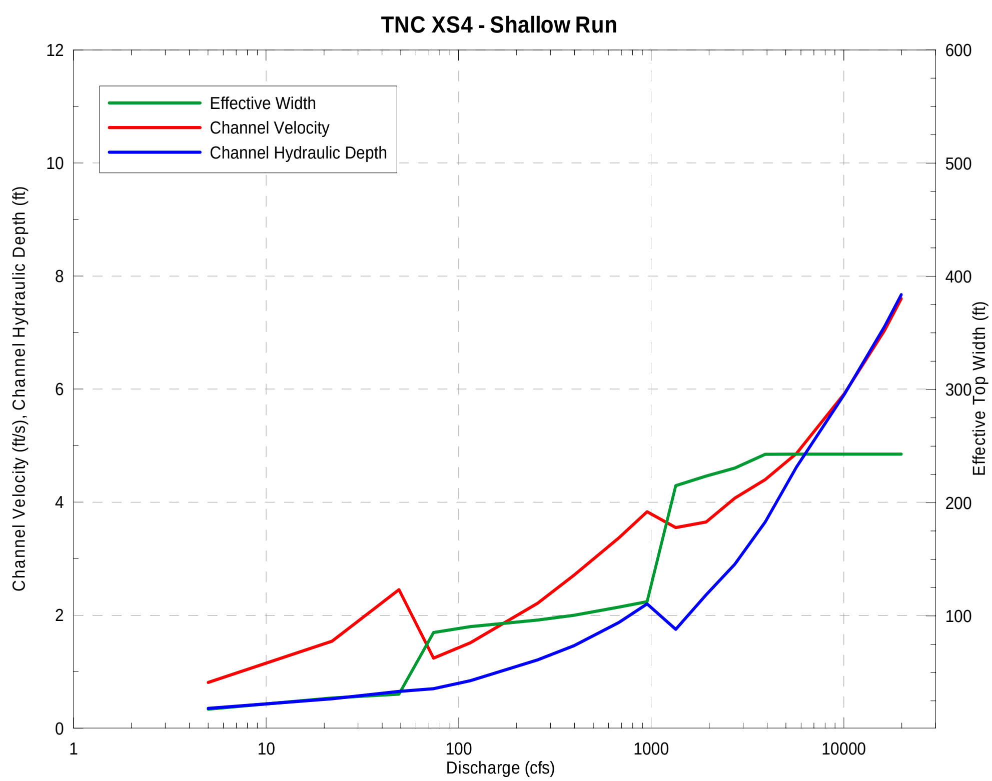
TNC XS4 - Shallow Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
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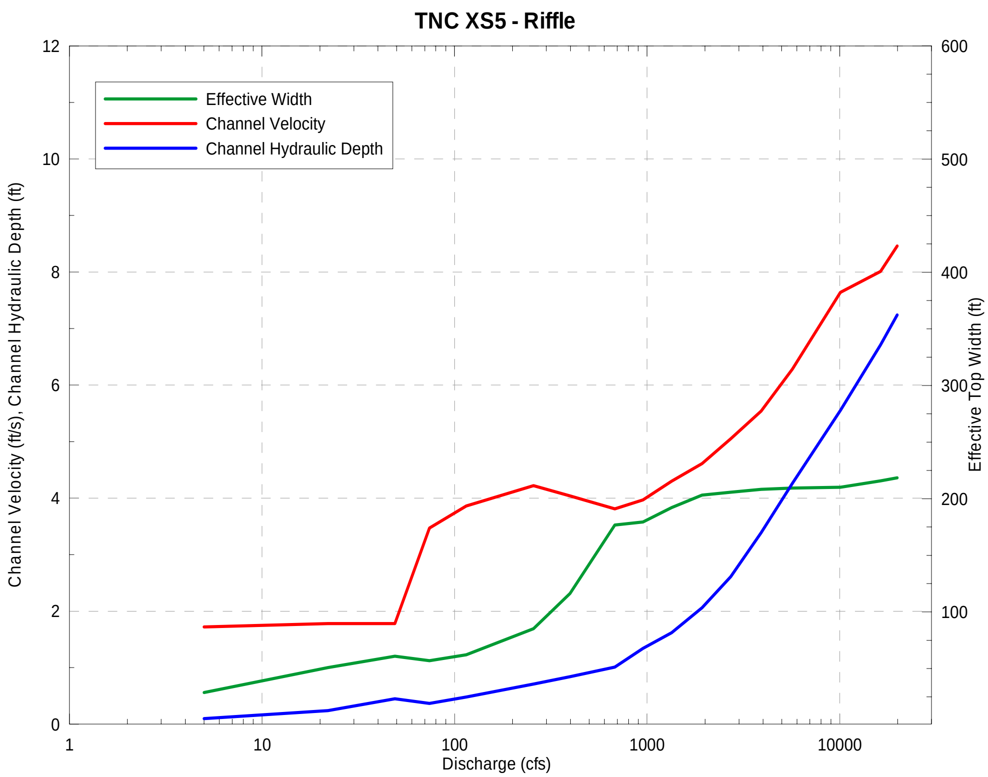
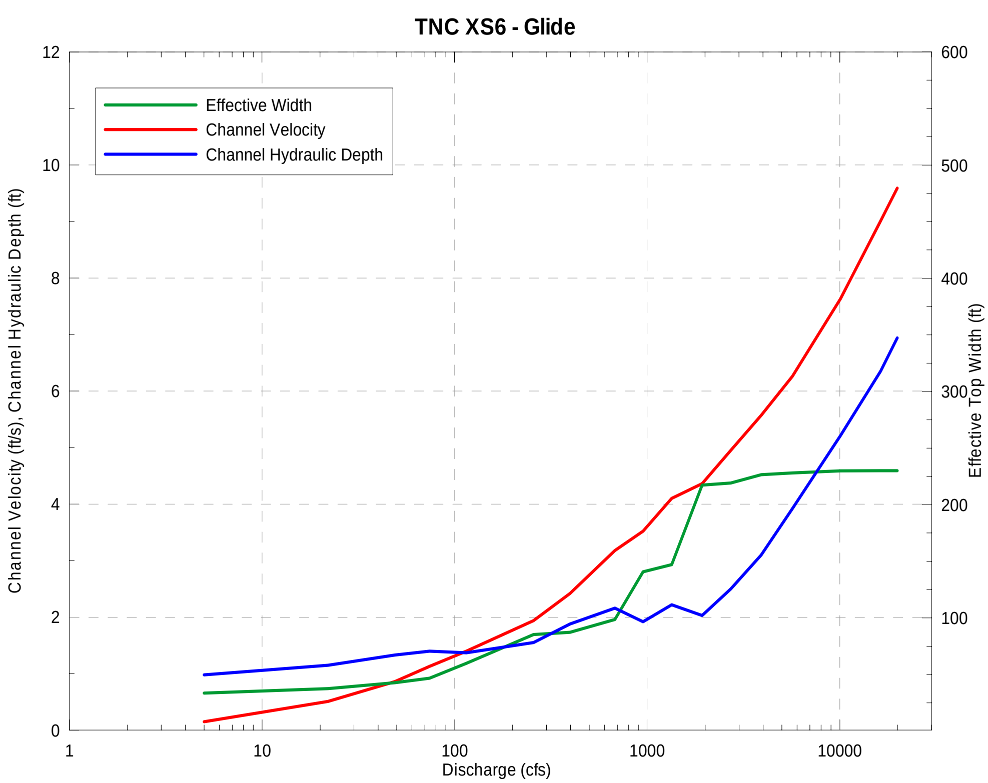
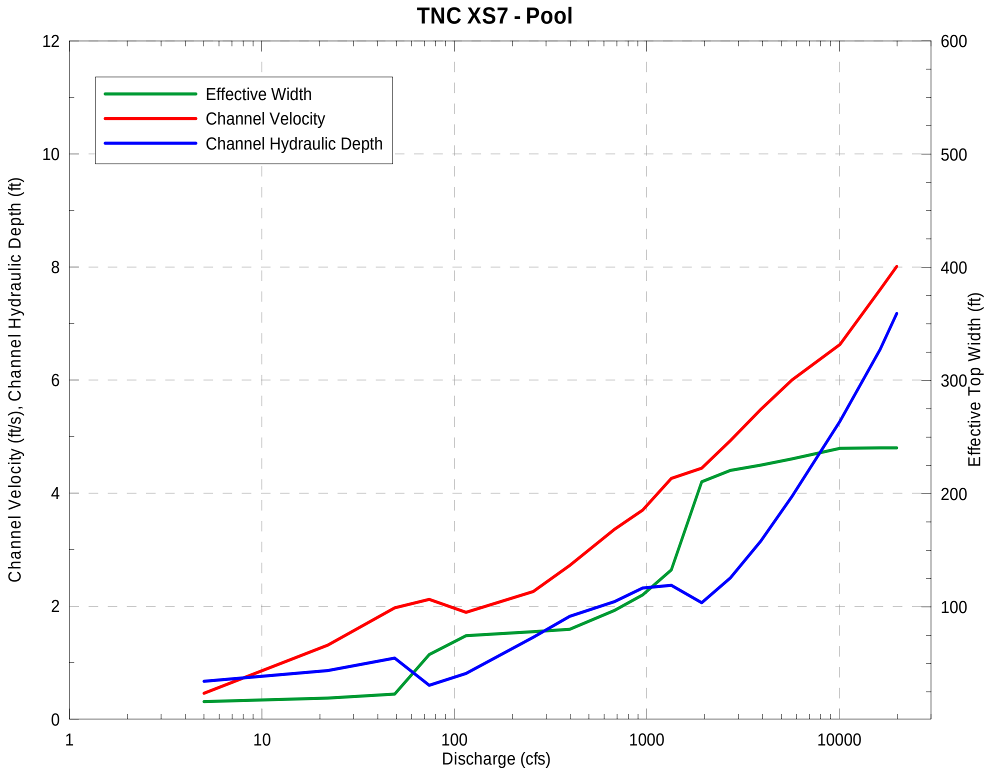
1000
10000

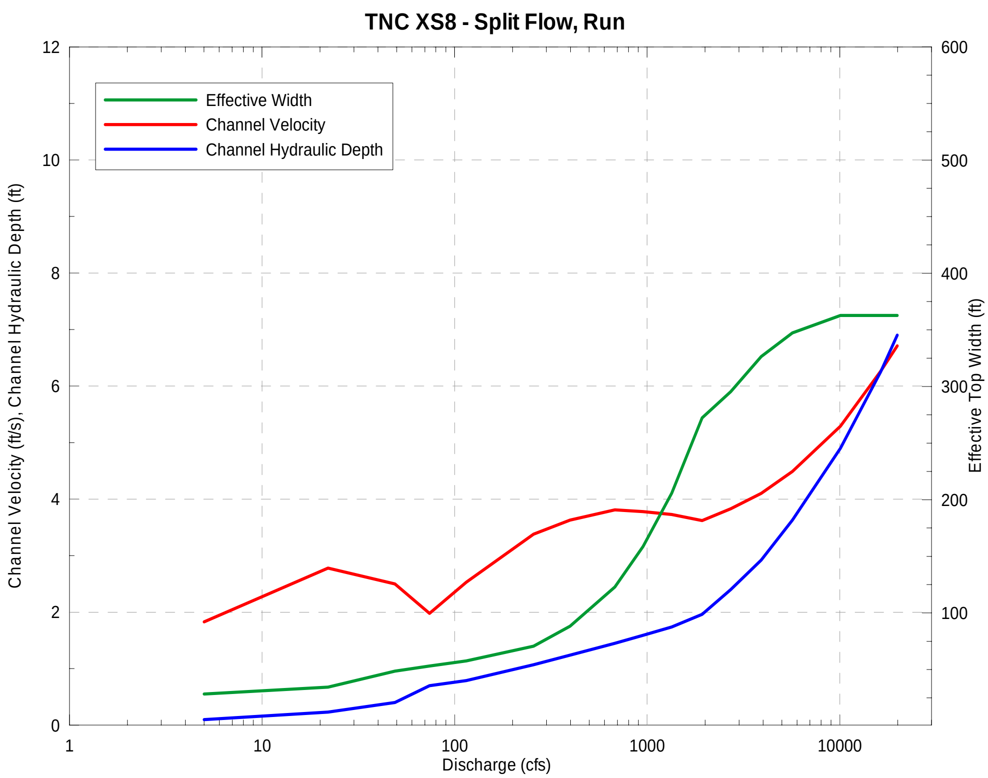


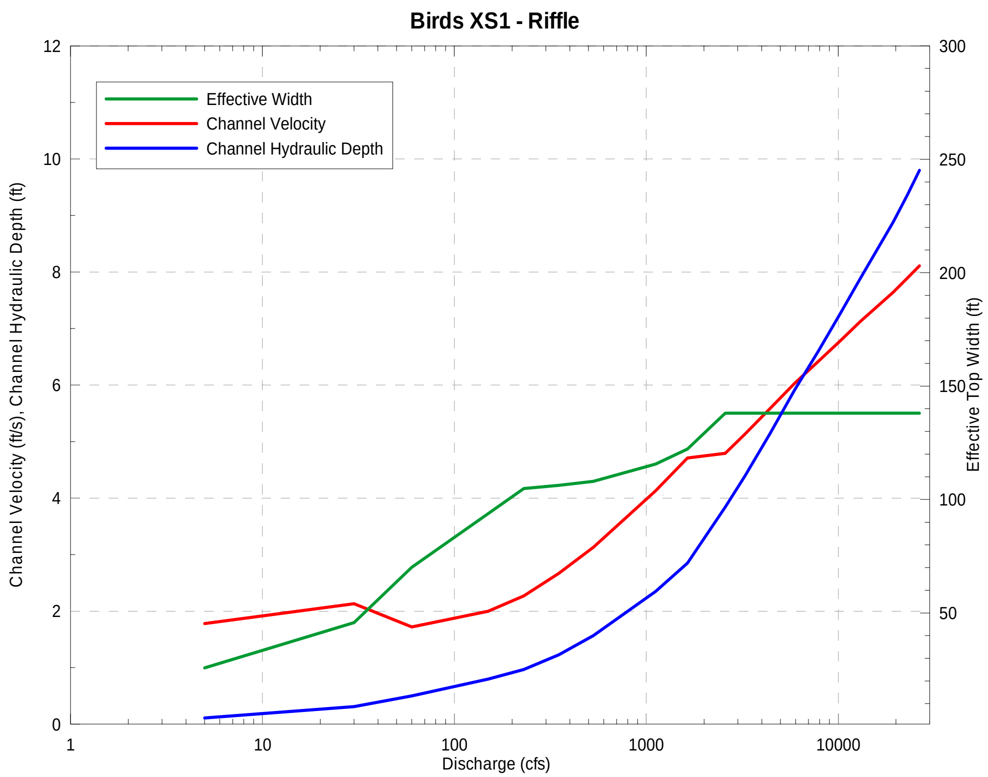
TNC XS5 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
100
200
300
400
500
600
1
10
100
1000
10000

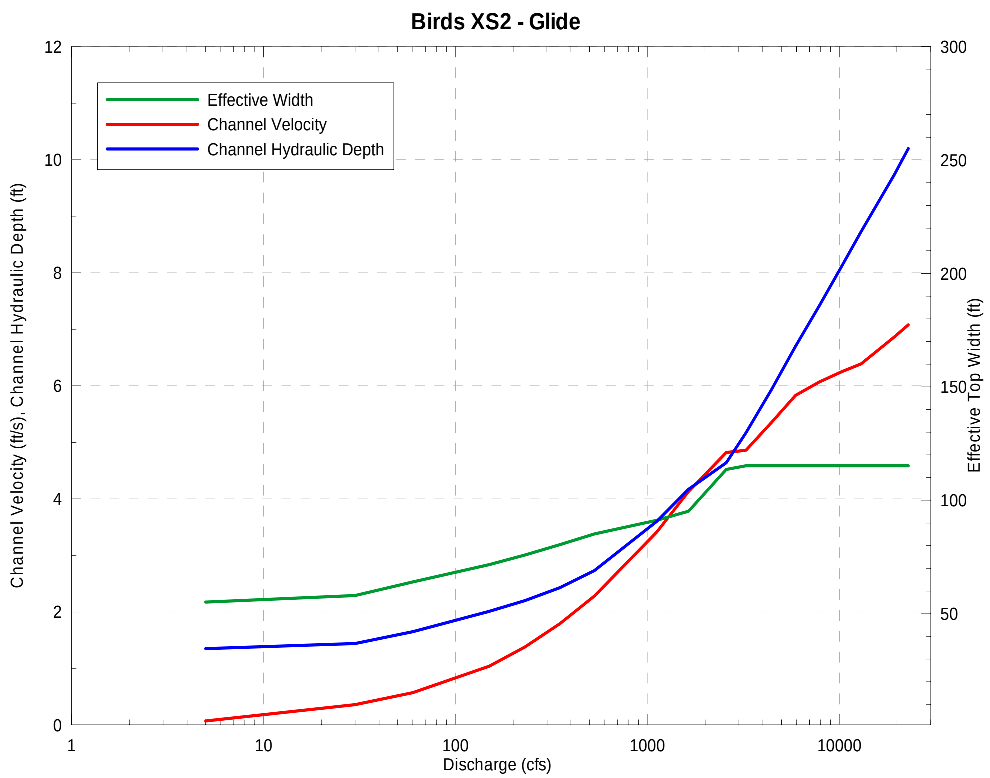


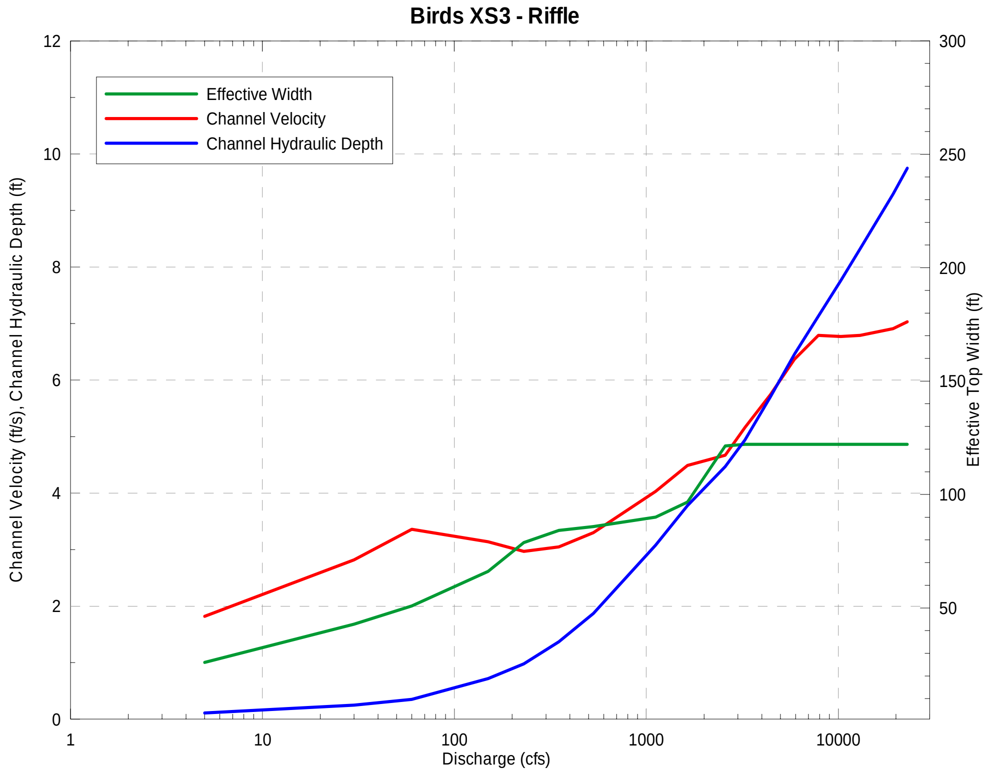
TNC XS6 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
100
200
300
400
500
600
1
10
100
1000
10000


TNC XS7 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
100
200
300
400
500
600
1
10
100
1000
10000


TNC XS8 - Split Flow, Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
100
200
300
400
500
600
1
10
100
1000
10000


Birds XS1 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
50
100
150
200
250
300
1
10
100
1000
10000


Birds XS2 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
50
100
150
200
250
300
1
10
100
1000
10000


Birds XS3 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
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4
6
8
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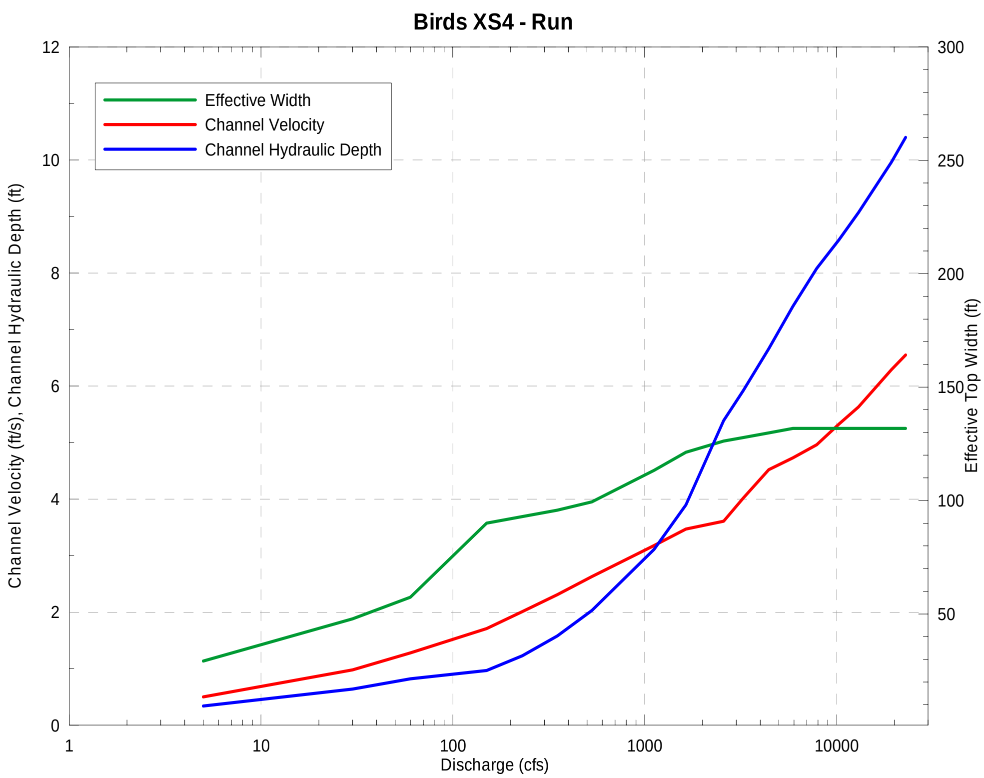
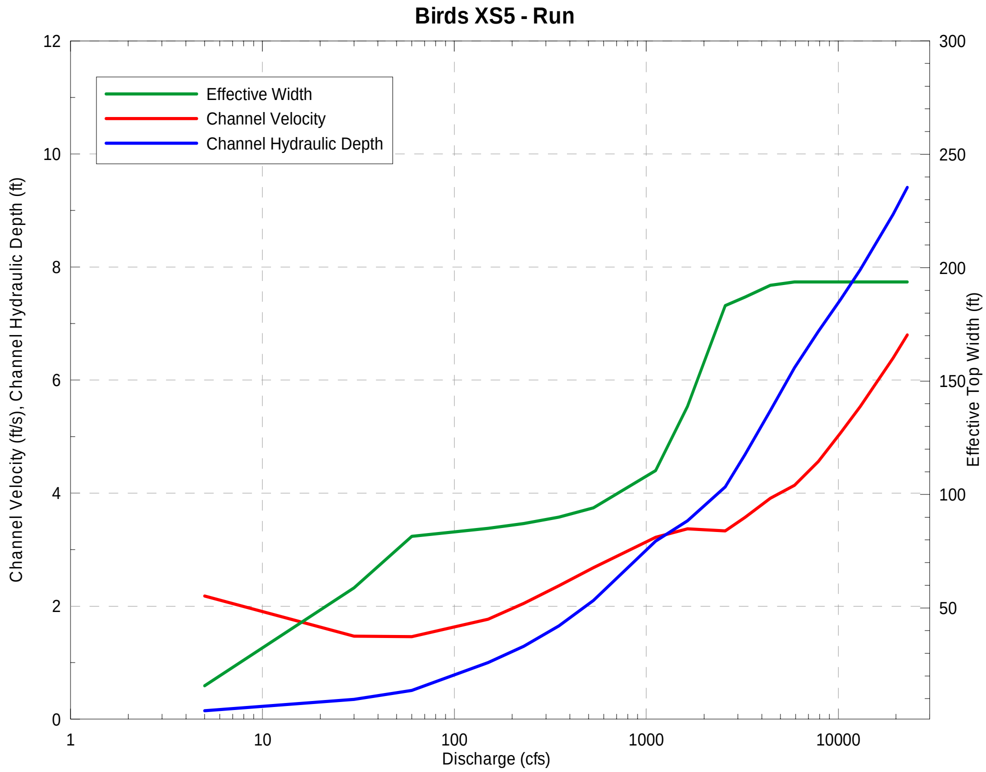
1
10
100
1000
10000


Birds XS4 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
50
100
150
200
250
300
1
10
100
1000
10000


Birds XS5 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
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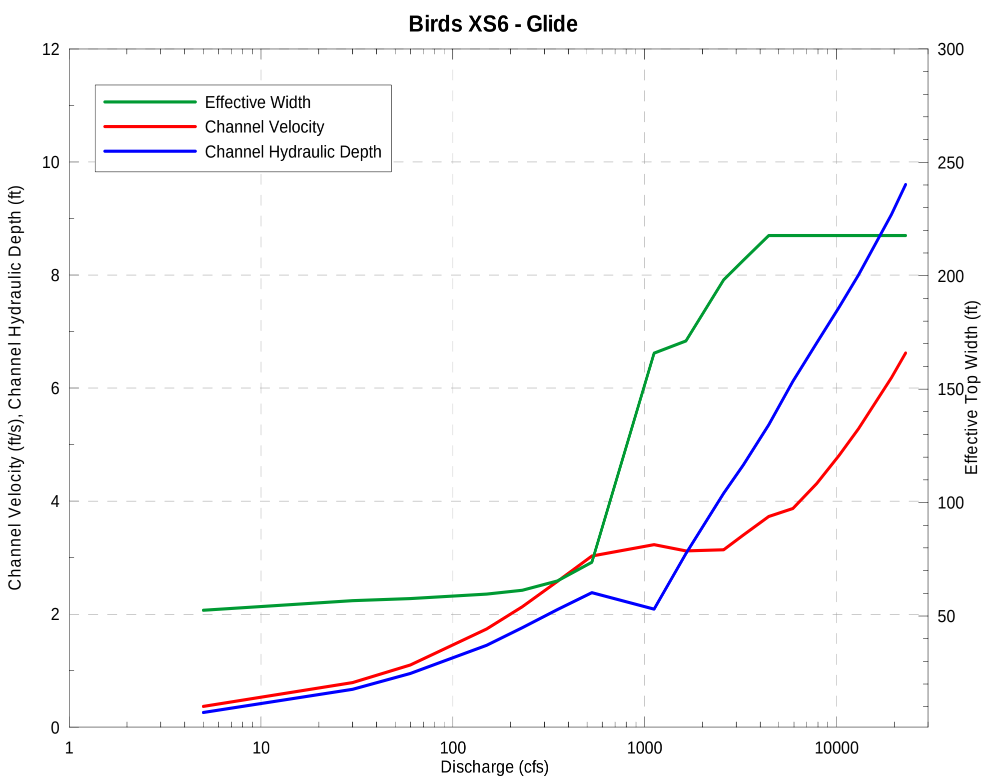
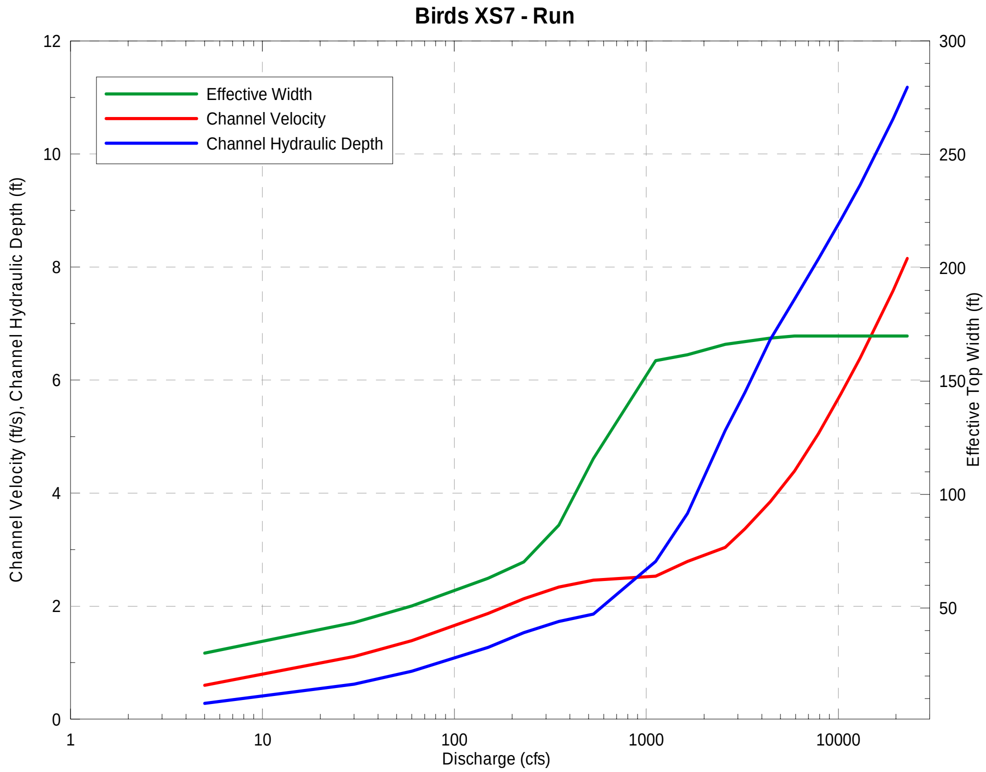
300
1
10
100
1000
10000


Birds XS6 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
50
100
150
200
250
300
1
10
100
1000
10000


Birds XS7 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
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2
4
6
8
10
12
50
100
150
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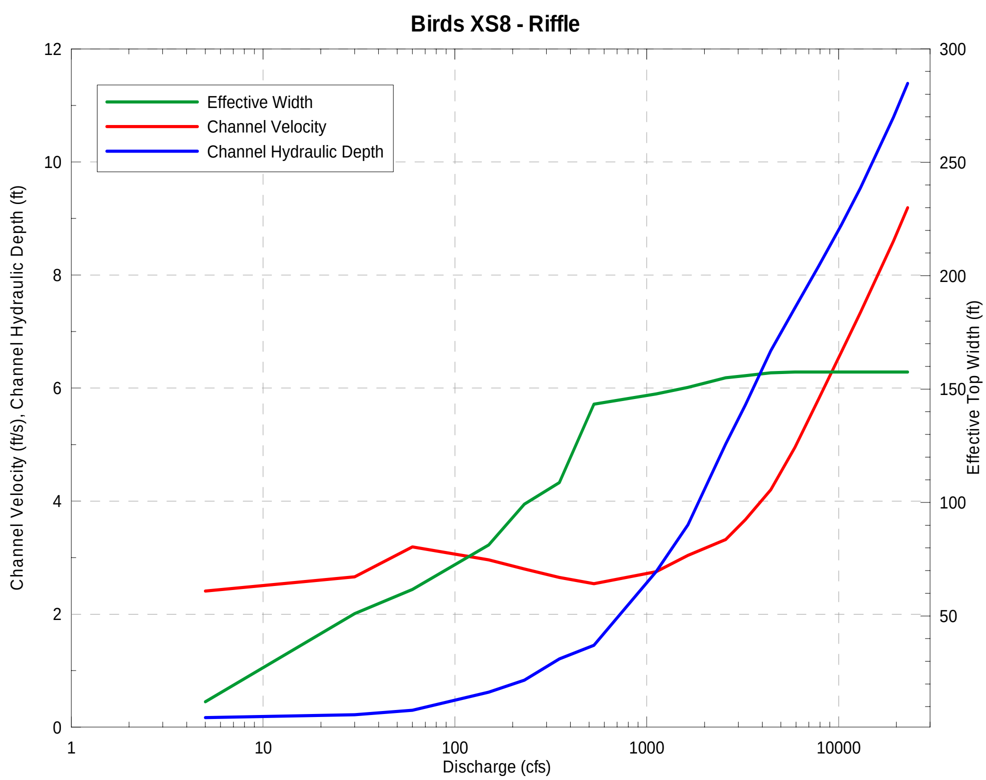
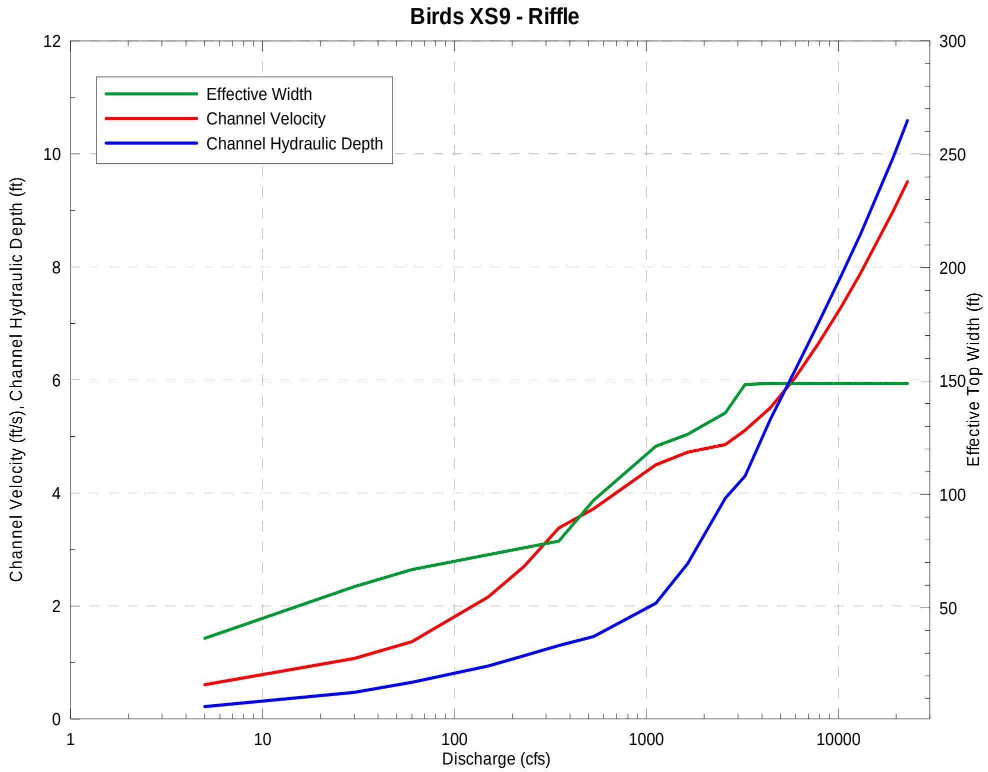
250
300
1
10
100
1000
10000


Birds XS8 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
50
100
150
200
250
300
1
10
100
1000
10000


Birds XS9 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
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12
50
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200
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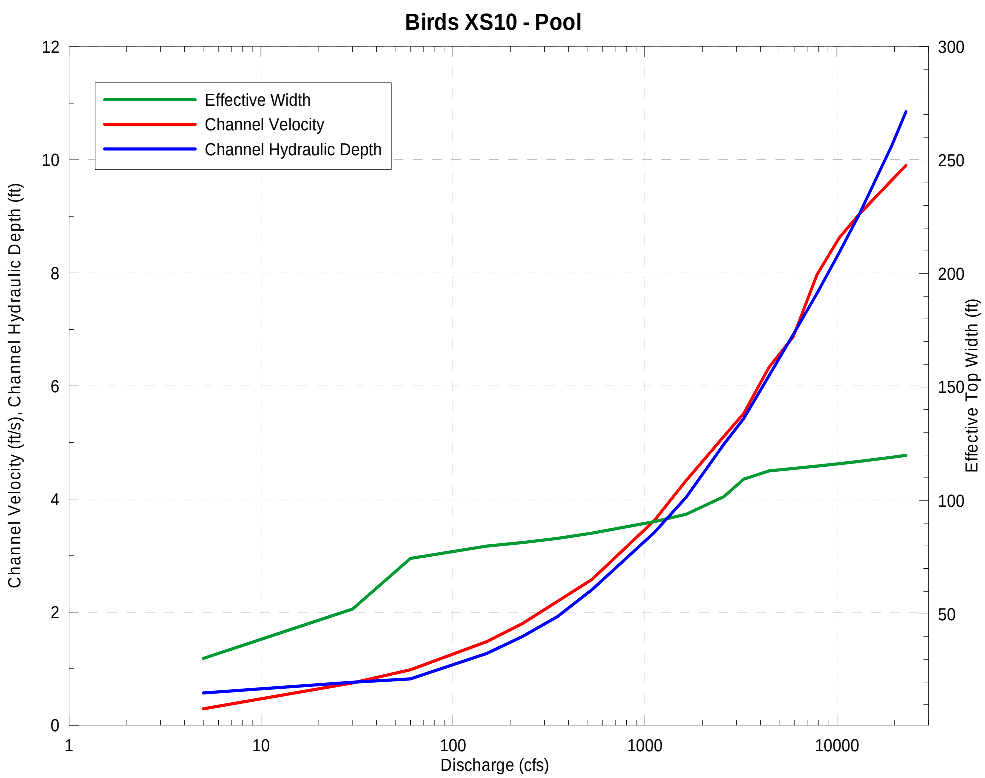
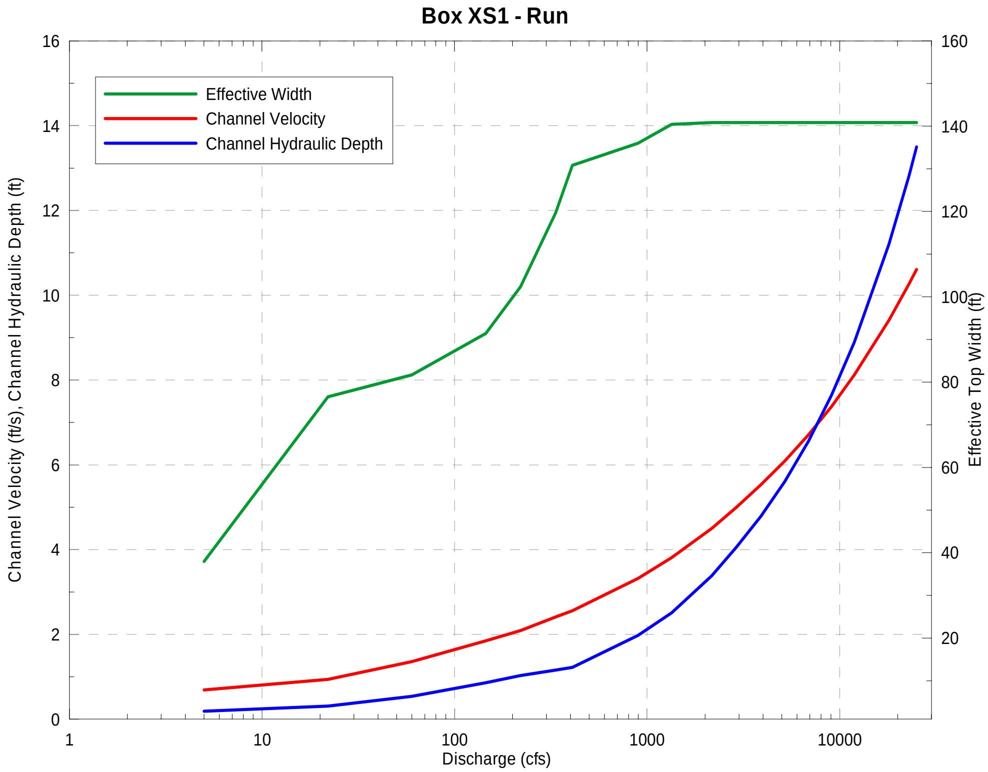
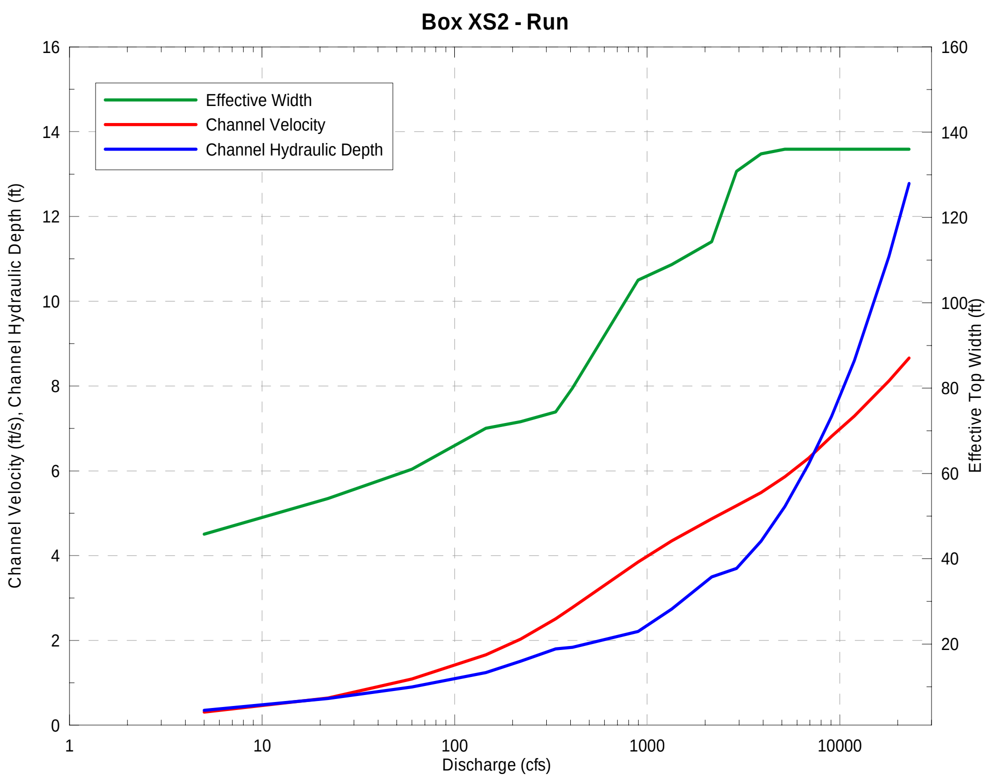
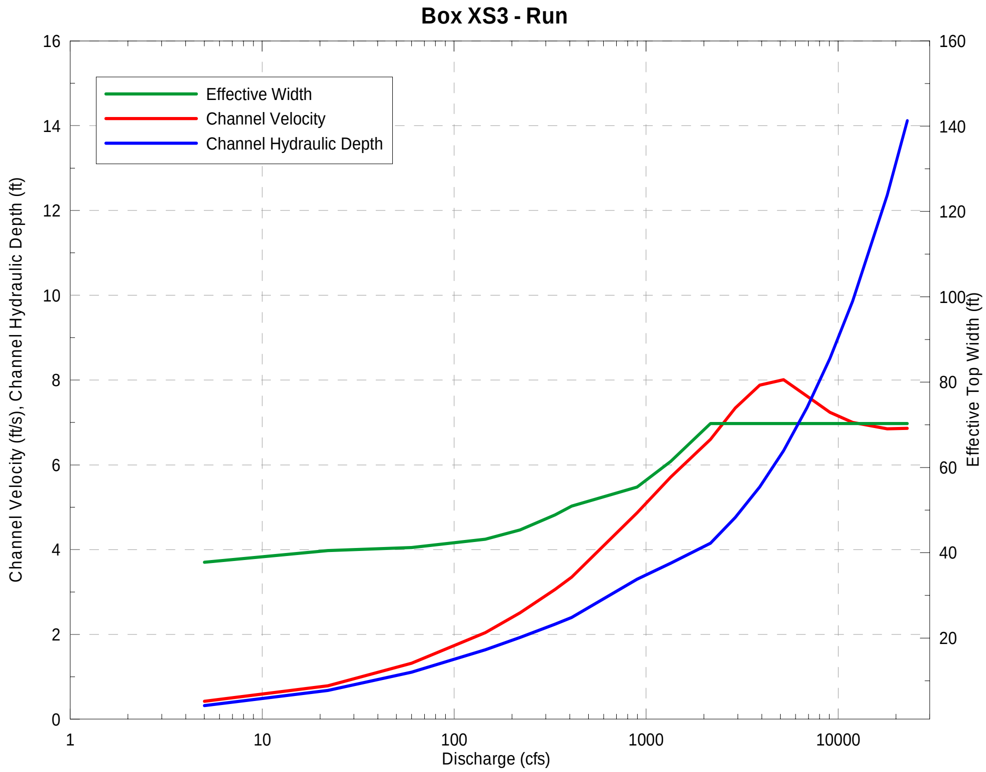
300
1
10
100
1000
10000

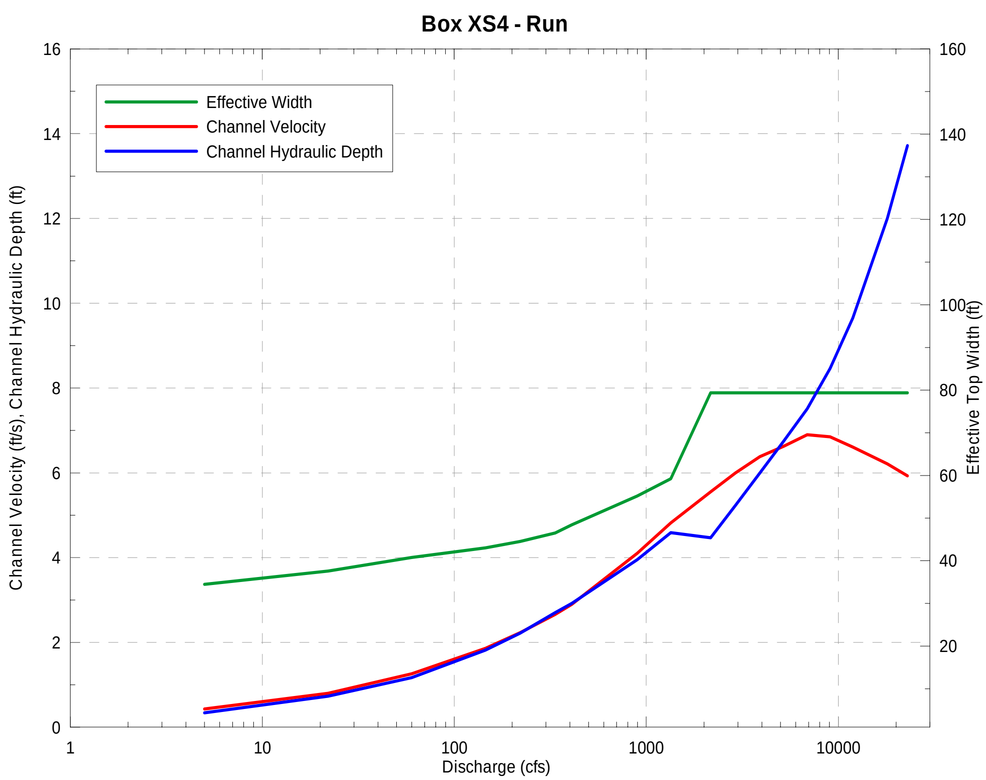

Birds XS10 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
50
100
150
200
250
300
1
10
100
1000
10000


Box XS1 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000

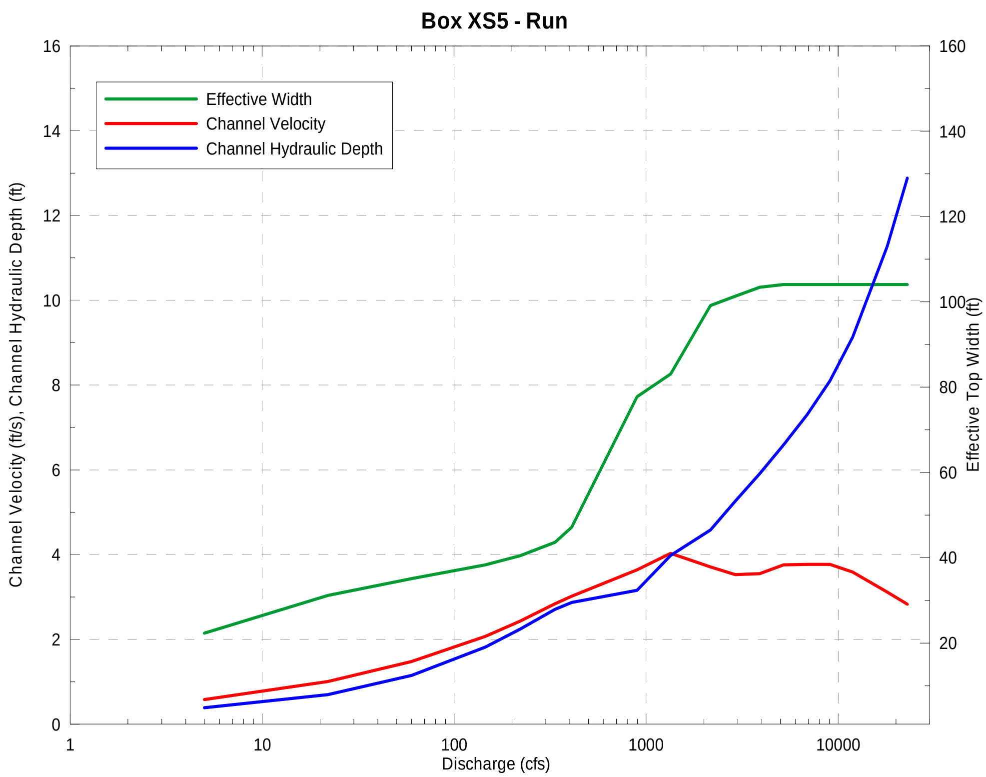

Box XS2 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000

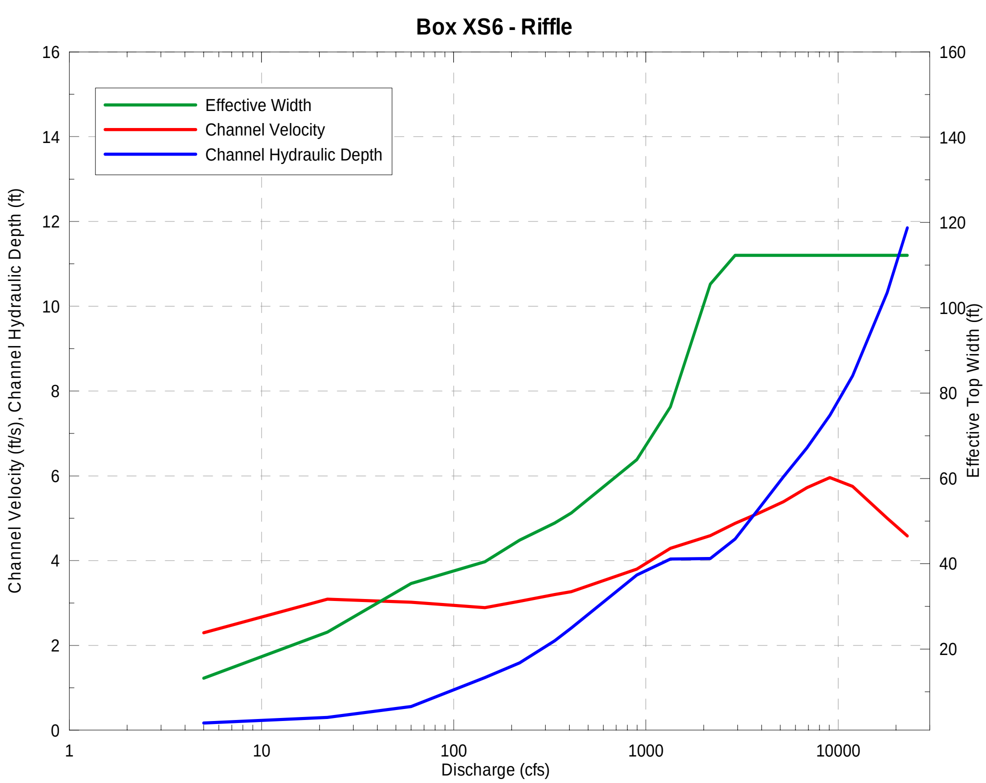


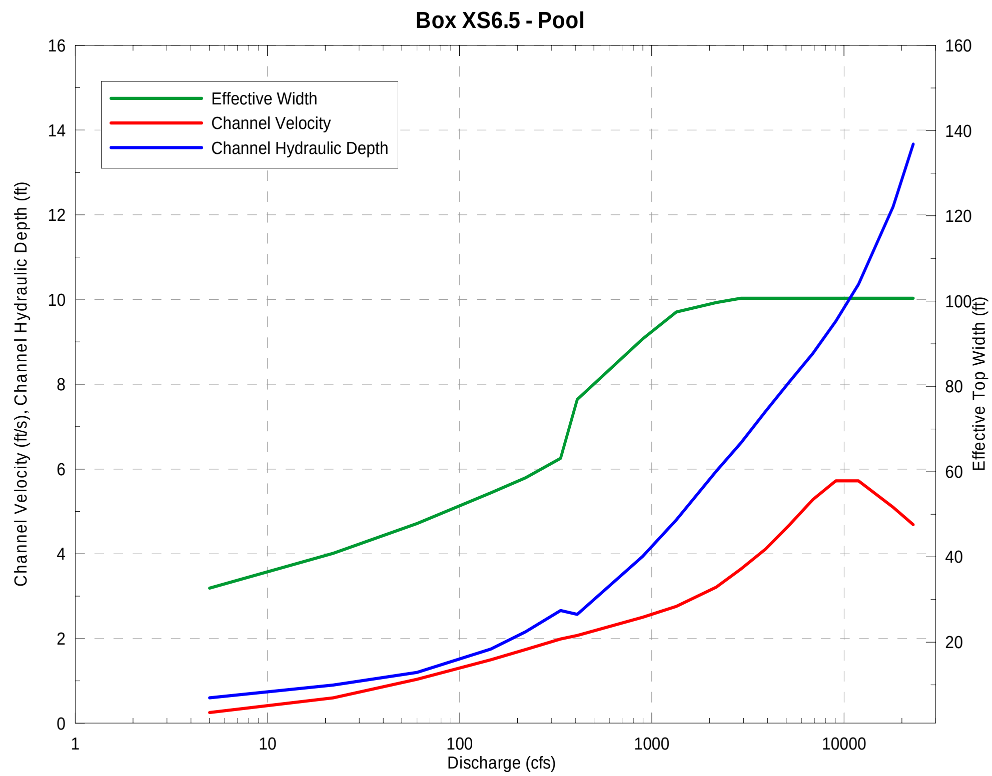
Box XS3 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000



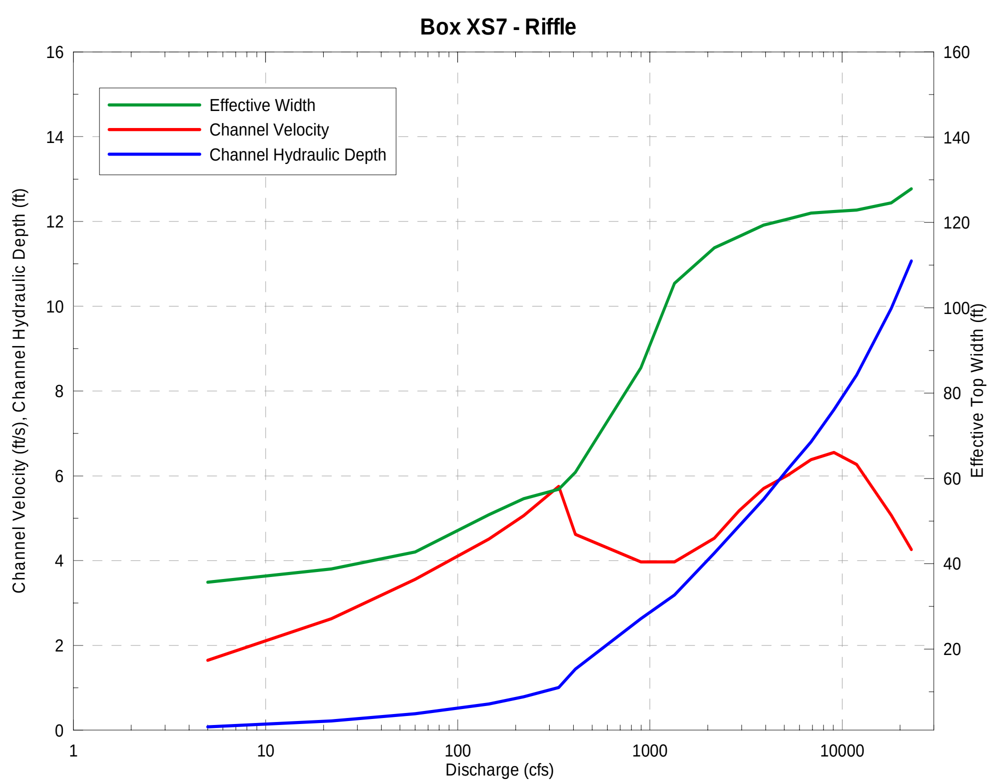
Box XS4 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000


Box XS5 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000


Box XS6 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000

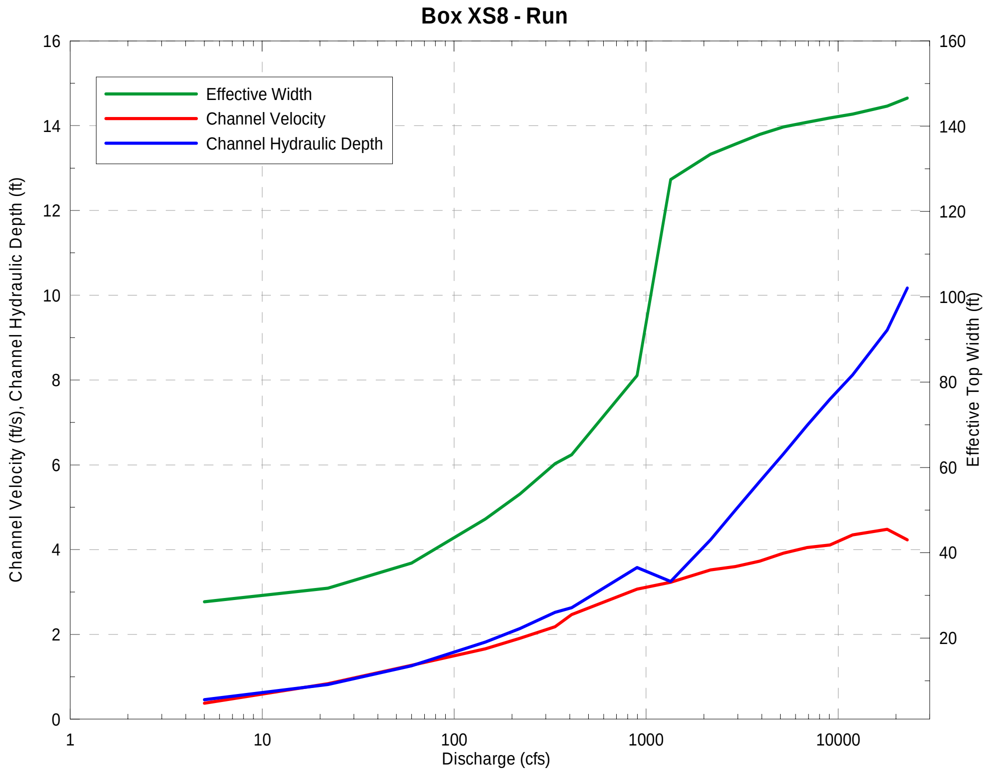


Box XS6.5 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000

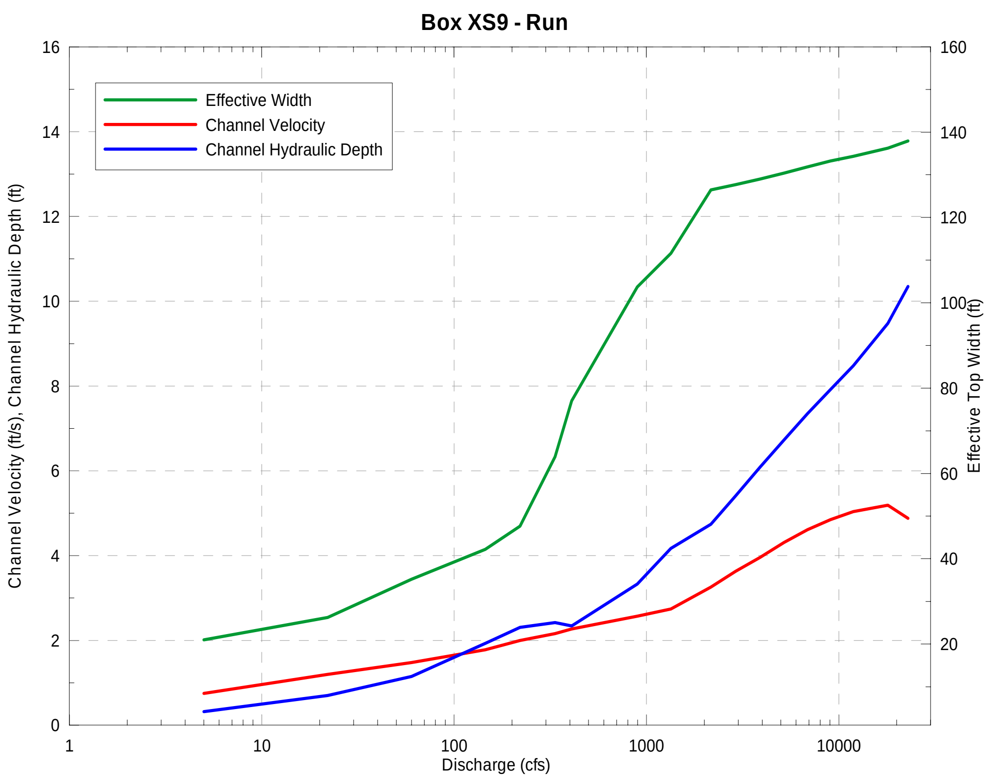


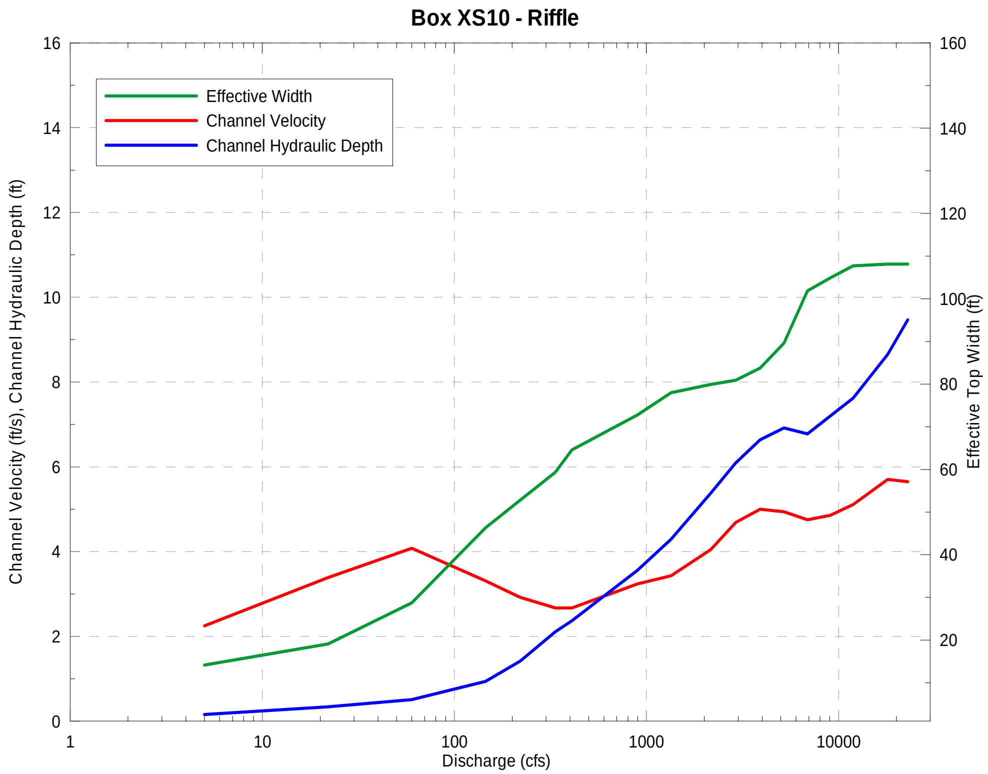
Box XS7 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000

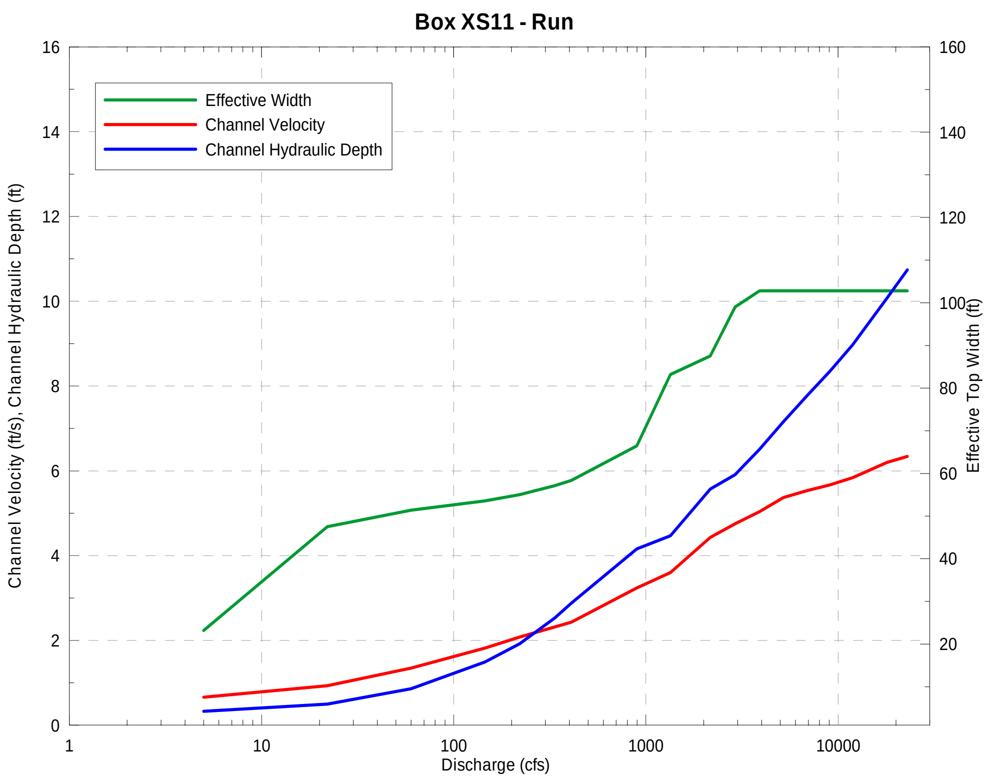
Box XS8 - Run

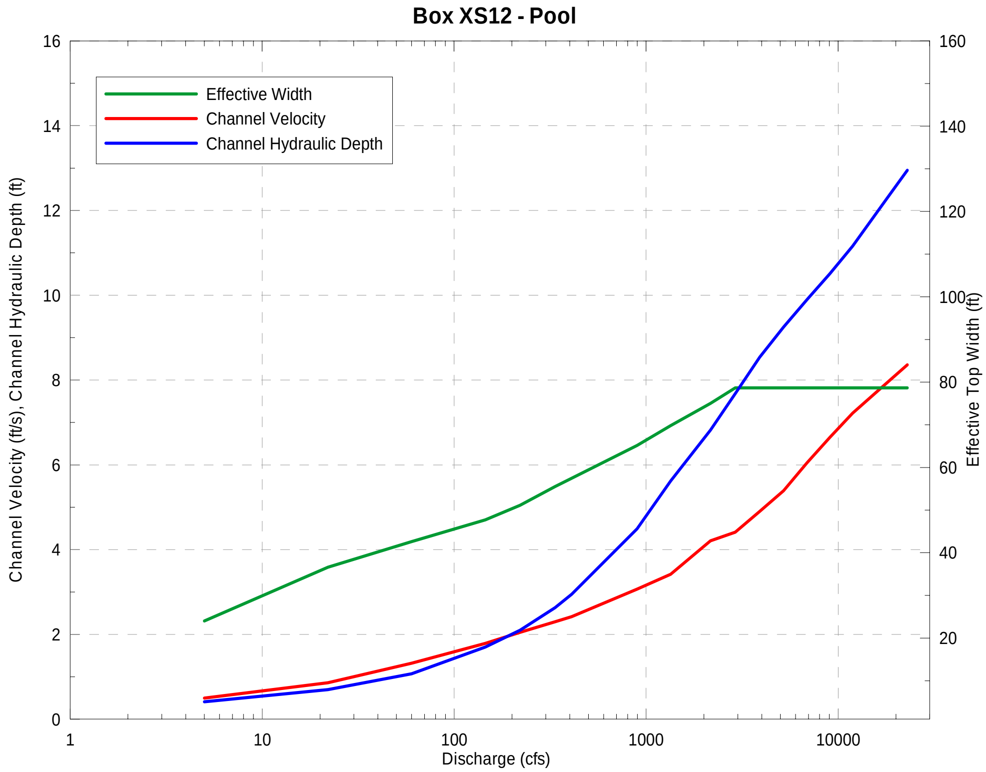


Box XS9 - Run




Box XS10 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000


Box XS11 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
4
6
8
10
12
14
16
20
40
60
80
100
120
140
160
1
10
100
1000
10000



Box XS12 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
2
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6
8
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12
14
16
20
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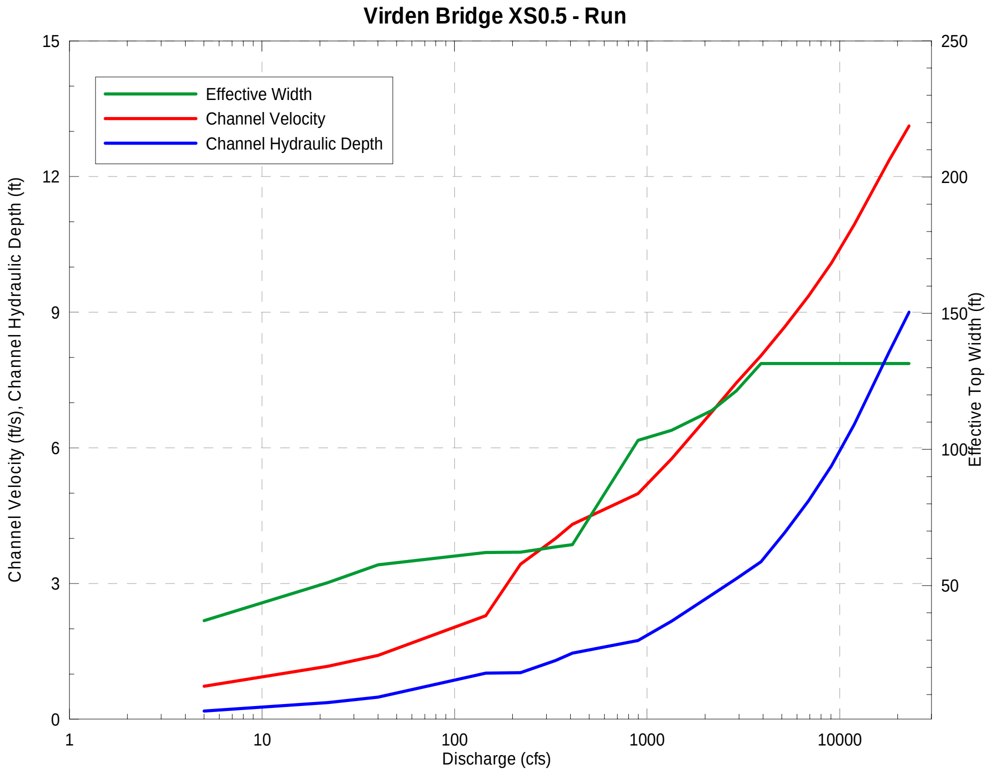
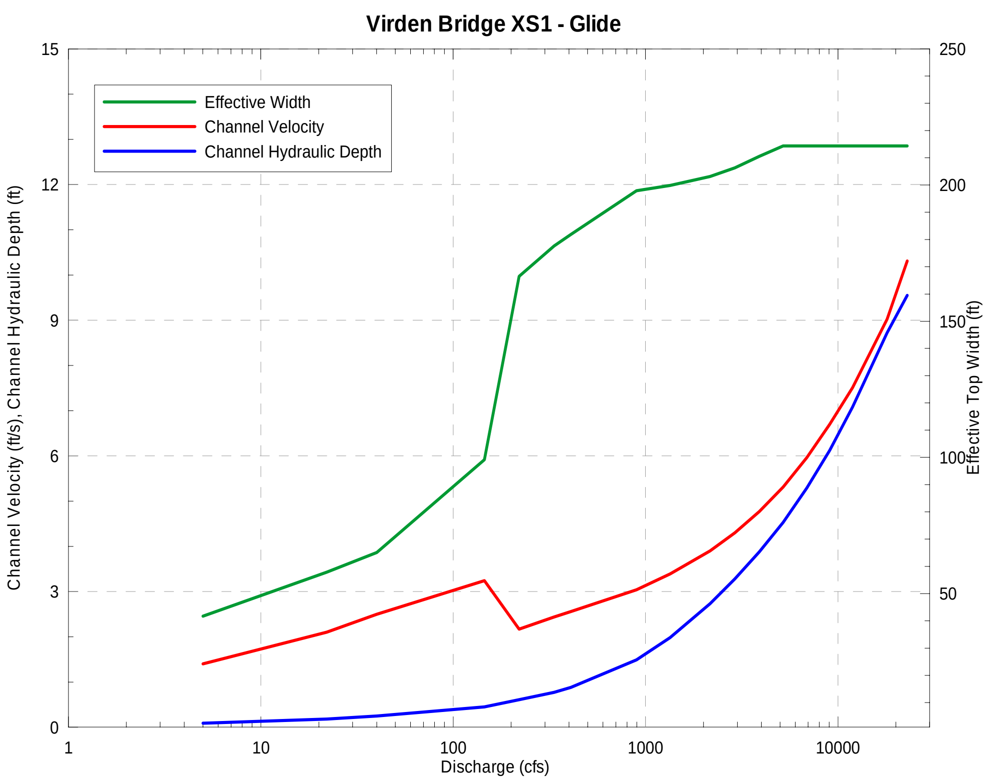
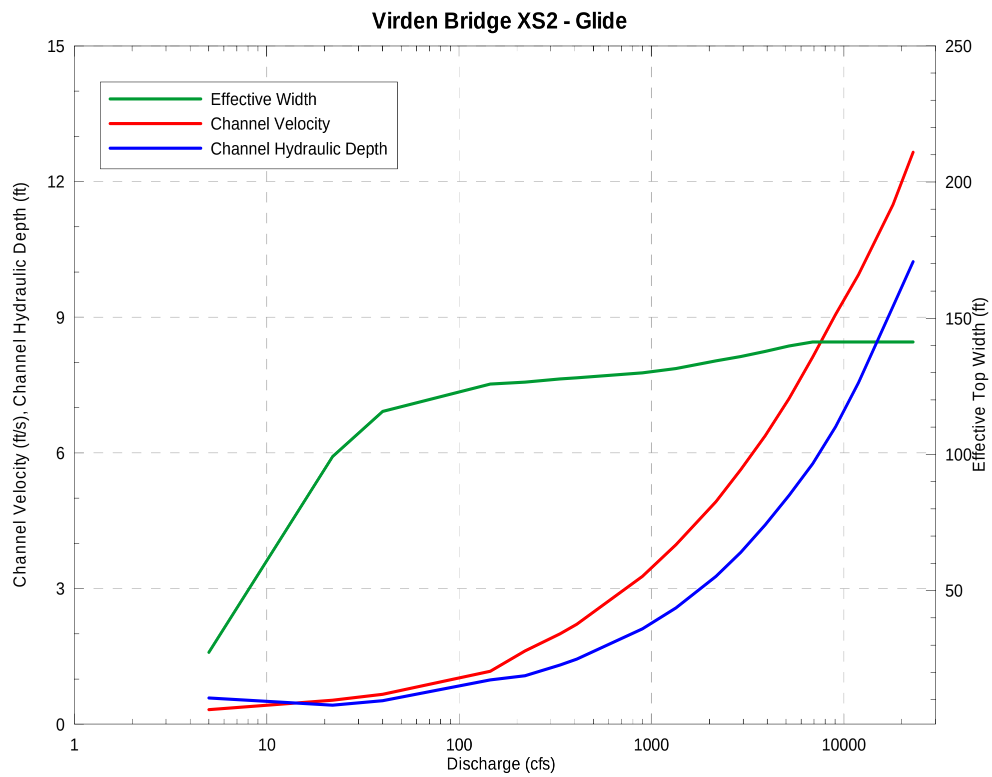
1
10
100
1000
10000

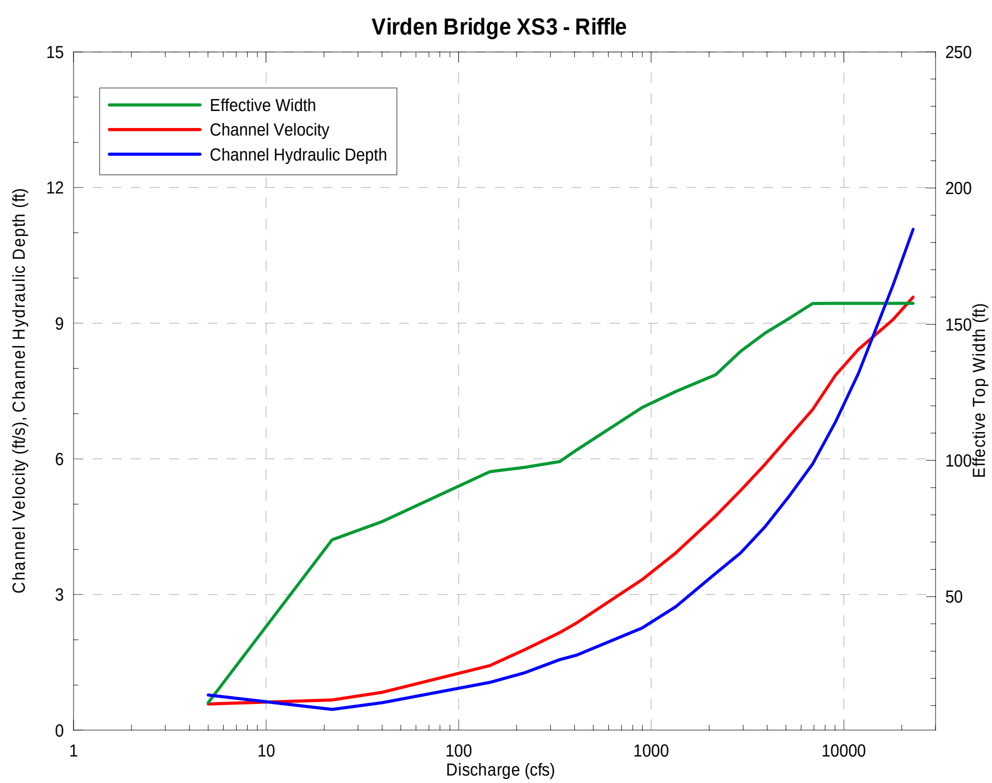


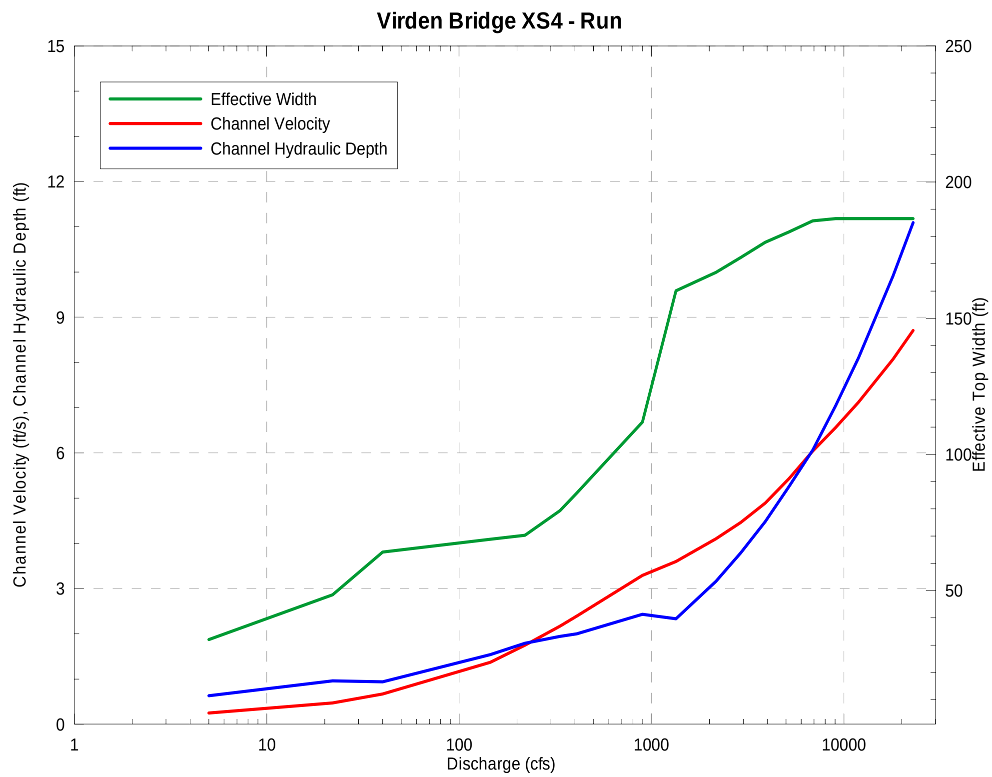
Virden Bridge XS0.5 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
15
12
9
6
3
0
250
200
150
100
50
1
10
100
1000
10000

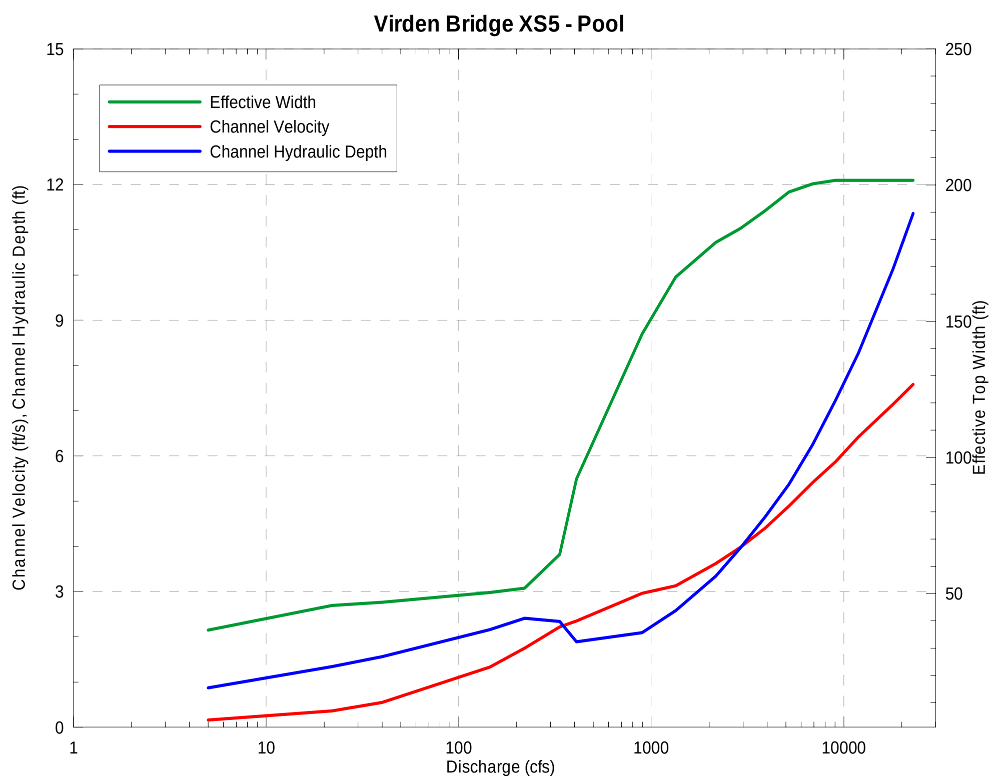


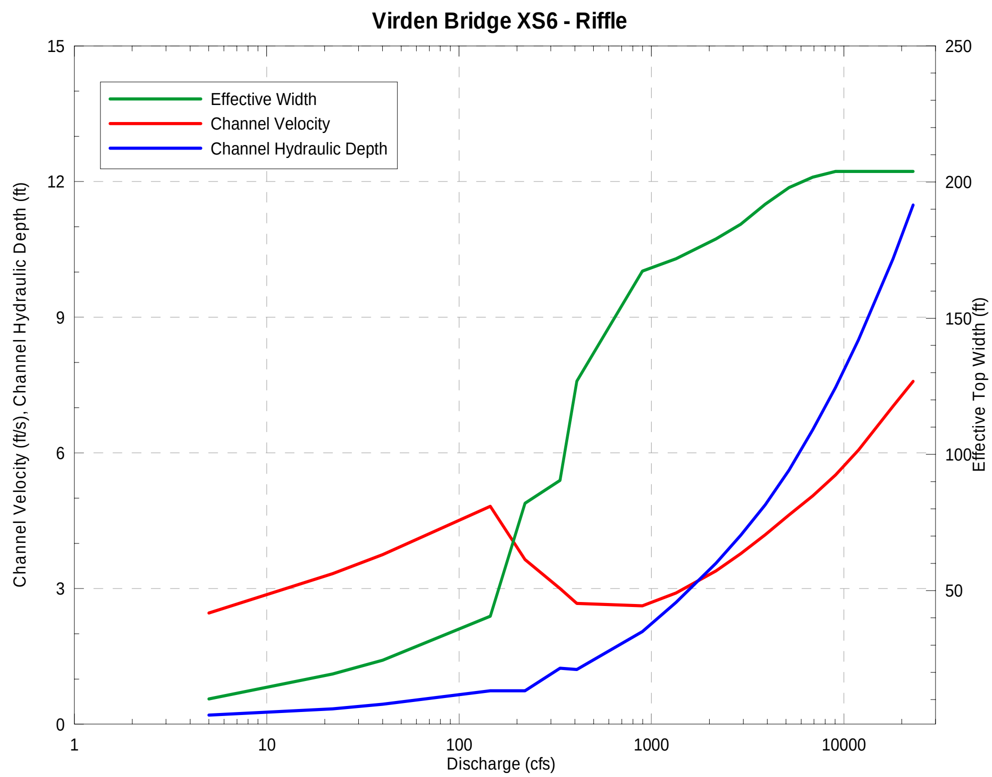
Virden Bridge XS1 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
15
12
9
6
3
0
250
200
150
100
50
1
10
100
1000
10000

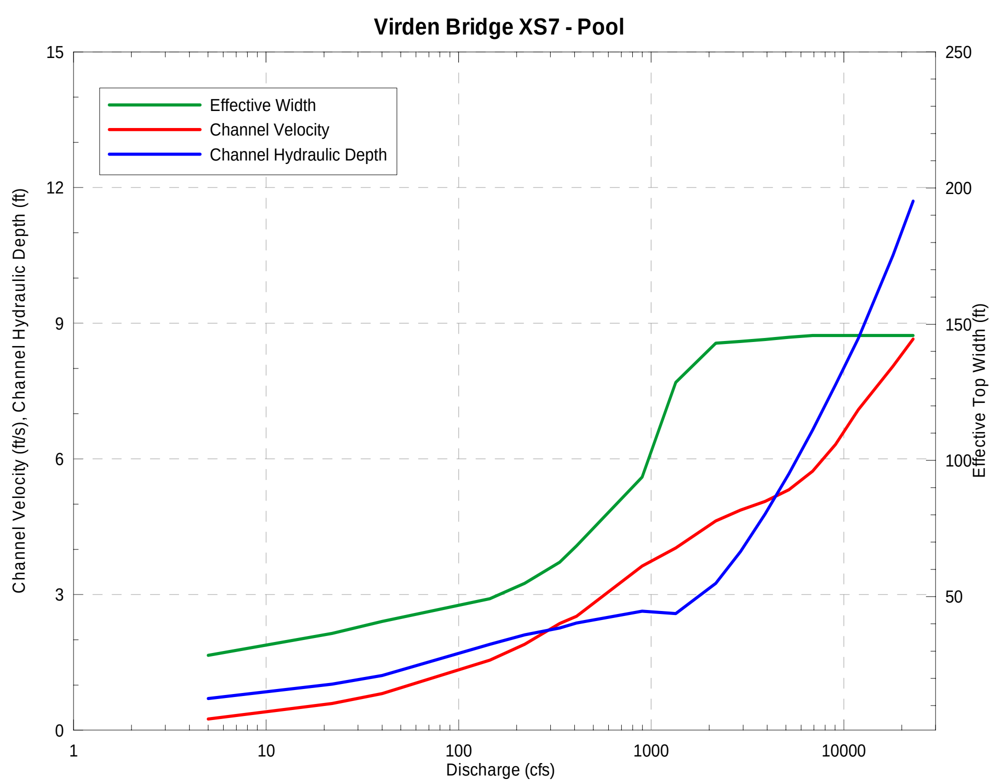

Virden Bridge XS2 - Glide
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000

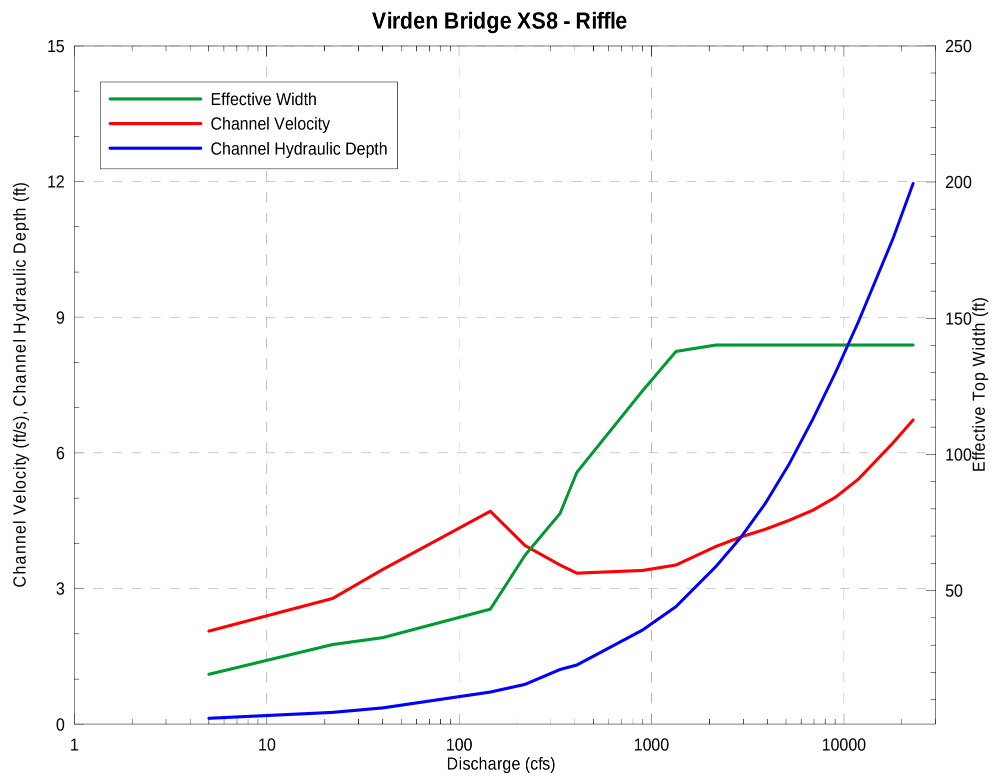

Virden Bridge XS3 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000


Virden Bridge XS4 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000


Virden Bridge XS5 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000


Virden Bridge XS6 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000


Virden Bridge XS7 - Pool
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000


Virden Bridge XS8 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
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150
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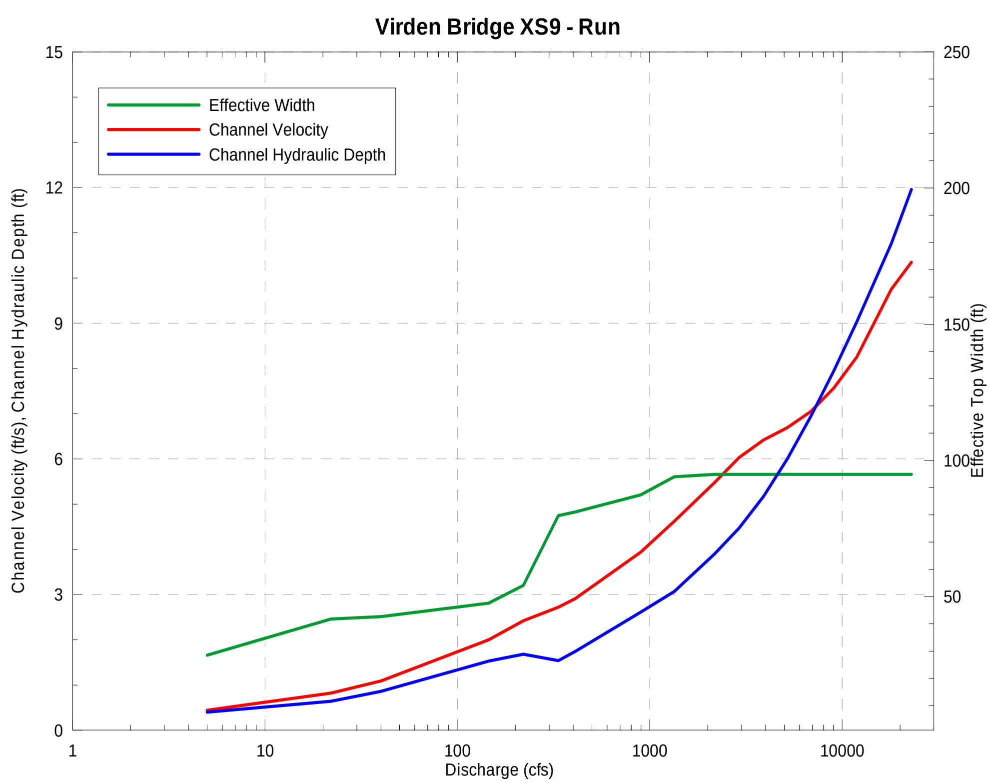
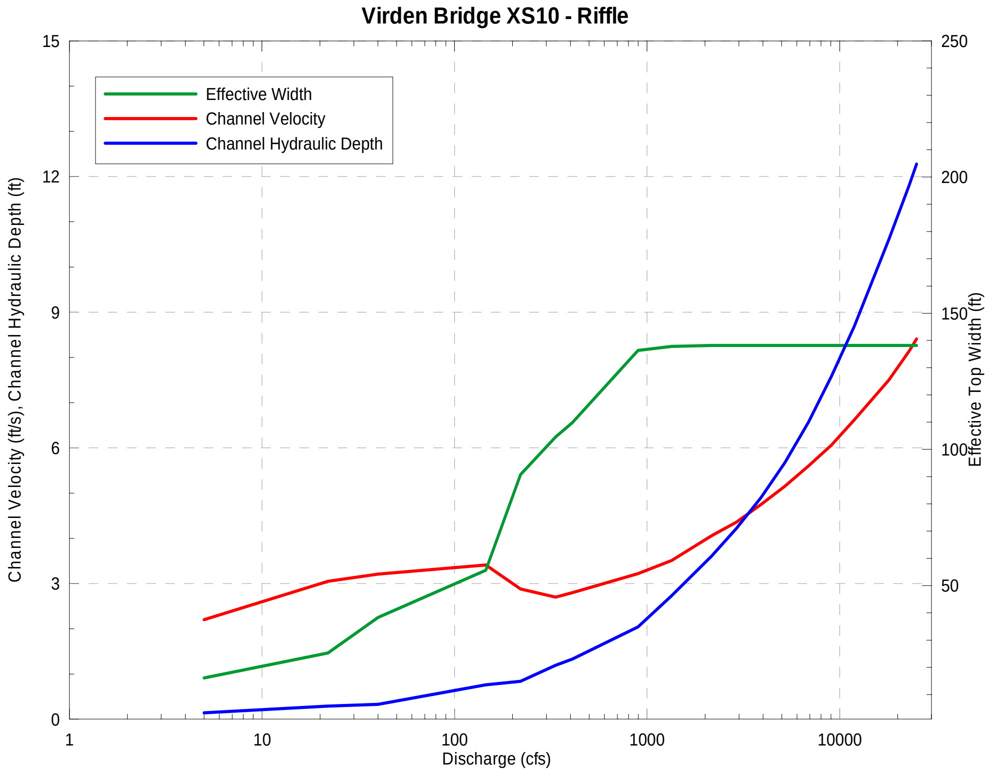
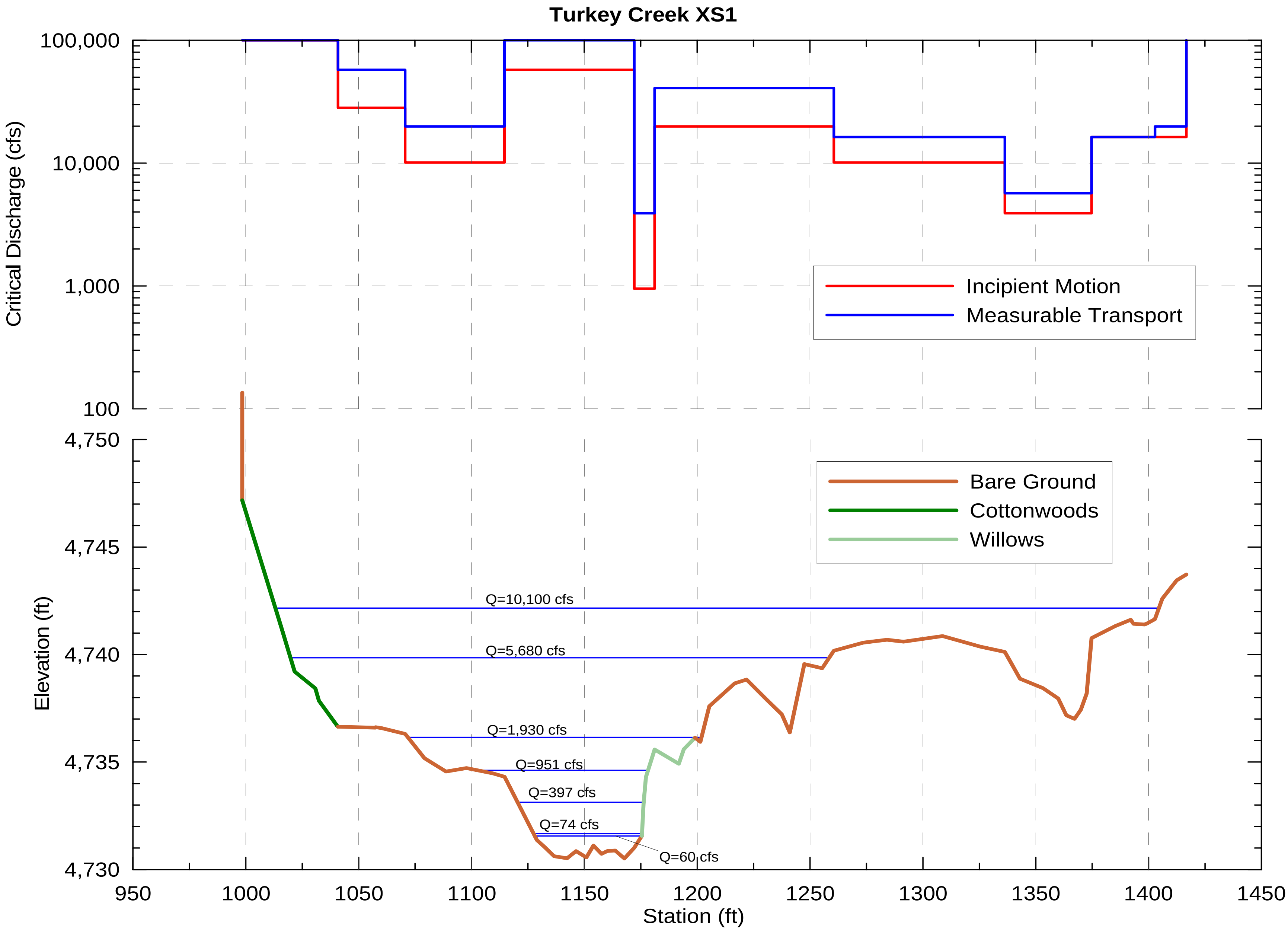
1
10
100
1000
10000

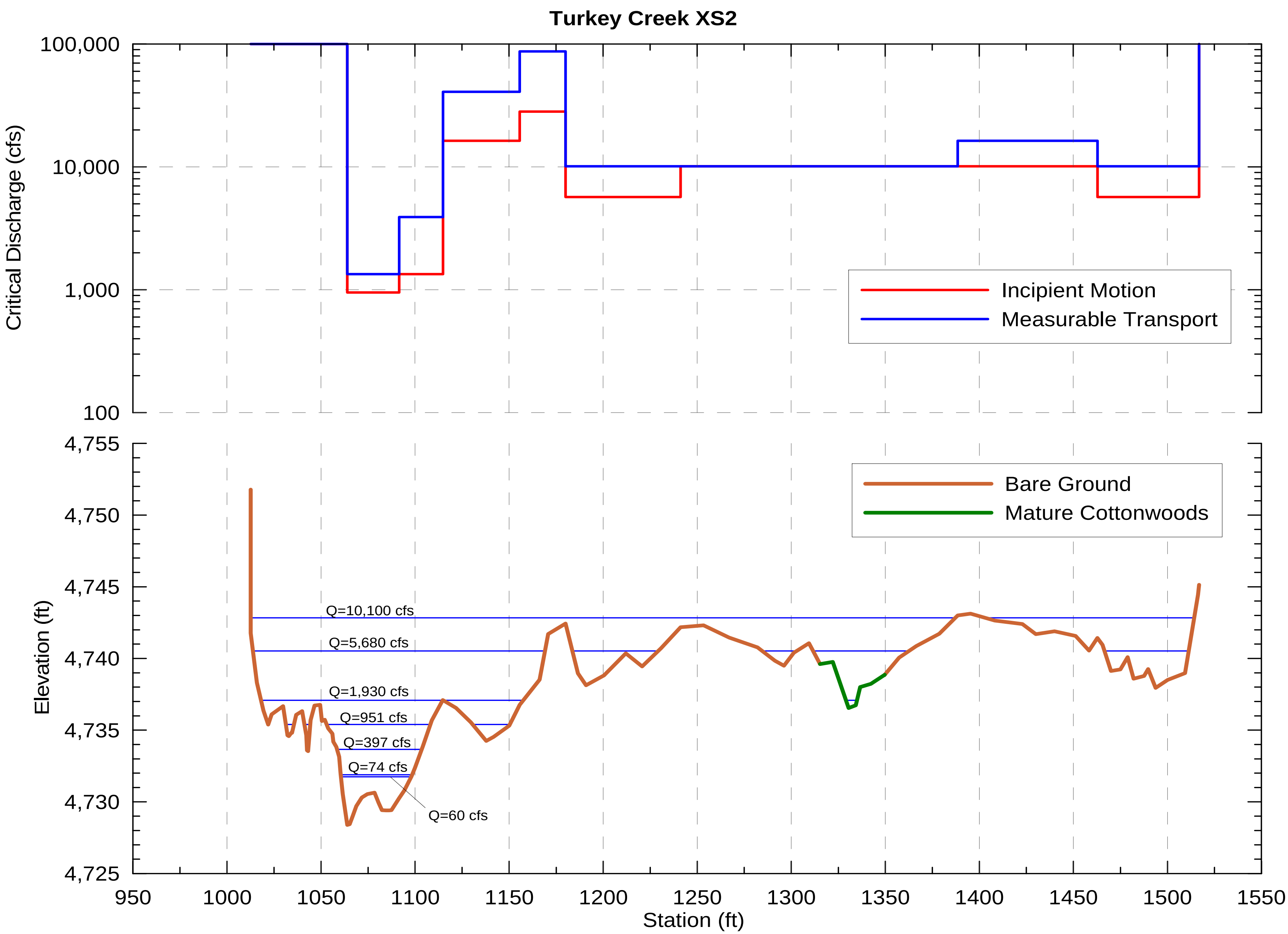

Virden Bridge XS9 - Run
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000

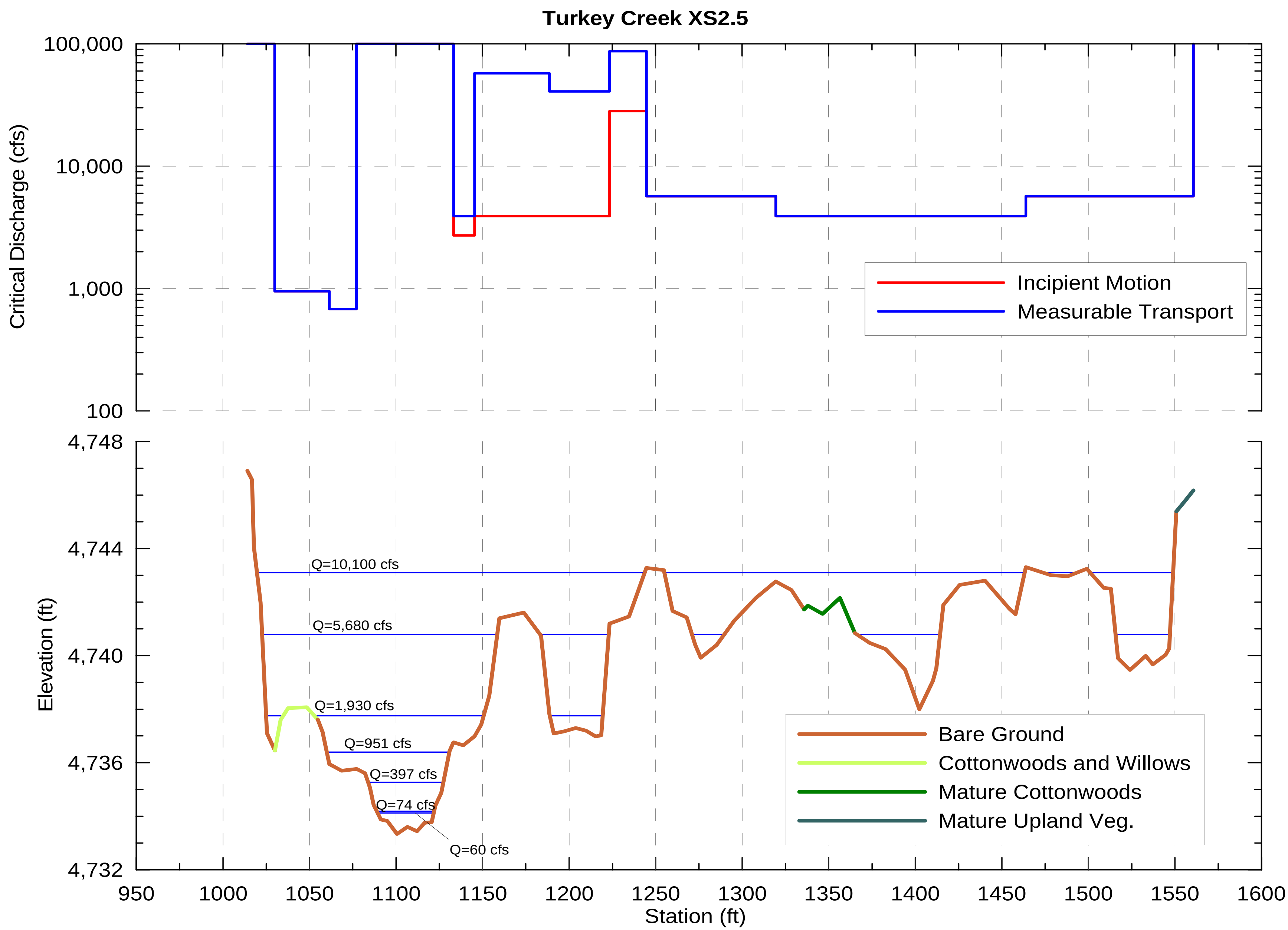

Virden Bridge XS10 - Riffle
Effective Width
Channel Velocity
Channel Hydraulic Depth
Channel Velocity (ft/s), Channel Hydraulic Depth (ft)
Effective Top Width (ft)
Discharge (cfs)
0
3
6
9
12
15
50
100
150
200
250
1
10
100
1000
10000

APPENDIX C

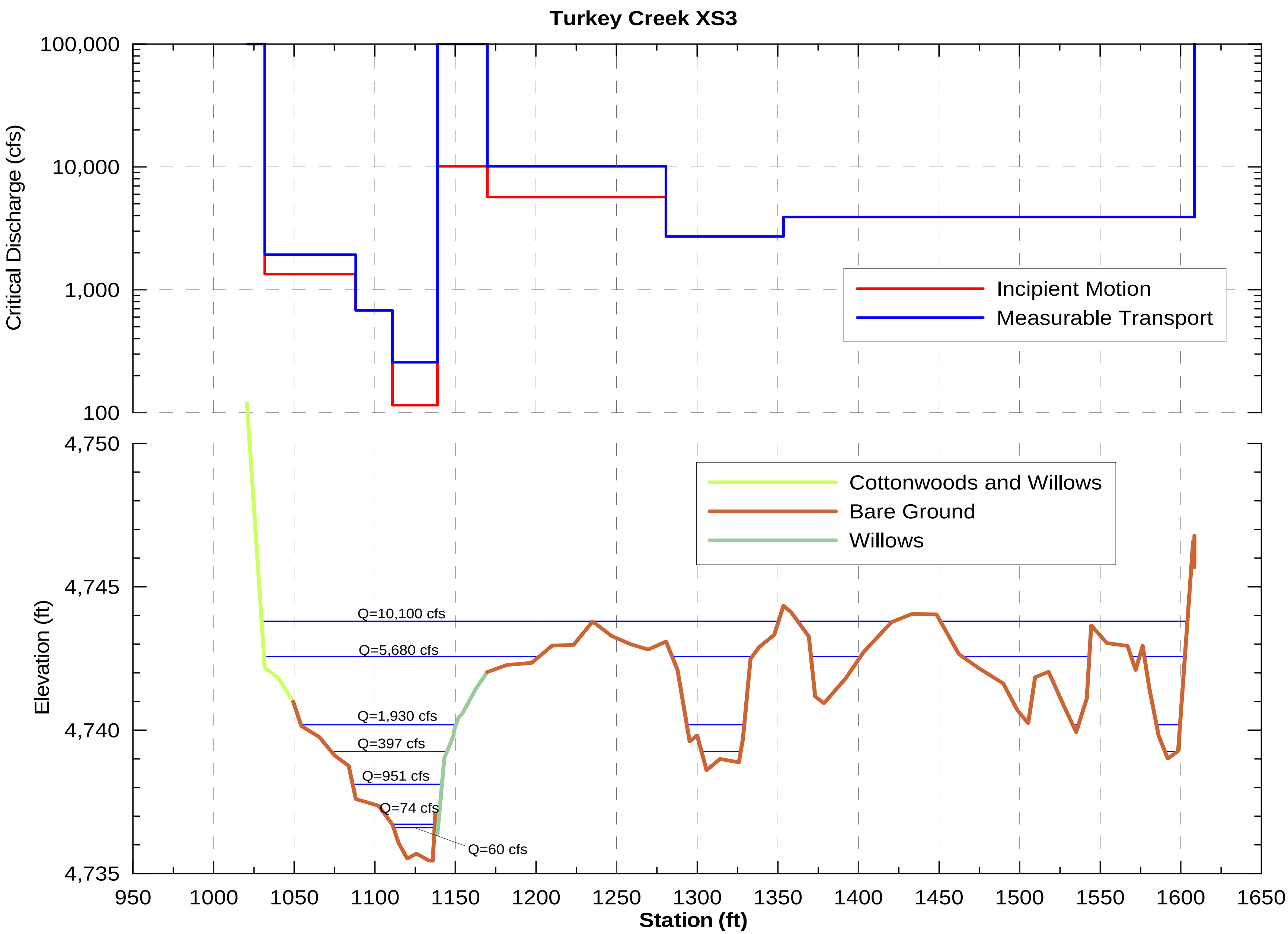
Plotted Cross Sections for the Turkey Creek, TNC, Birds, Box, and Virden Sites and the Distribution of the Critical Flows for Initiation of Sediment Transport and Significant Bed-material Mobilization

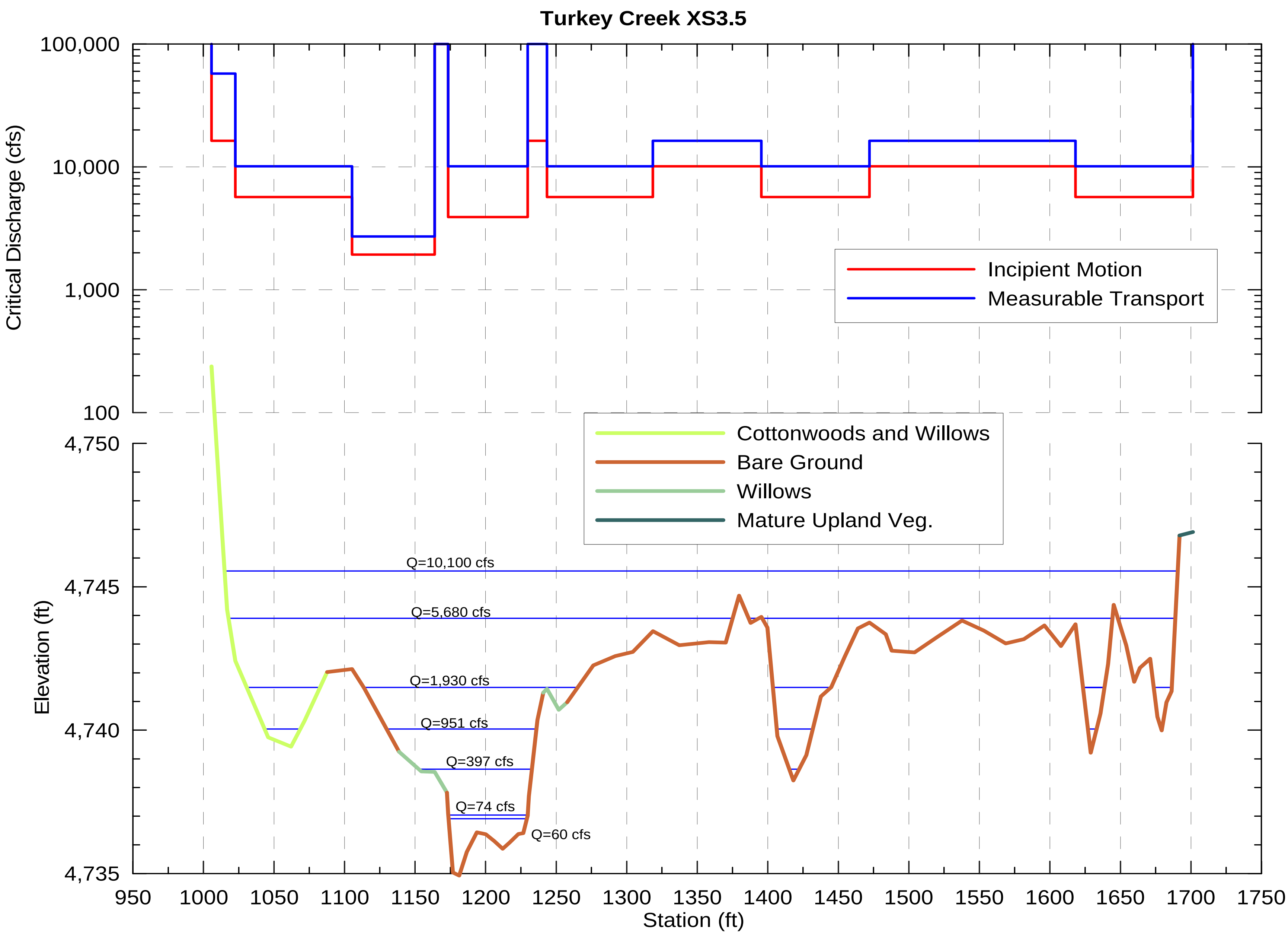

Turkey Creek XS1
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,750
4,745
4,740
4,735
4,730
Bare Ground
Cottonwoods
Willows
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
Station (ft)

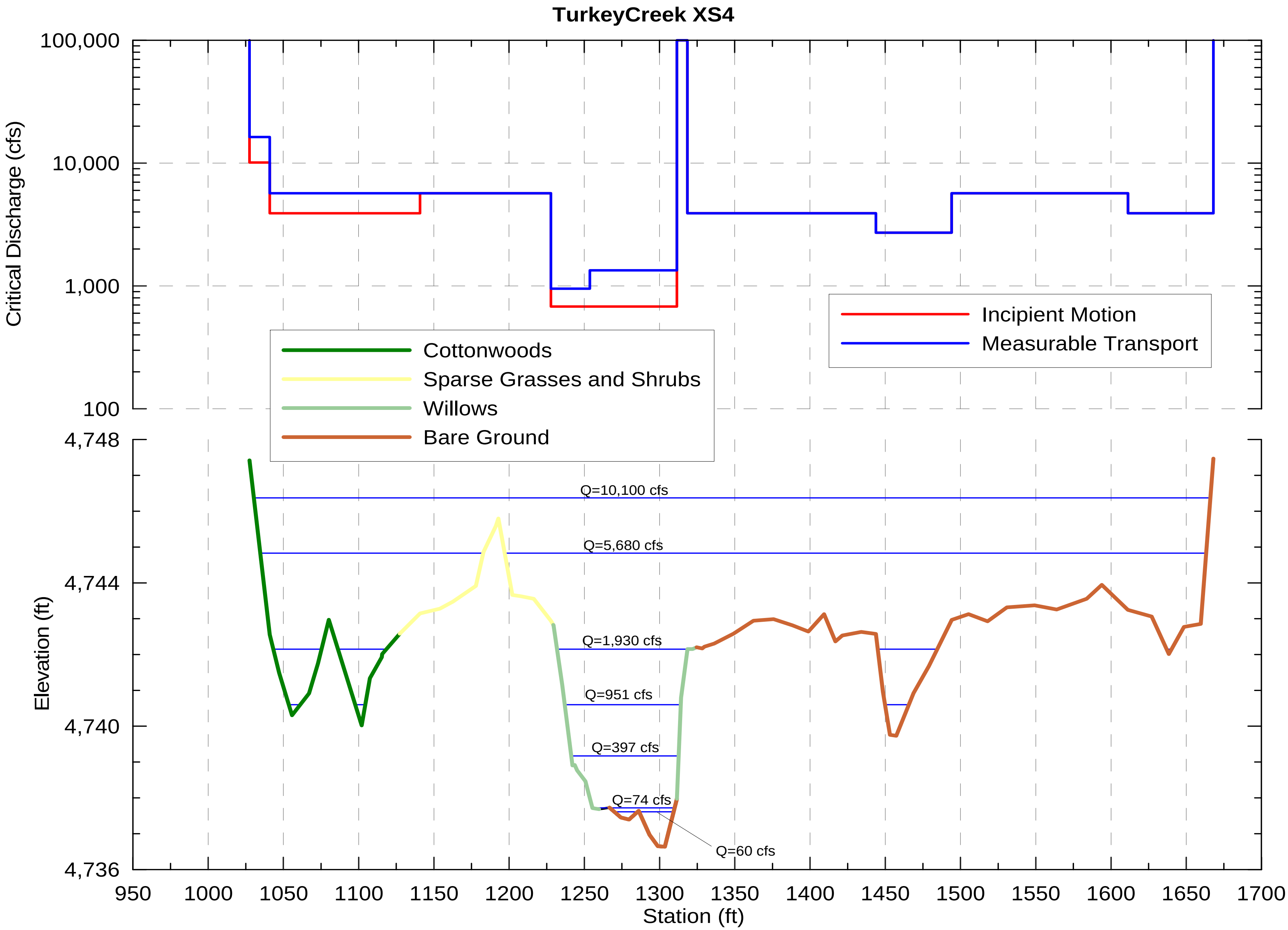

Turkey Creek XS2
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,755
4,750
4,745
4,740
4,735
4,730
4,725
Bare Ground
Mature Cottonwoods
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
Station (ft)

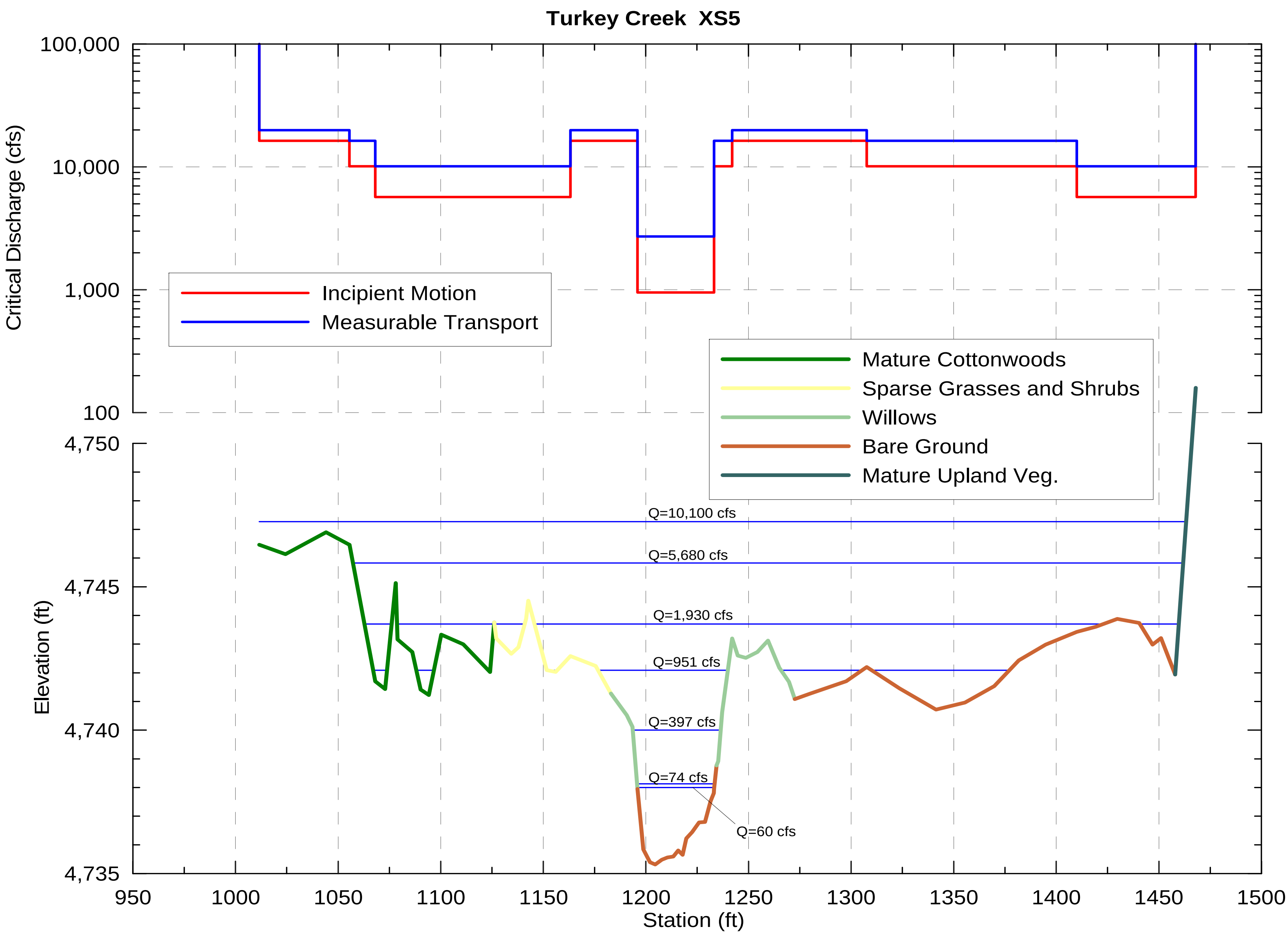


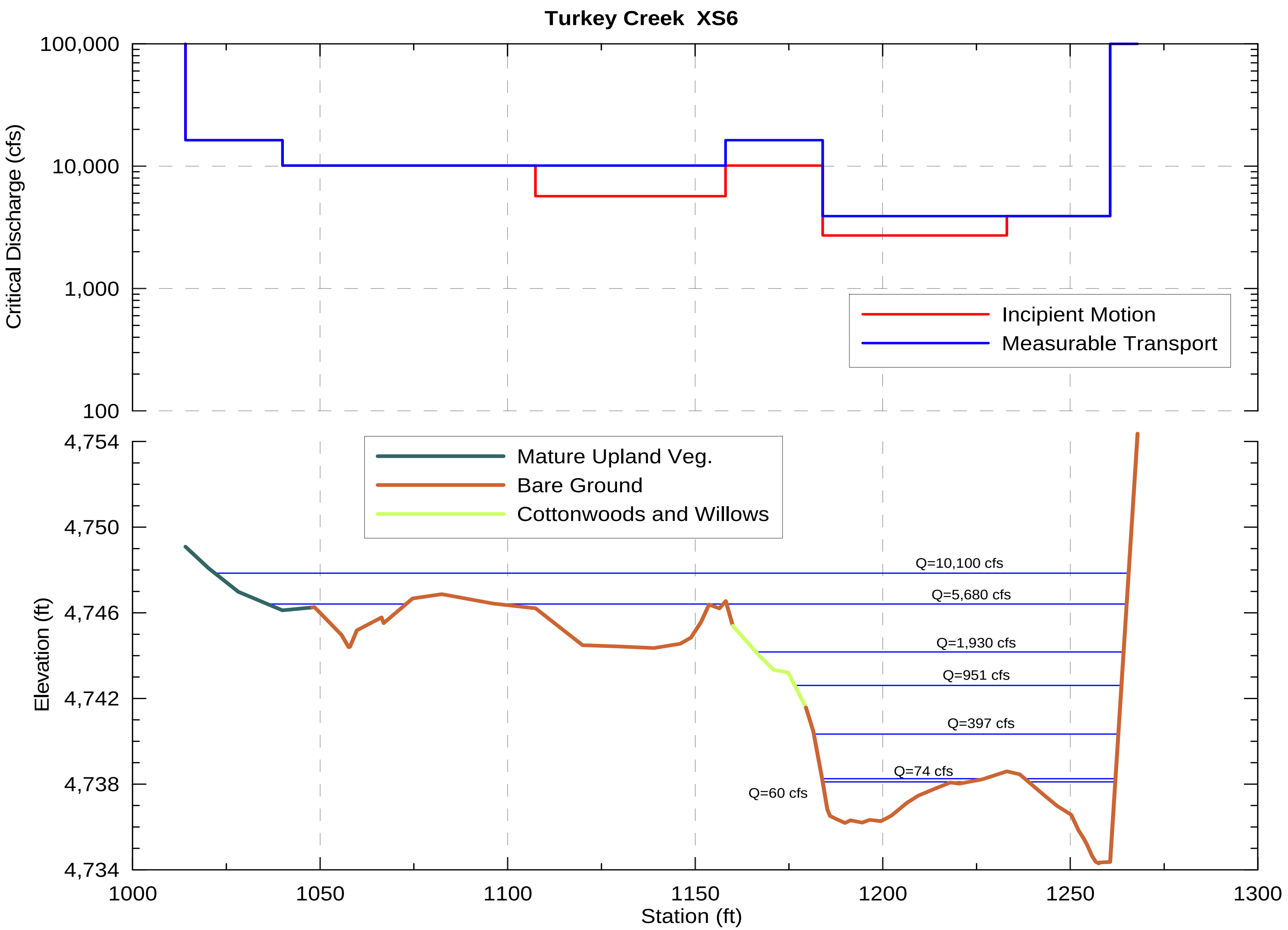
Turkey Creek XS2.5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,748
4,744
4,740
4,736
4,732
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
Bare Ground
Cottonwoods and Willows
Mature Cottonwoods
Mature Upland Veg.
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
Station (ft)

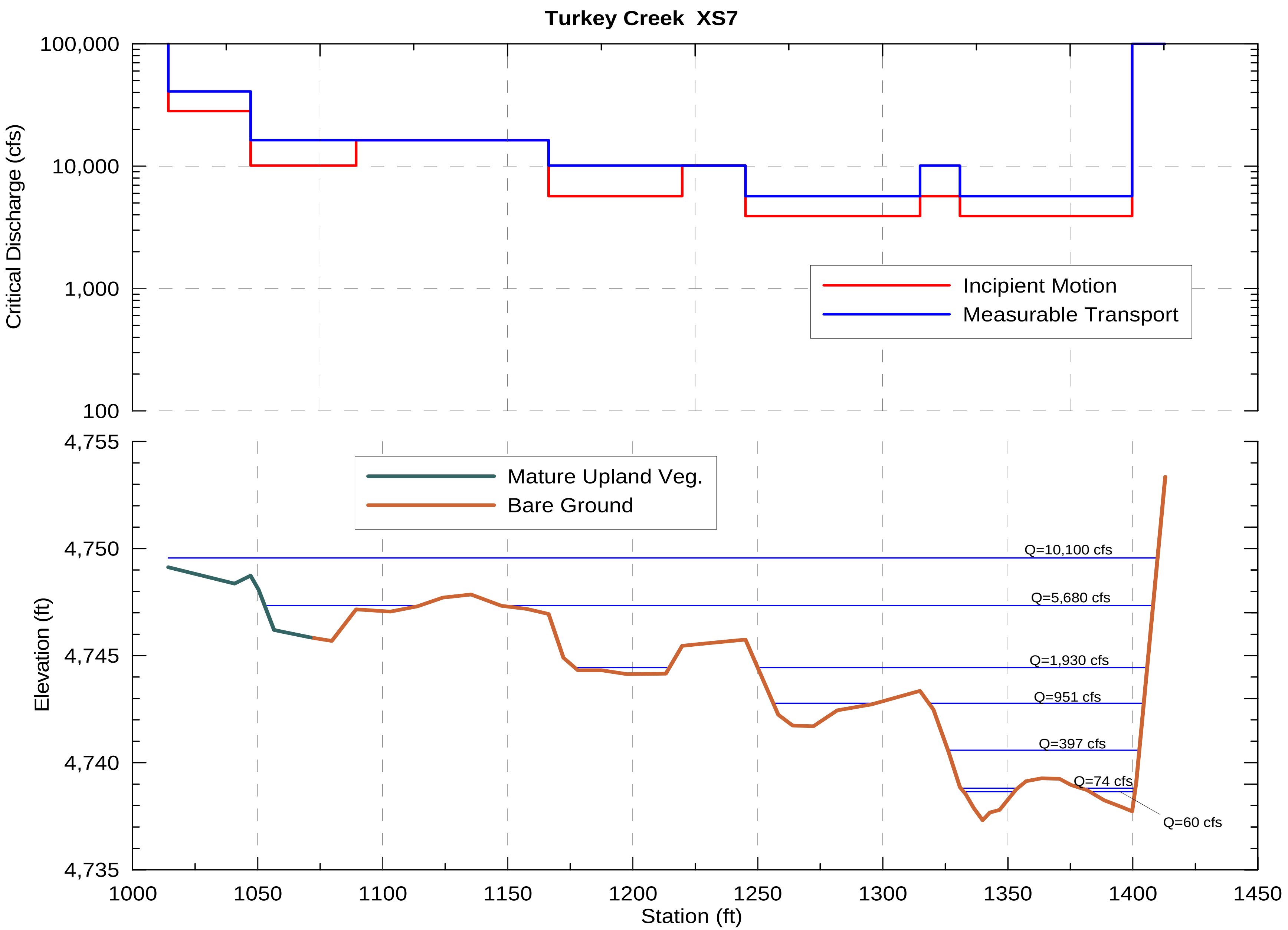

Turkey Creek XS3
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,750
4,745
4,740
4,735
Cottonwoods and Willows
Bare Ground
Willows
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=397 cfs
Q=951 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
Station (ft)


Turkey Creek XS3.5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,750
4,745
4,740
4,735
Cottonwoods and Willows
Bare Ground
Willows
Mature Upland Veg.
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
1750
Station (ft)

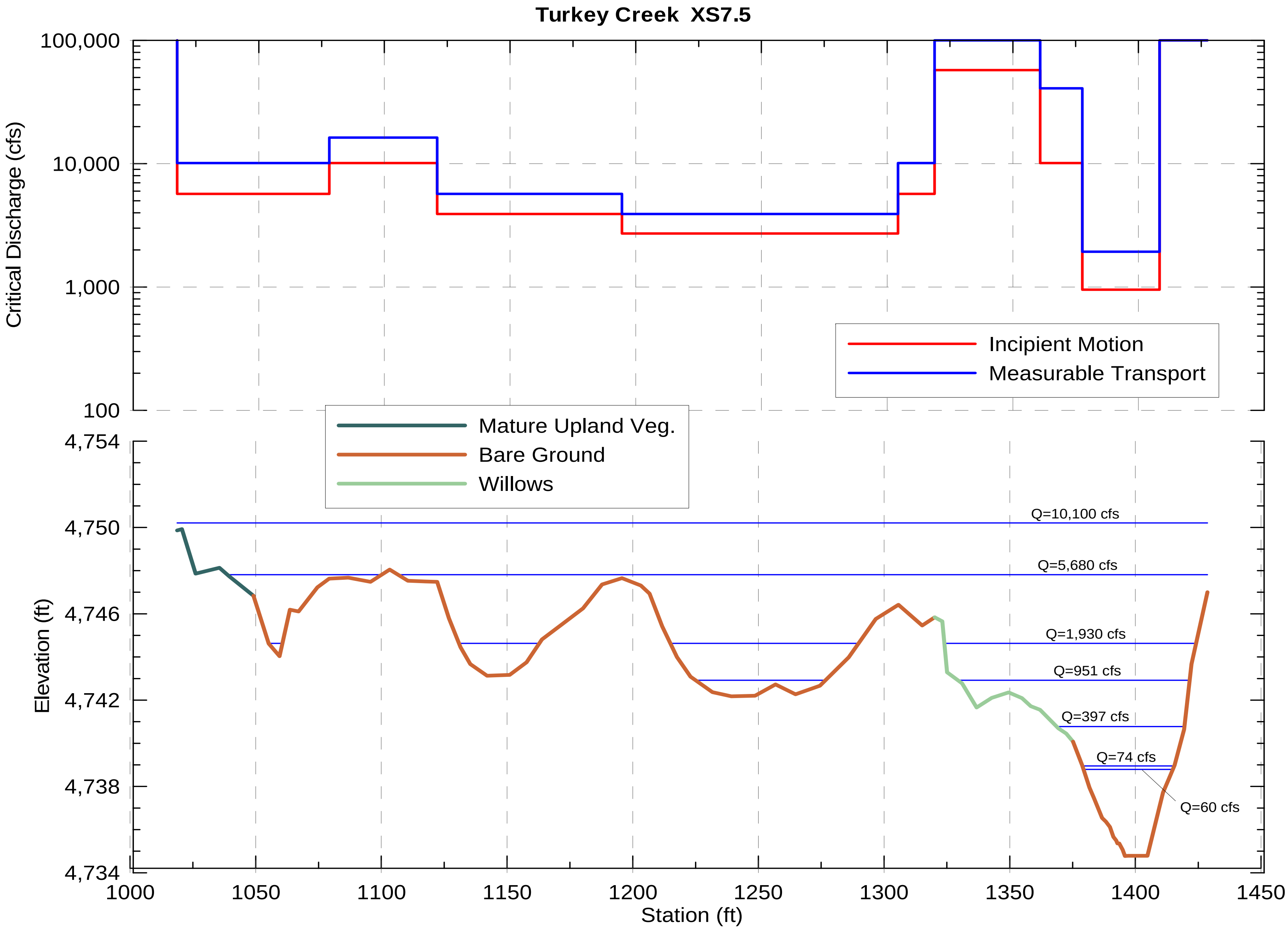

TurkeyCreek XS4
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Cottonwoods
Sparse Grasses and Shrubs
Willows
Bare Ground
Elevation (ft)
4,748
4,744
4,740
4,736
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
Station (ft)


Turkey Creek XS5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Mature Cottonwoods
Sparse Grasses and Shrubs
Willows
Bare Ground
Mature Upland Veg.
Elevation (ft)
4,750
4,745
4,740
4,735
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Station (ft)

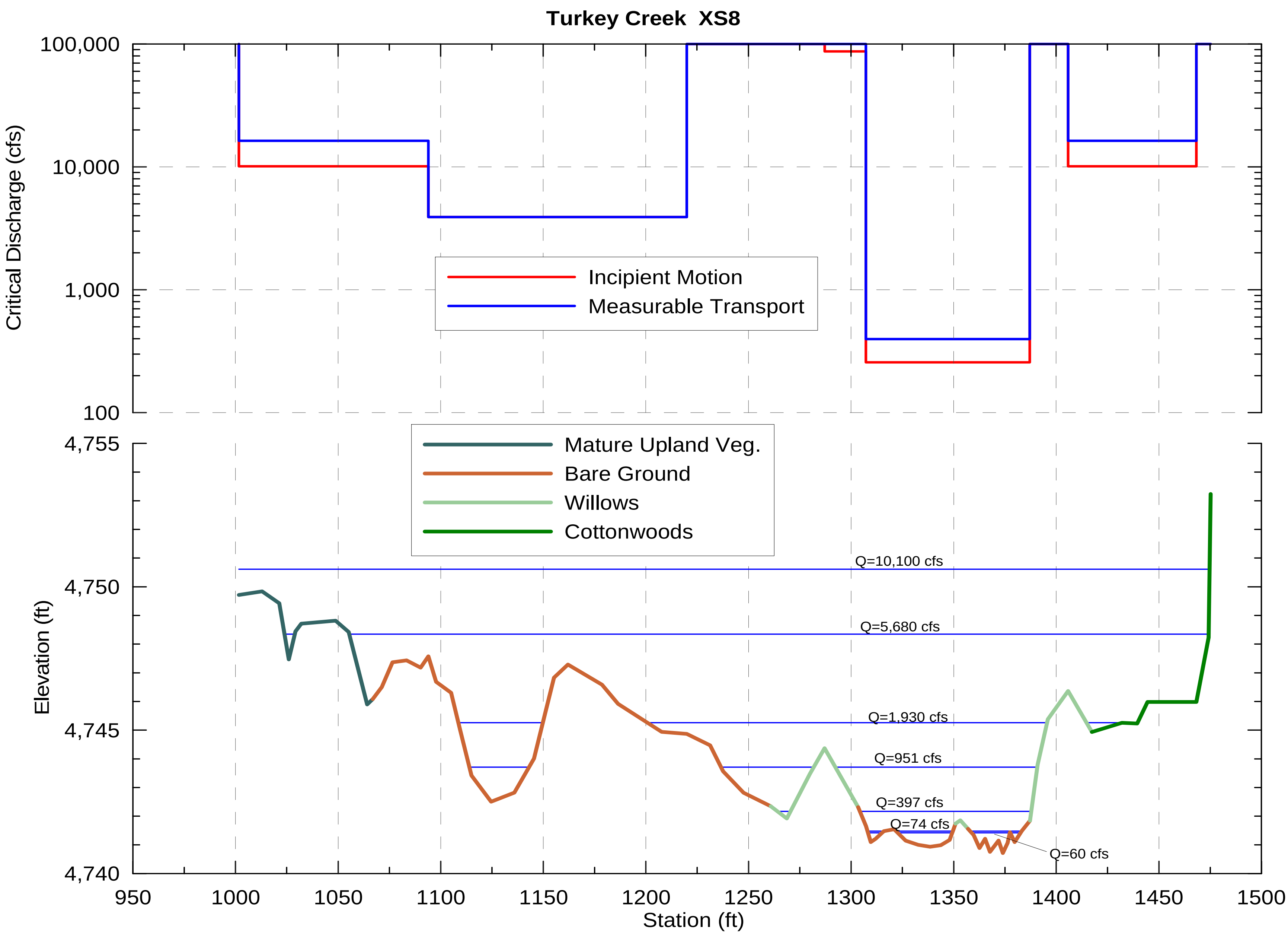

Turkey Creek XS6
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,754
4,750
4,746
4,742
4,738
4,734
Mature Upland Veg.
Bare Ground
Cottonwoods and Willows
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
1000
1050
1100
1150
1200
1250
1300
Station (ft)



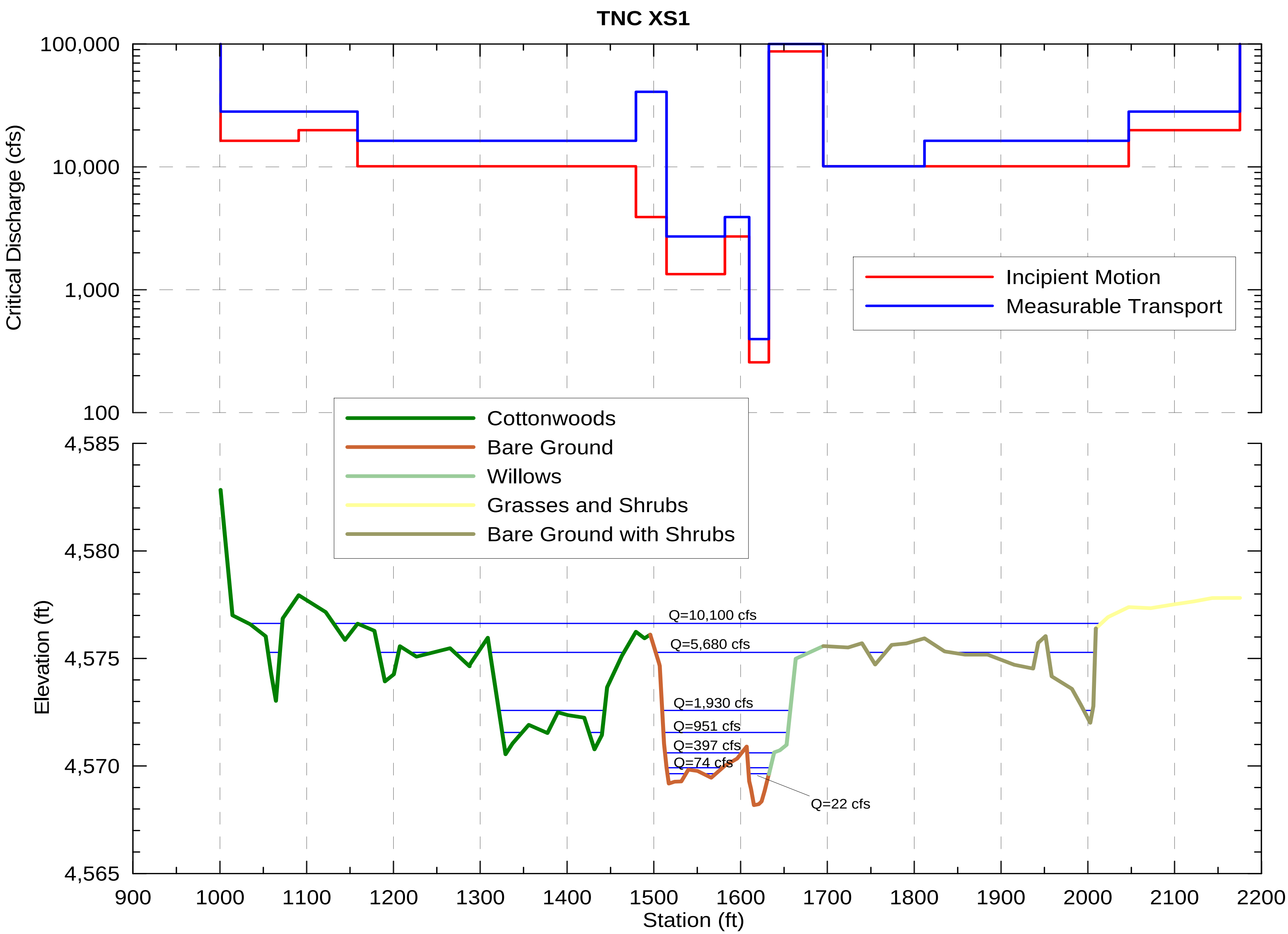
Turkey Creek XS7
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,755
4,750
4,745
4,740
4,735
Mature Upland Veg.
Bare Ground
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
Station (ft)



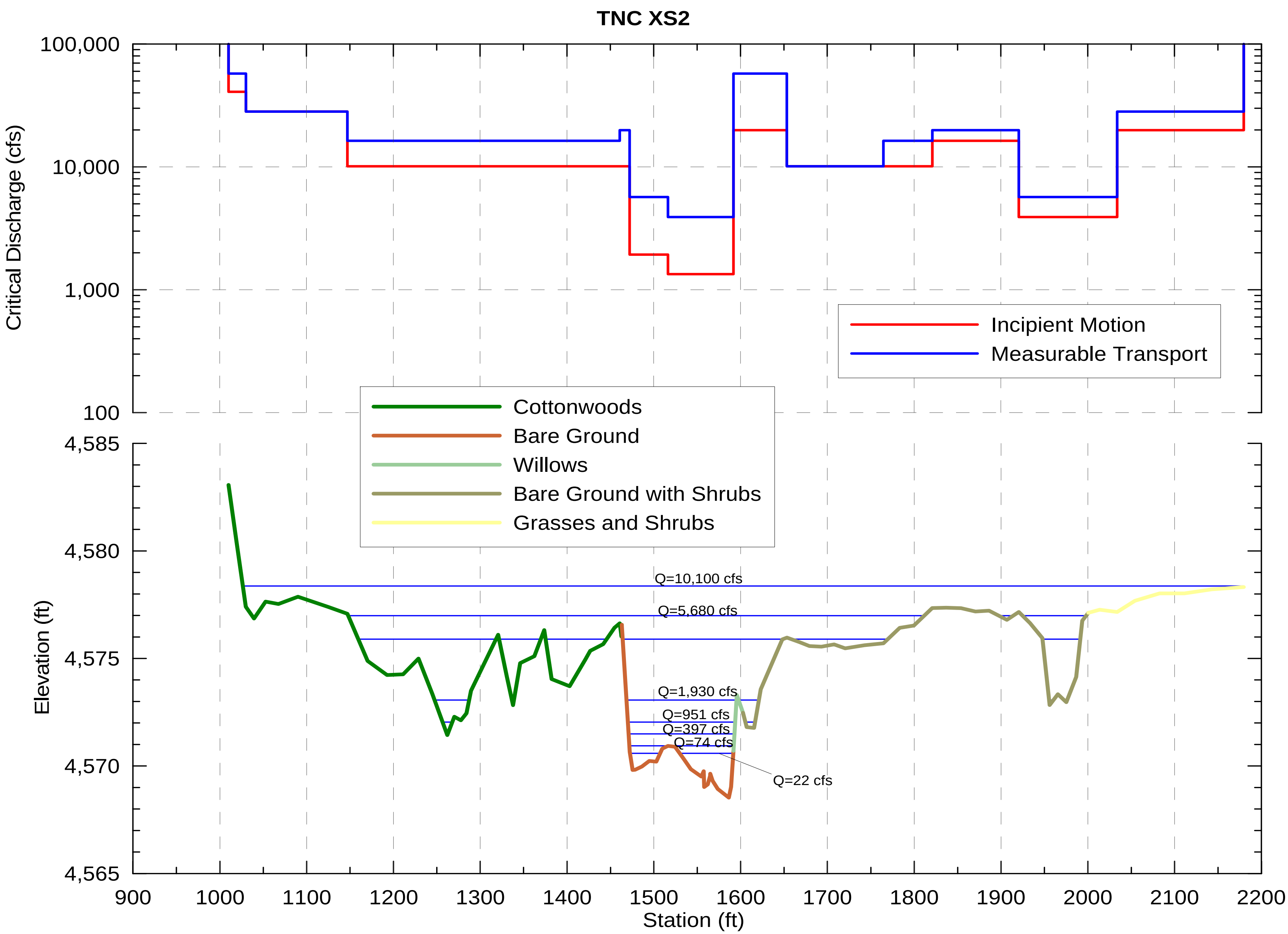
Turkey Creek XS7.5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Mature Upland Veg.
Bare Ground
Willows
Elevation (ft)
4,754
4,750
4,746
4,742
4,738
4,734
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
Station (ft)

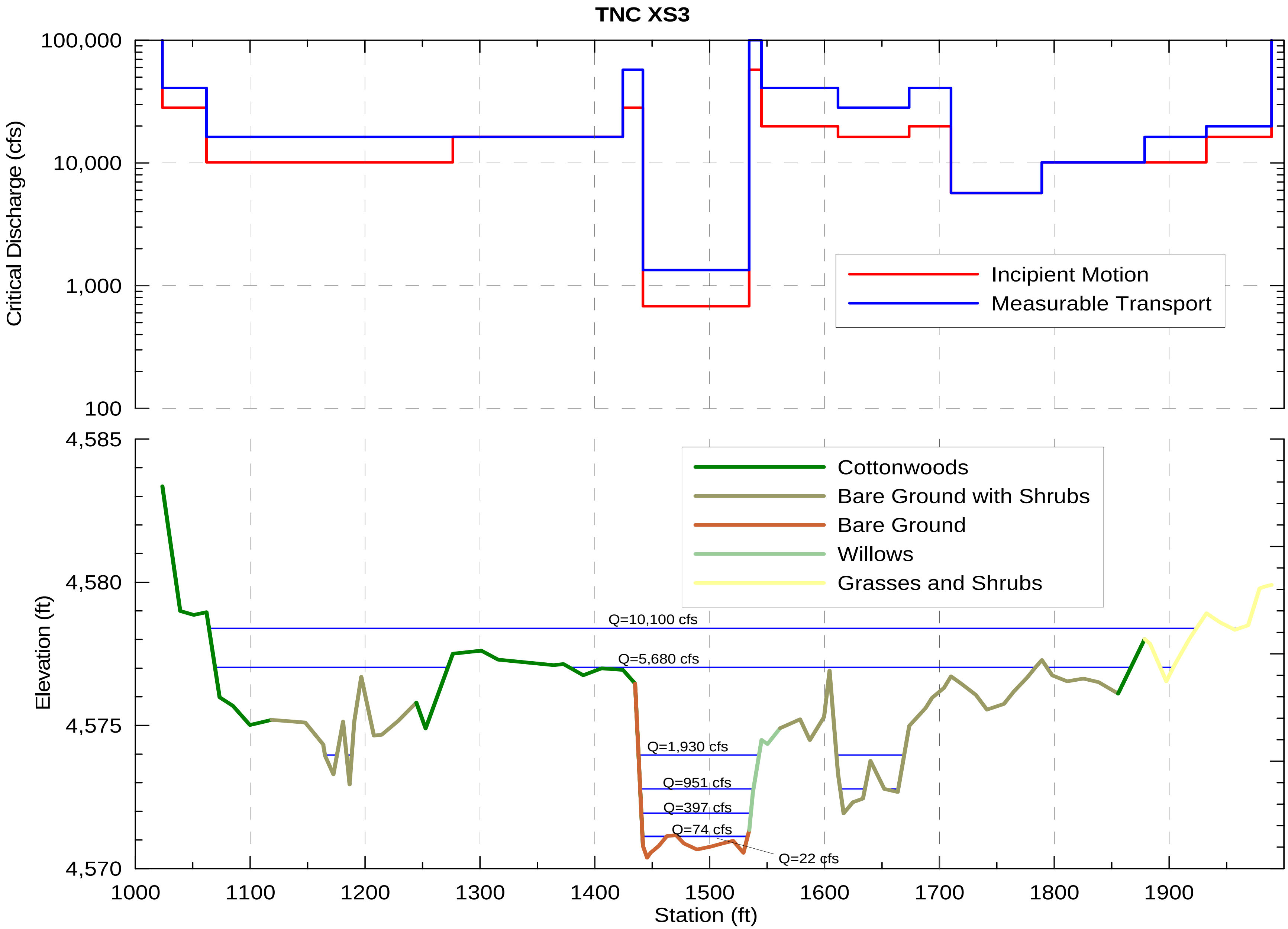


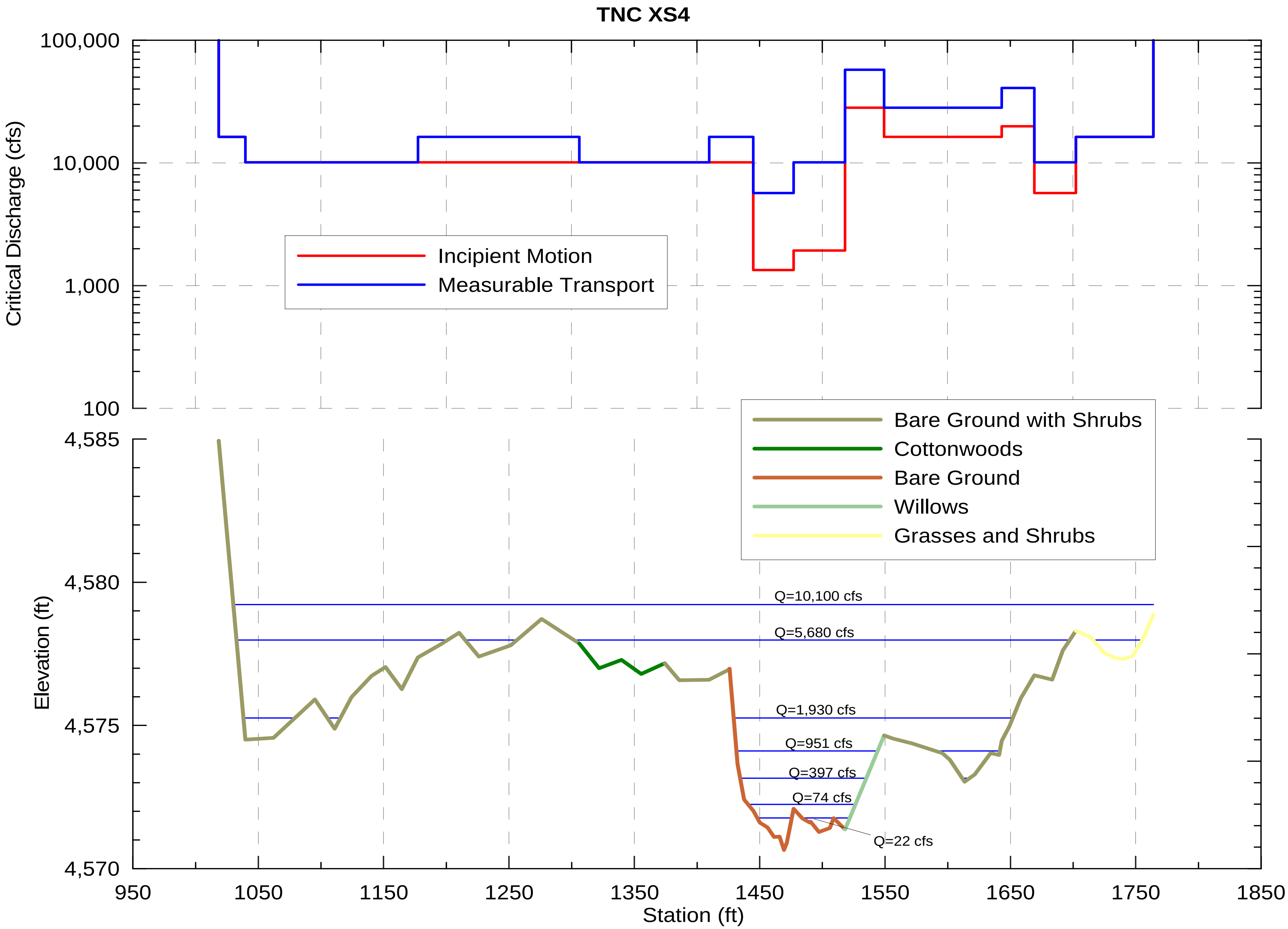
Turkey Creek XS8
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,755
4,750
4,745
4,740
Mature Upland Veg.
Bare Ground
Willows
Cottonwoods
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=60 cfs
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Station (ft)

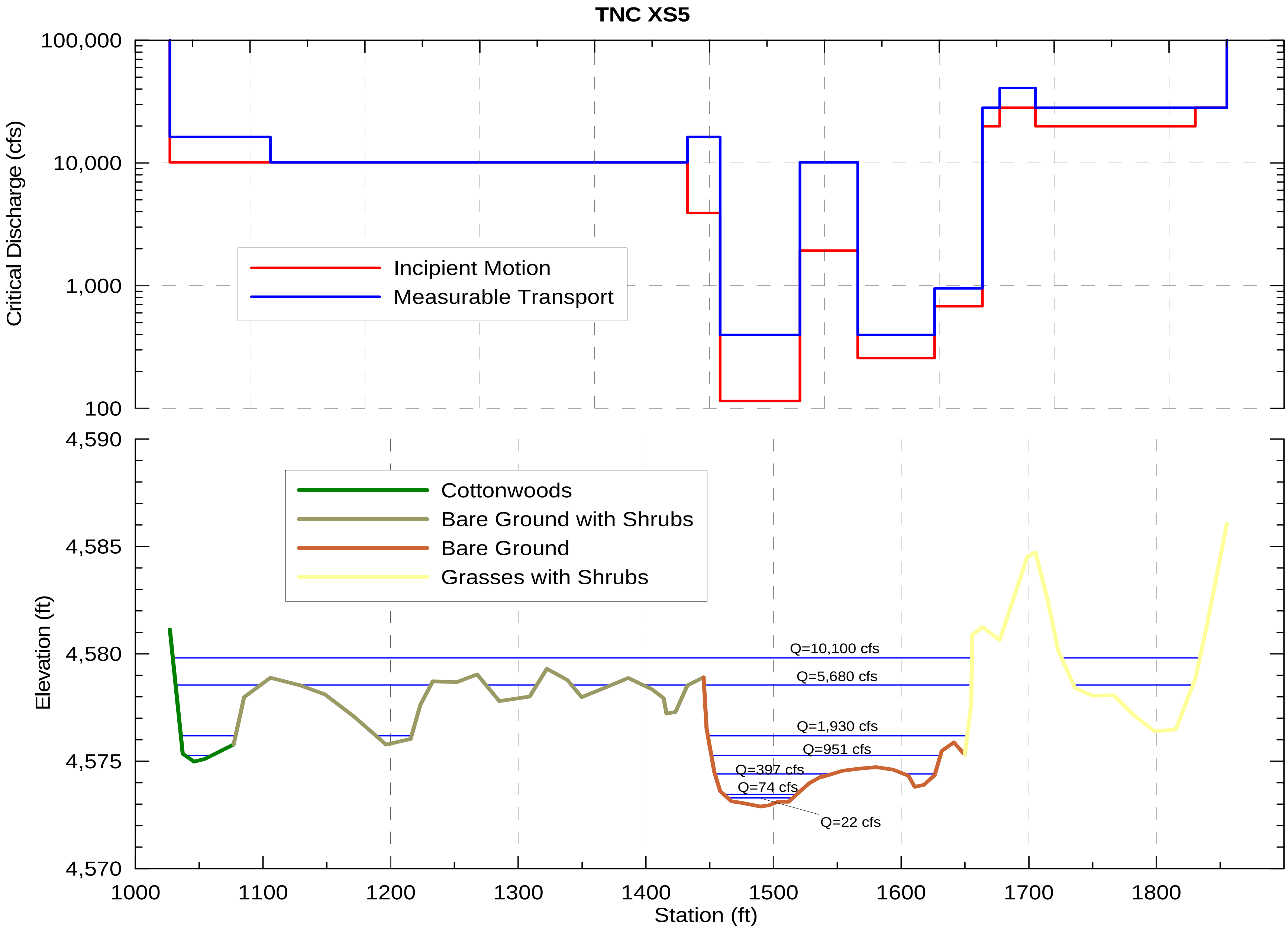


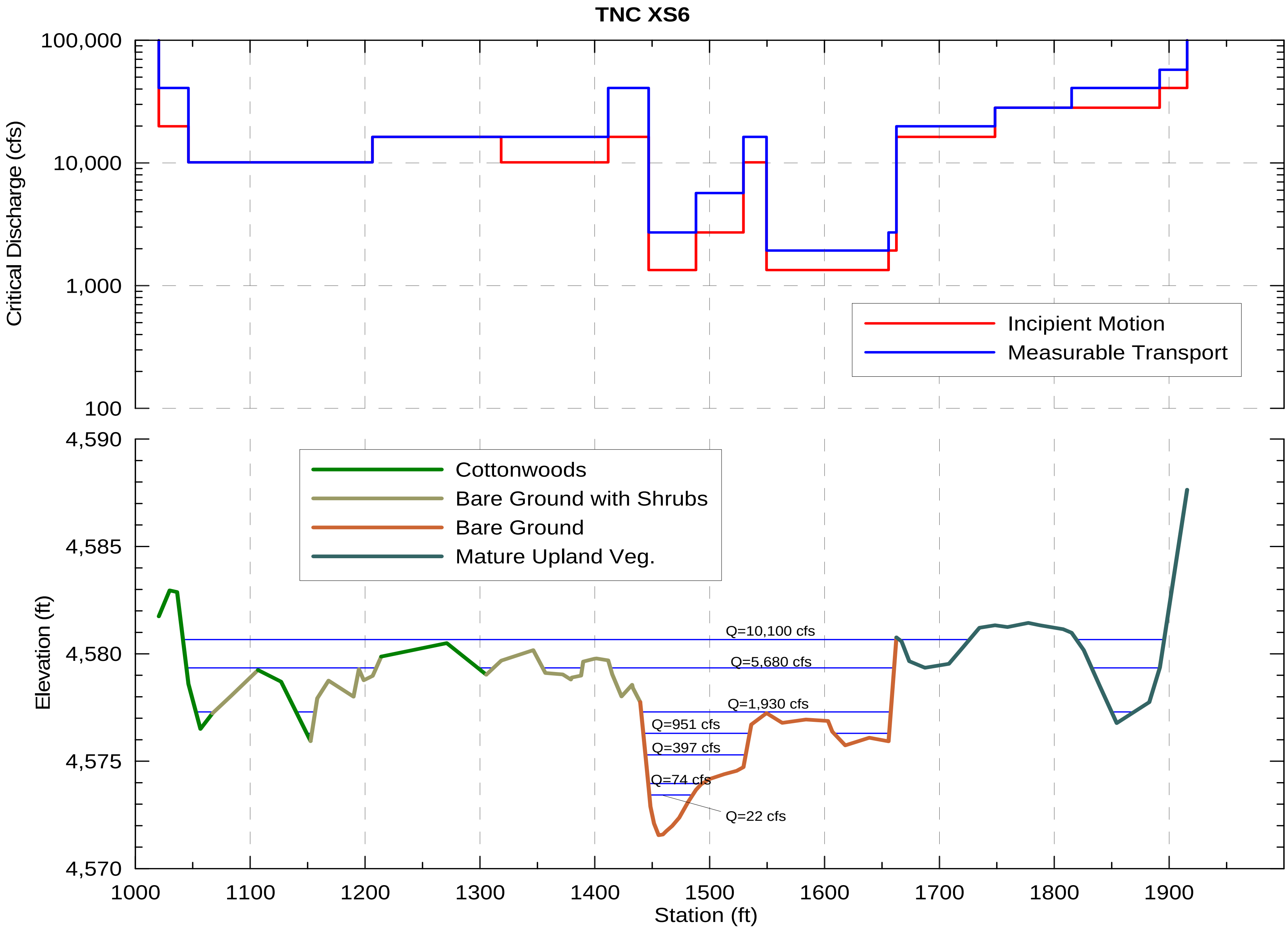
TNC XS1
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Cottonwoods
Bare Ground
Willows
Grasses and Shrubs
Bare Ground with Shrubs
Elevation (ft)
4,585
4,580
4,575
4,570
4,565
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
Station (ft)

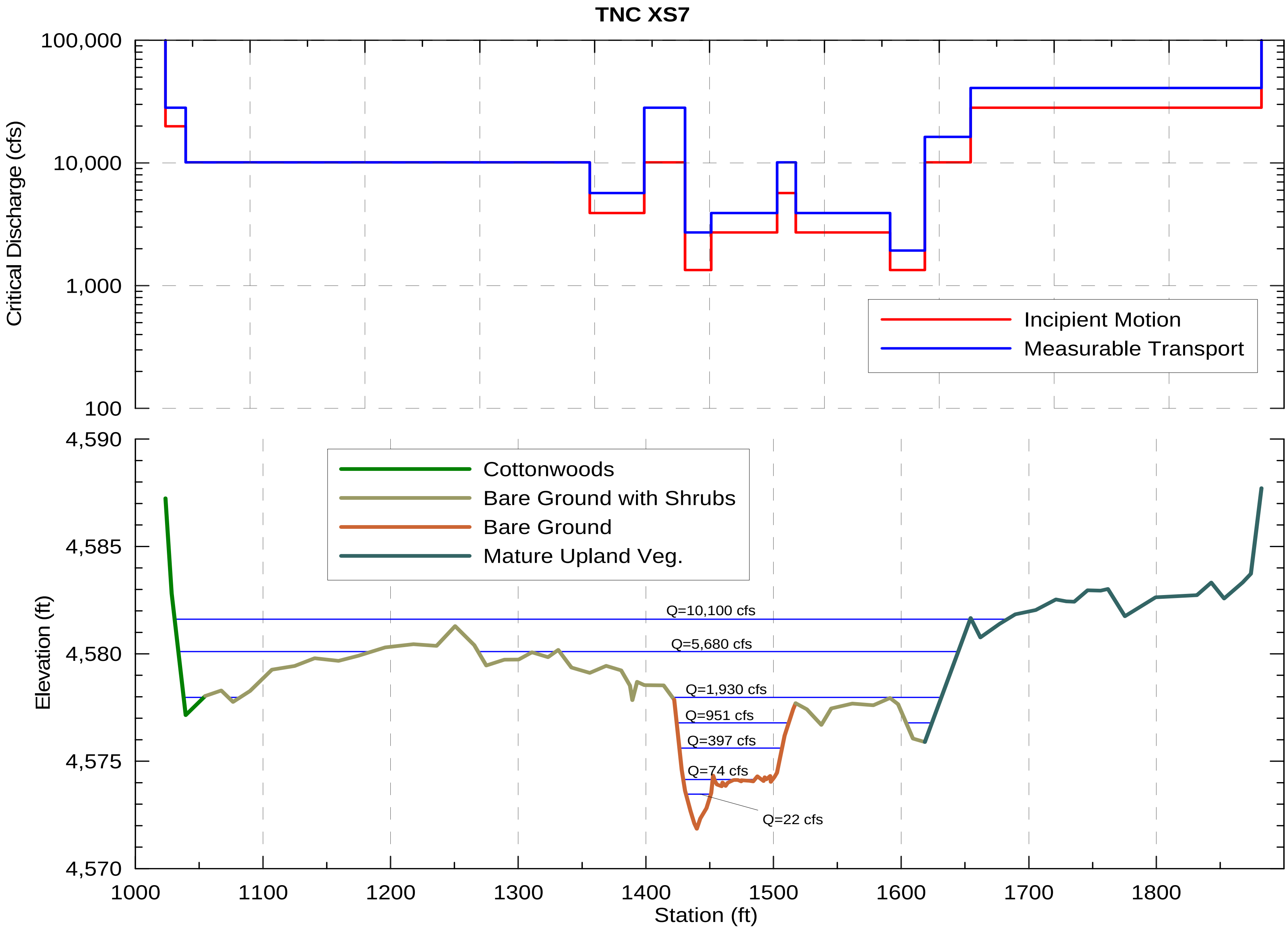

TNC XS2
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Cottonwoods
Bare Ground
Willows
Bare Ground with Shrubs
Grasses and Shrubs
Elevation (ft)
4,585
4,580
4,575
4,570
4,565
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
Station (ft)

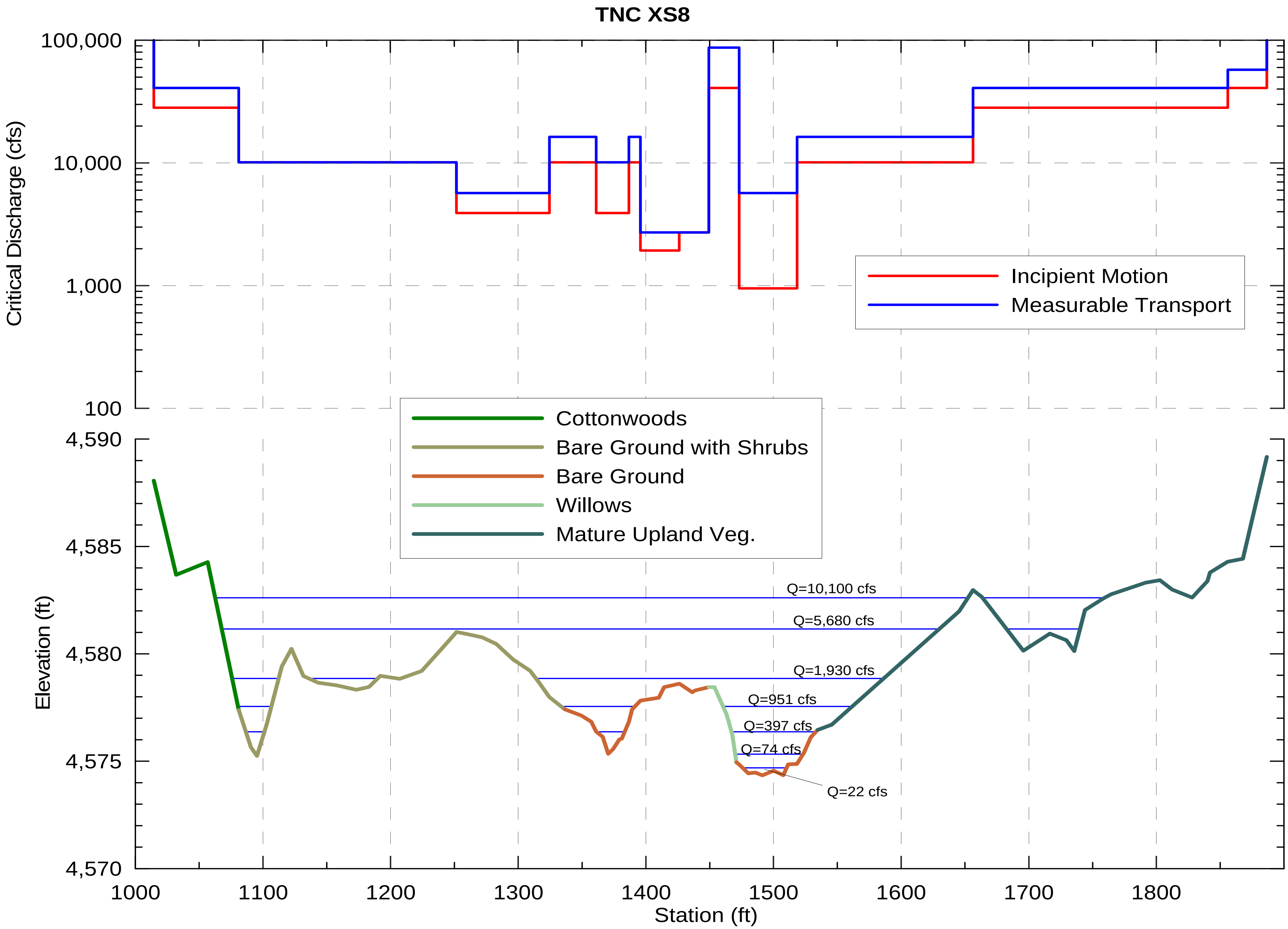

TNC XS3
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,585
4,580
4,575
4,570
Cottonwoods
Bare Ground with Shrubs
Bare Ground
Willows
Grasses and Shrubs
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Station (ft)

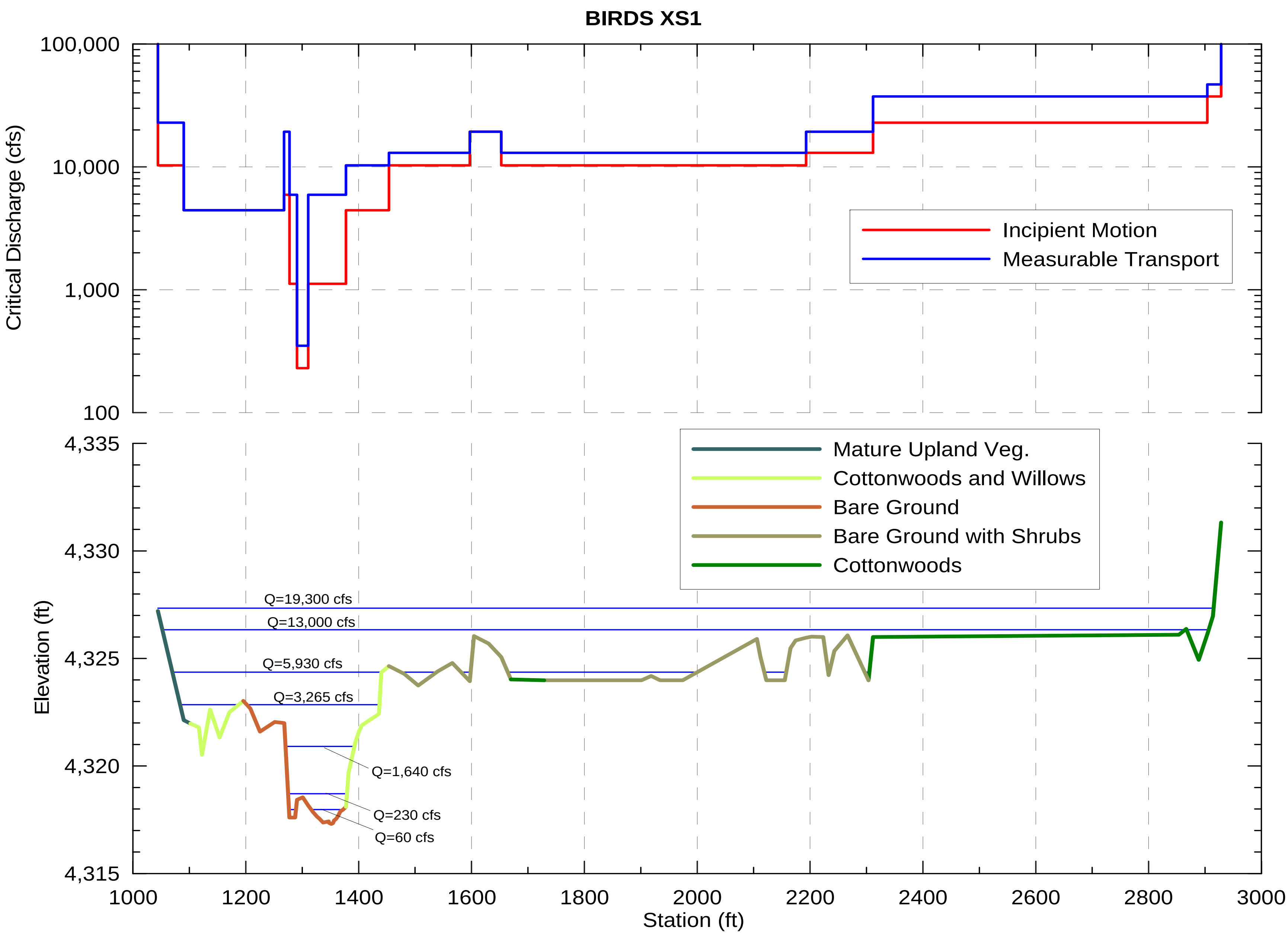

TNC XS4
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,585
4,580
4,575
4,570
Bare Ground with Shrubs
Cottonwoods
Bare Ground
Willows
Grasses and Shrubs
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
Station (ft)

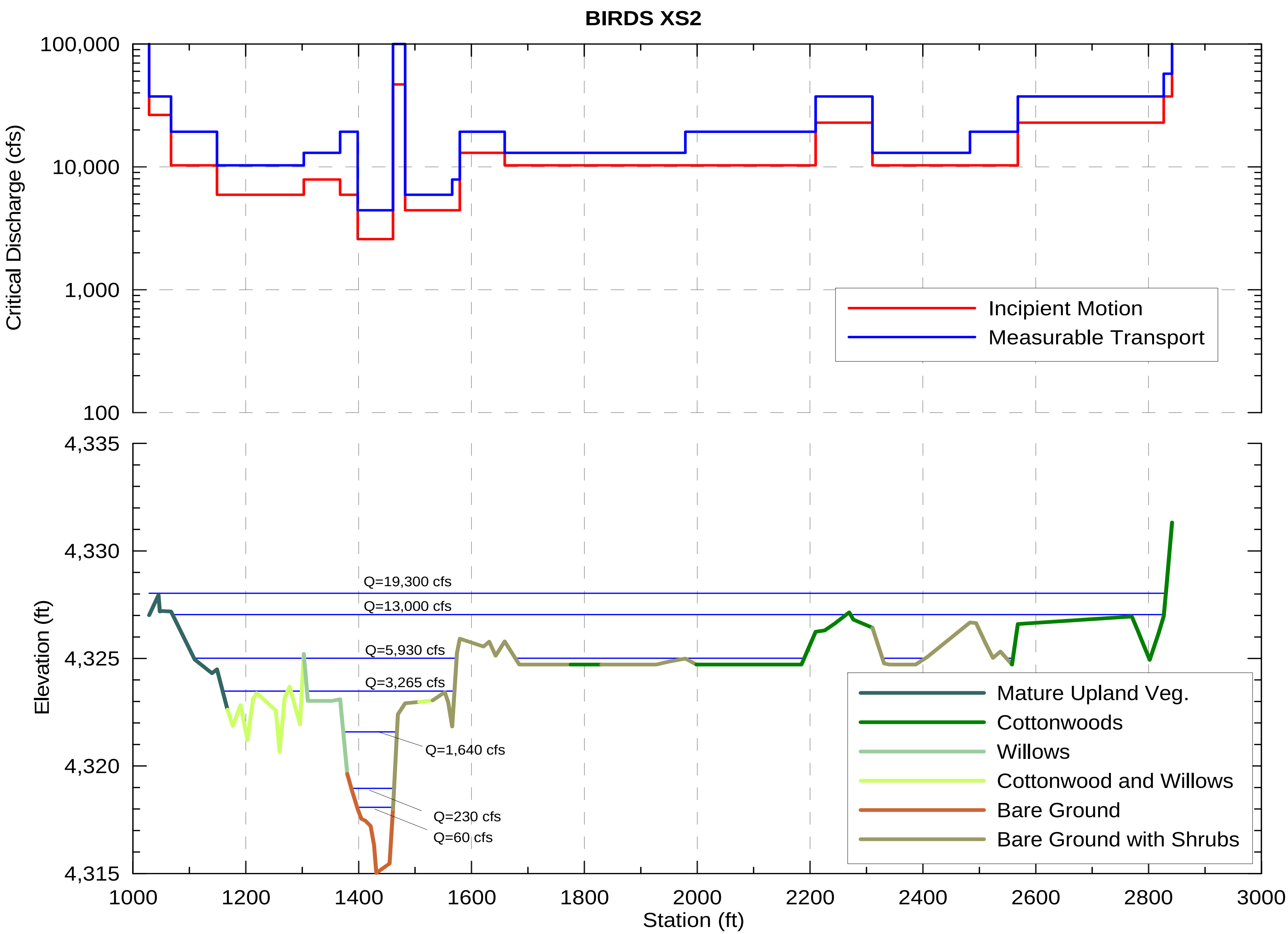

TNC XS5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,590
4,585
4,580
4,575
4,570
Cottonwoods
Bare Ground with Shrubs
Bare Ground
Grasses with Shrubs
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
Station (ft)

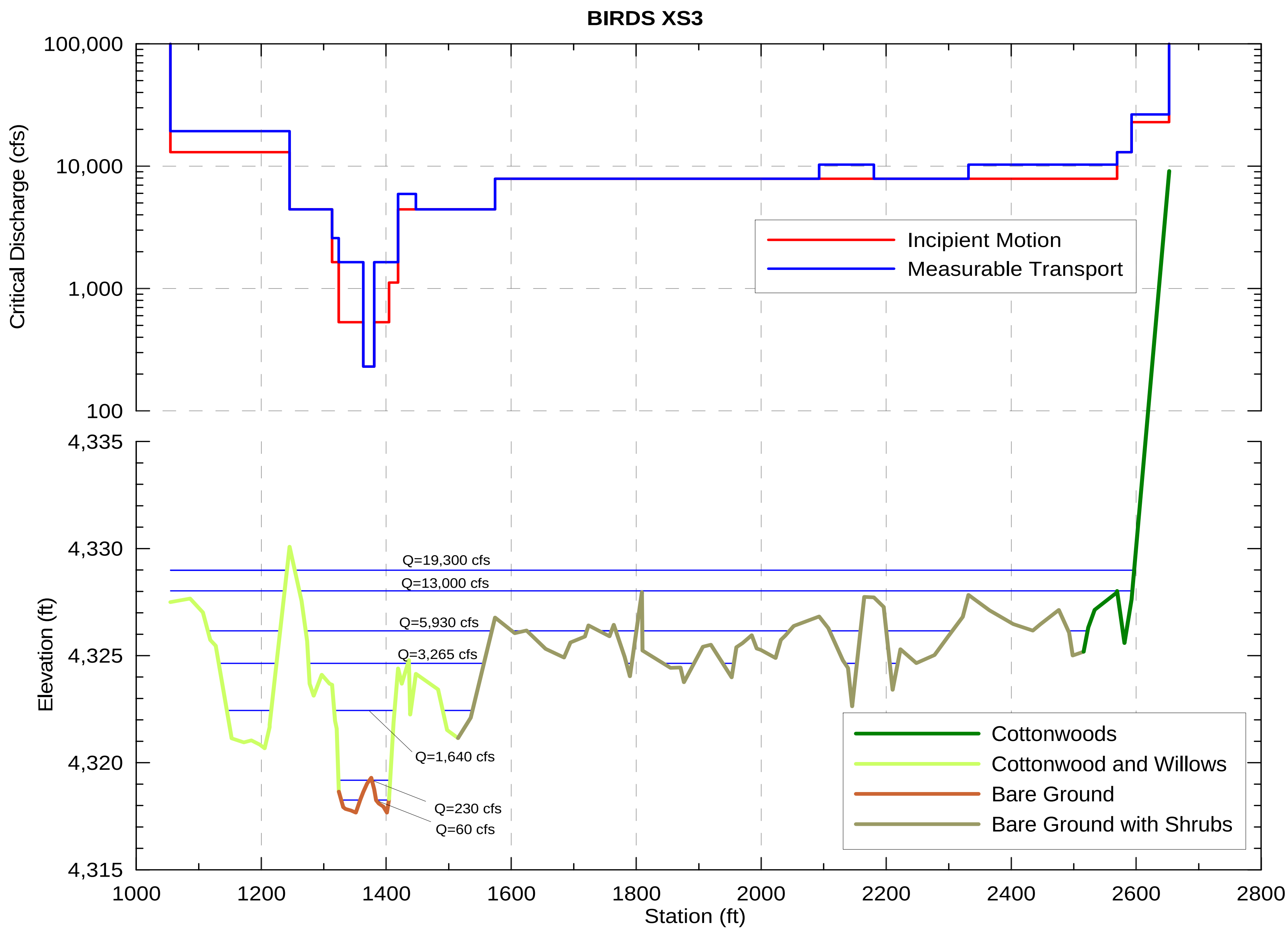

TNC XS6
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,590
4,585
4,580
4,575
4,570
Cottonwoods
Bare Ground with Shrubs
Bare Ground
Mature Upland Veg.
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Station (ft)

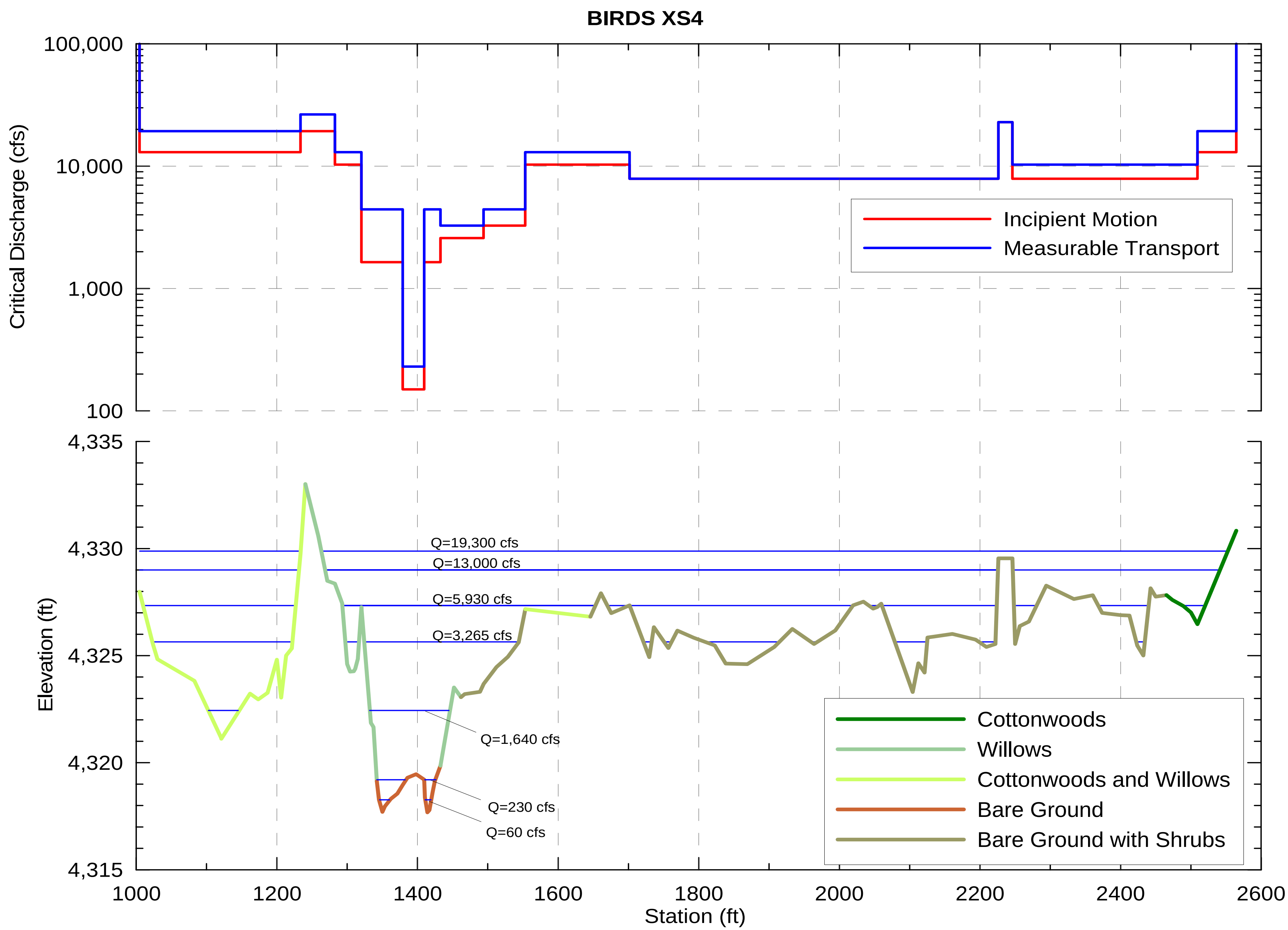

TNC XS7
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,590
4,585
4,580
4,575
4,570
Cottonwoods
Bare Ground with Shrubs
Bare Ground
Mature Upland Veg.
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
Station (ft)

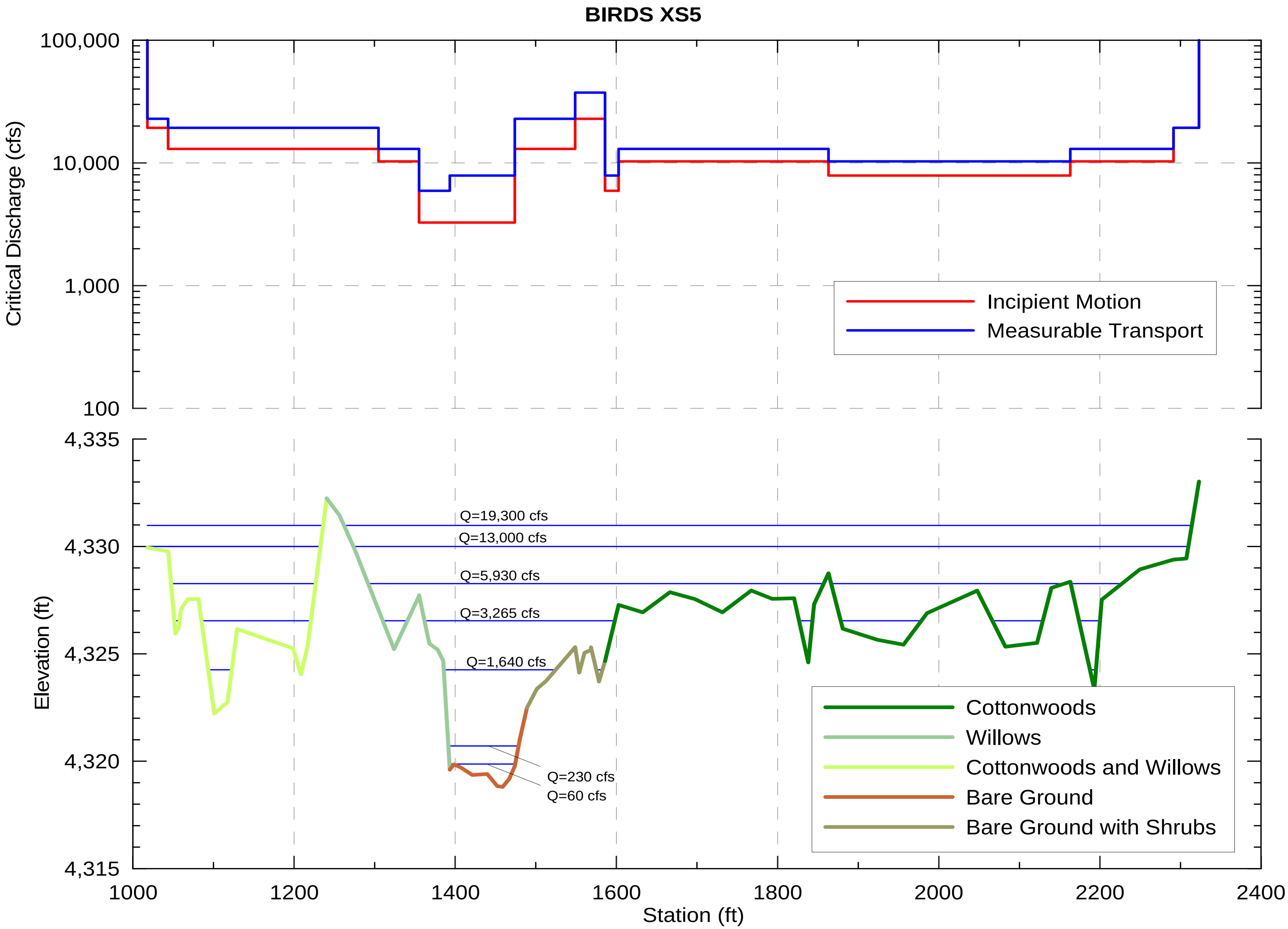

TNC XS8
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Cottonwoods
Bare Ground with Shrubs
Bare Ground
Willows
Mature Upland Veg.
Elevation (ft)
4,590
4,585
4,580
4,575
4,570
Q=10,100 cfs
Q=5,680 cfs
Q=1,930 cfs
Q=951 cfs
Q=397 cfs
Q=74 cfs
Q=22 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
Station (ft)


BIRDS XS1
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,335
4,330
4,325
4,320
4,315
Mature Upland Veg.
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Cottonwoods
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Station (ft)

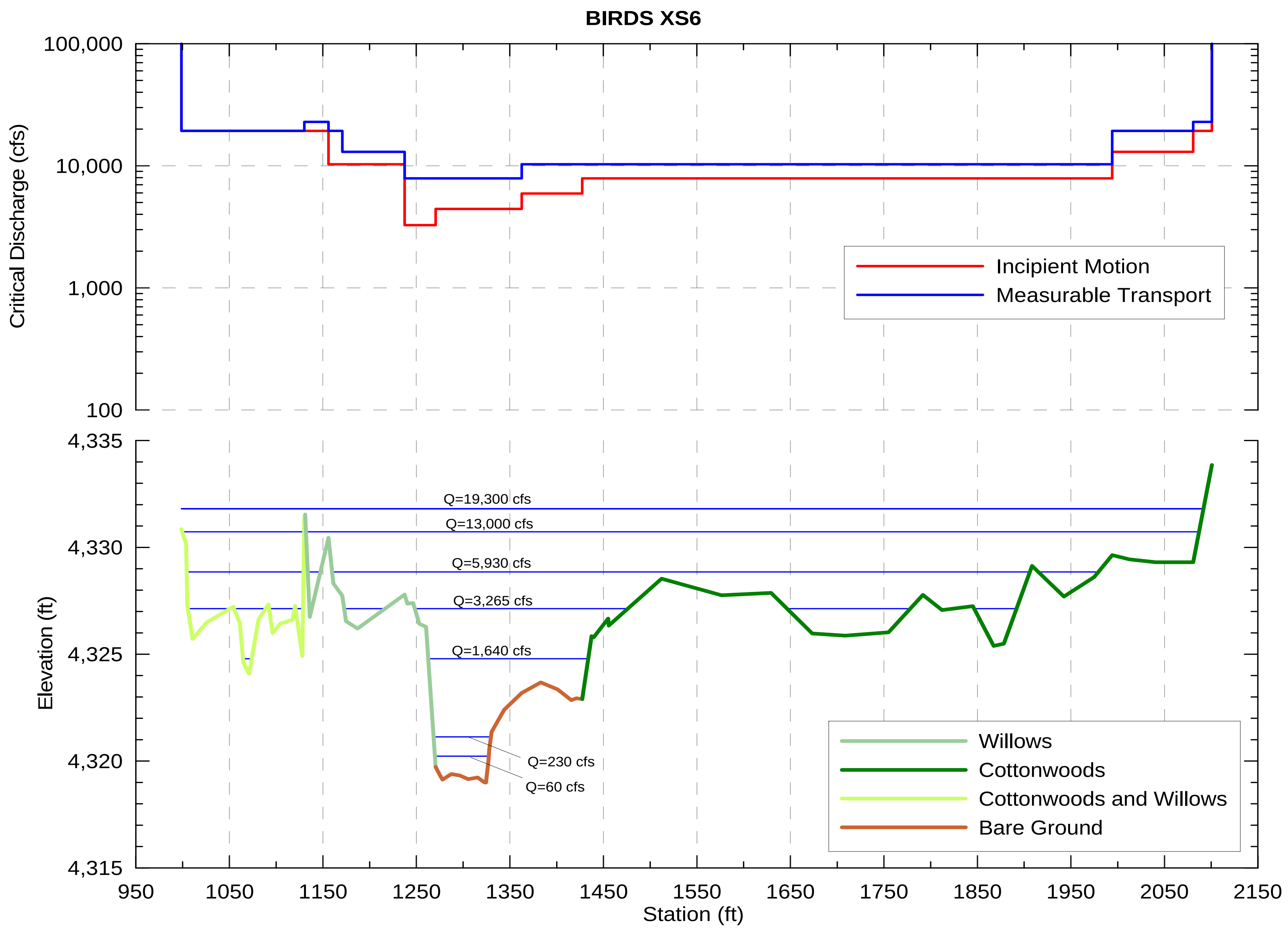

BIRDS XS2
100,000
10,000
1,000
100
Critical Discharge (cfs)
Incipient Motion
Measurable Transport
4,335
4,330
4,325
4,320
4,315
Elevation (ft)
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Mature Upland Veg.
Cottonwoods
Willows
Cottonwood and Willows
Bare Ground
Bare Ground with Shrubs
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Station (ft)

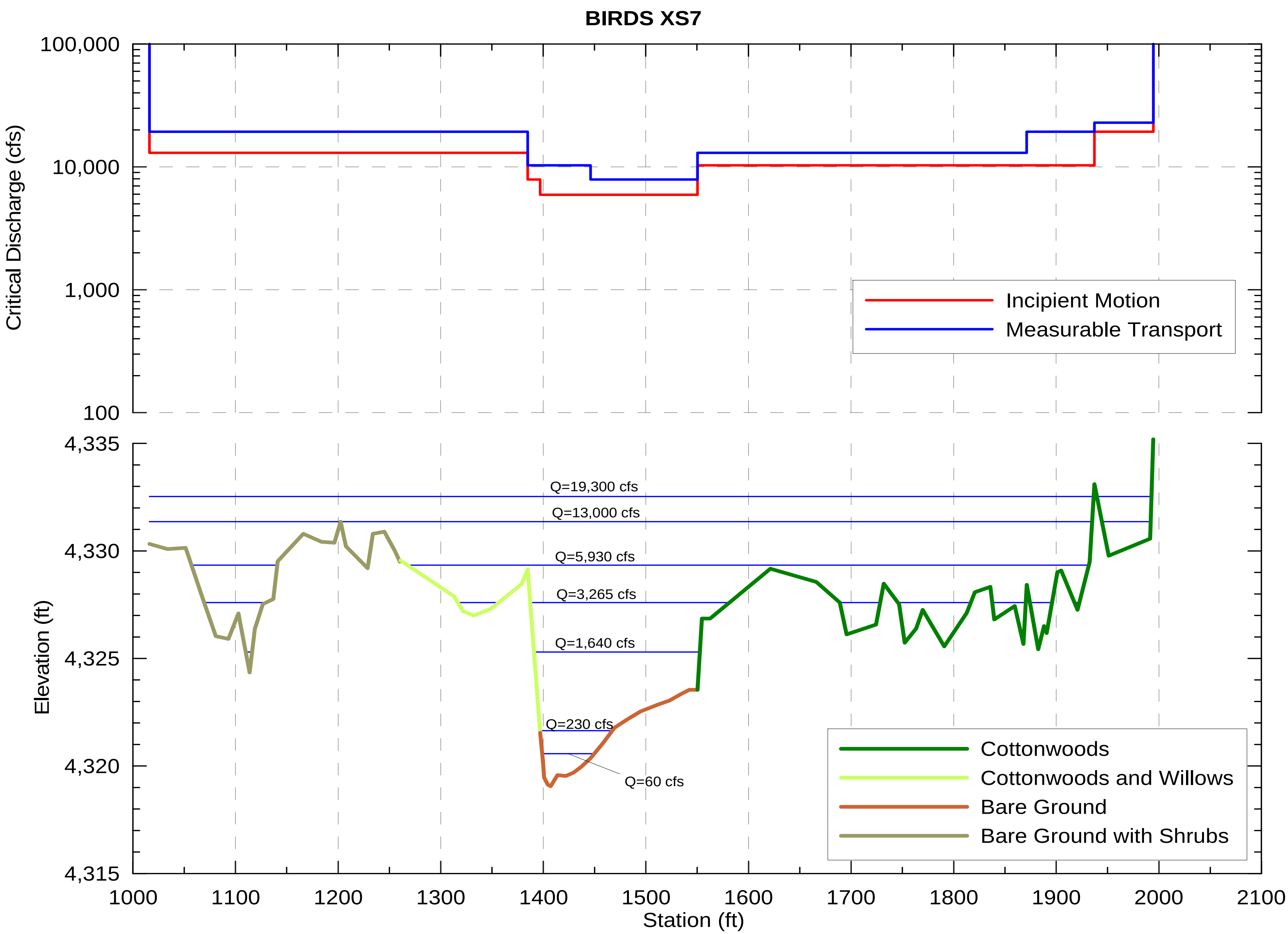

BIRDS XS3
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,335
4,330
4,325
4,320
4,315
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Cottonwoods
Cottonwood and Willows
Bare Ground
Bare Ground with Shrubs
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Station (ft)


BIRDS XS4
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,335
4,330
4,325
4,320
4,315
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Cottonwoods
Willows
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
1000
1200
1400
1600
1800
2000
2200
2400
2600
Station (ft)

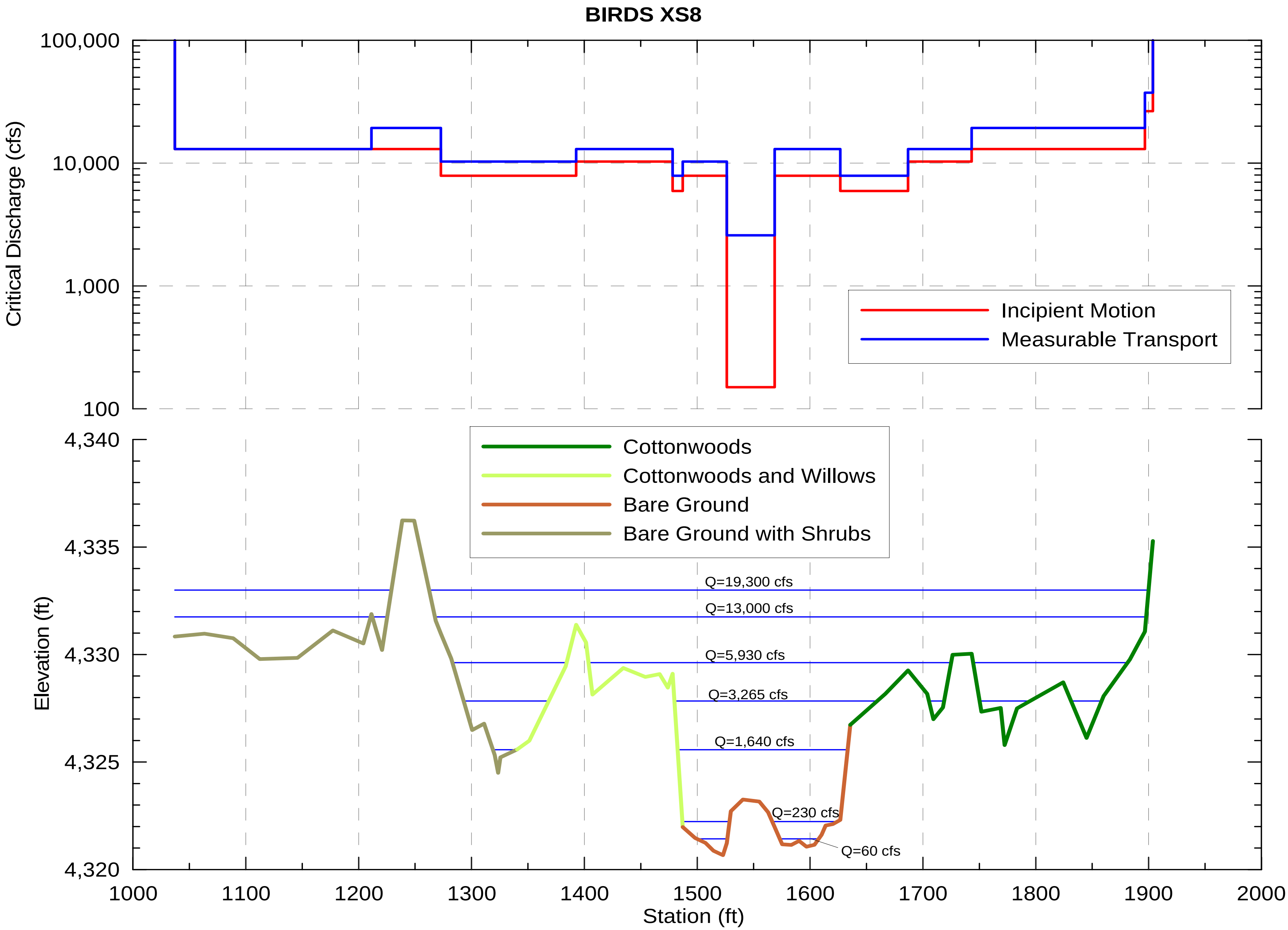


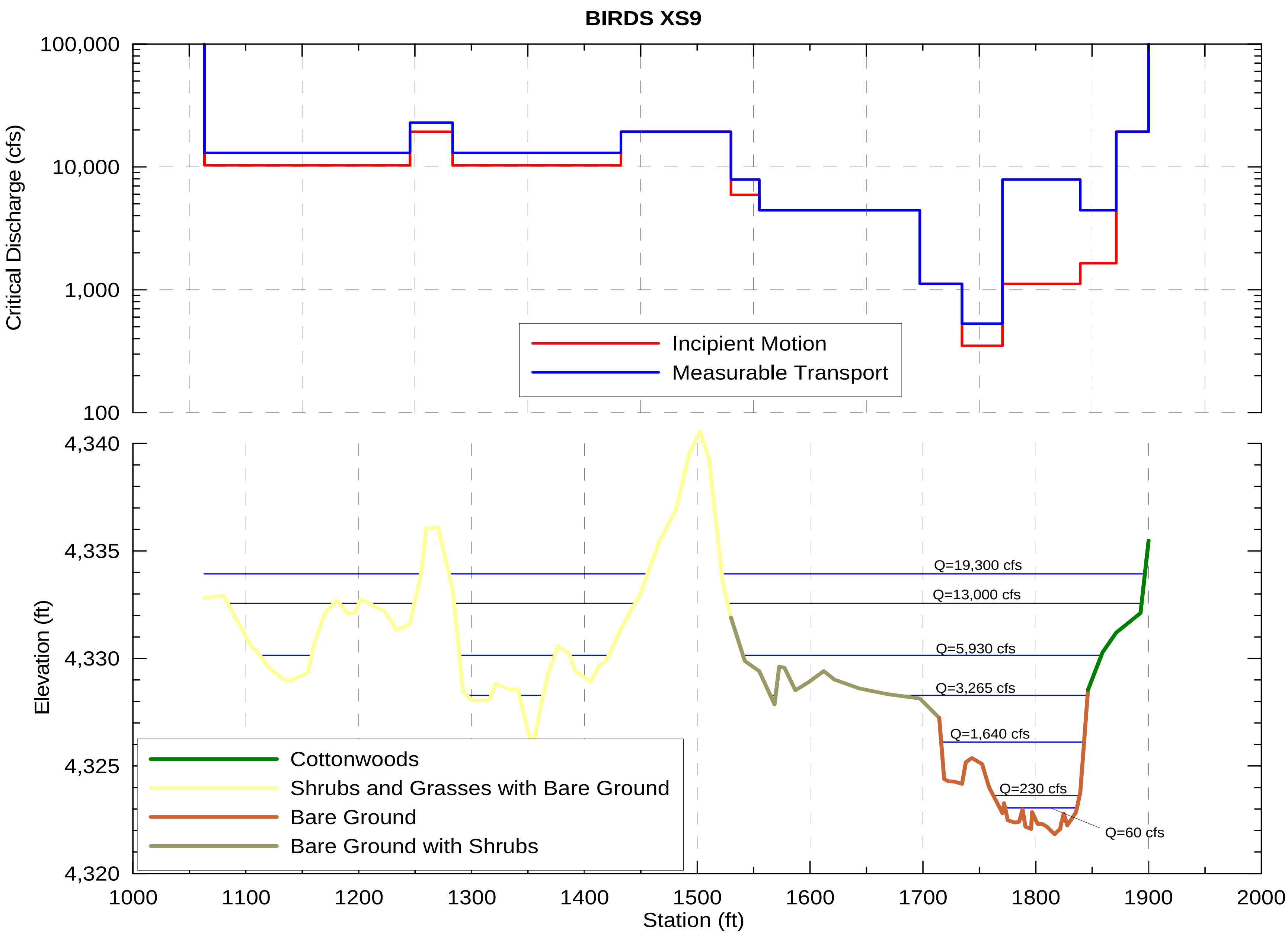
BIRDS XS5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,335
4,330
4,325
4,320
4,315
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Cottonwoods
Willows
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
1000
1200
1400
1600
1800
2000
2200
2400
Station (ft)


BIRDS XS6
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,335
4,330
4,325
4,320
4,315
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Willows
Cottonwoods
Cottonwoods and Willows
Bare Ground
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2050
2150
Station (ft)

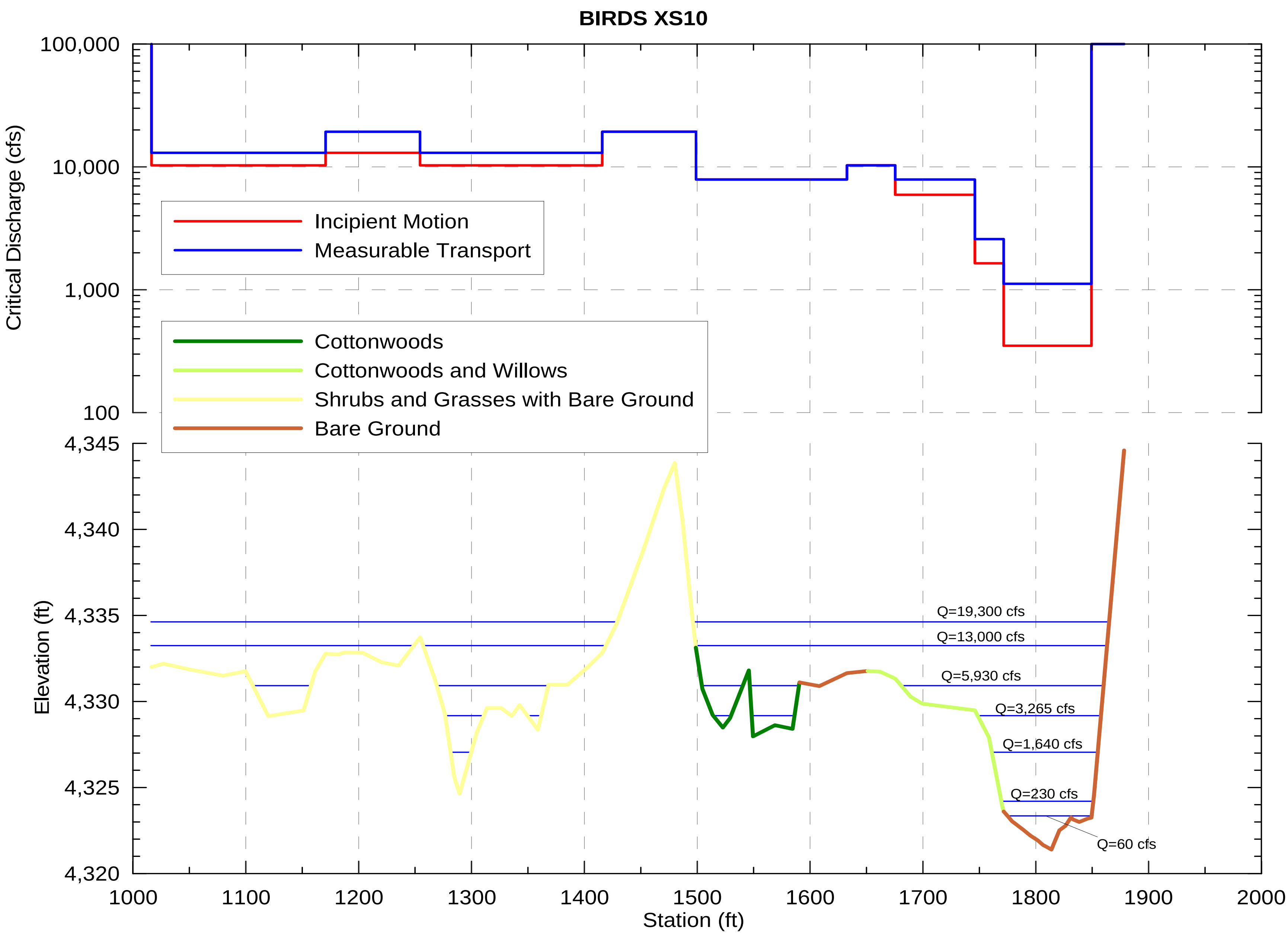


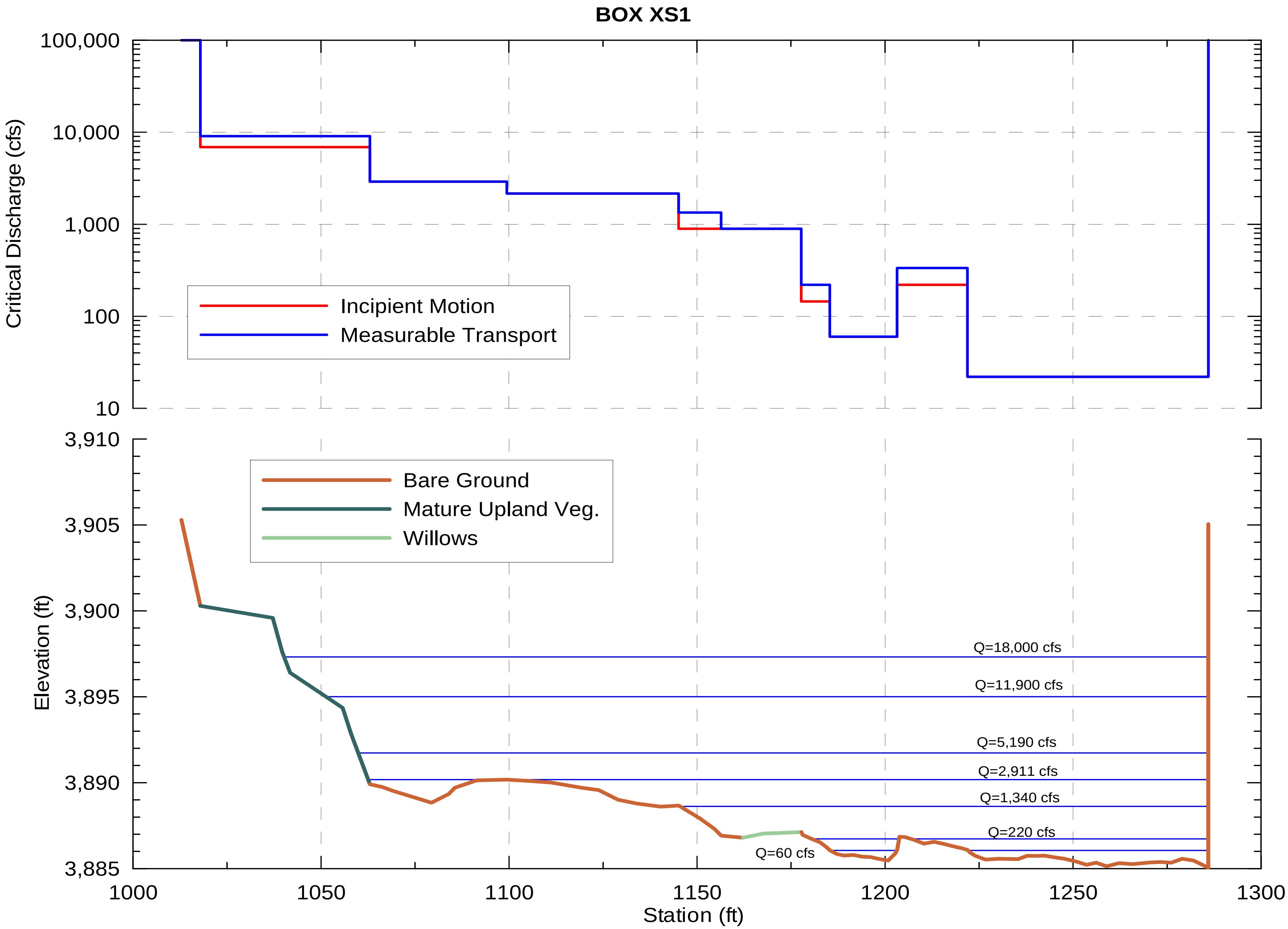
BIRDS XS7
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,335
4,330
4,325
4,320
4,315
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Station (ft)


BIRDS XS8
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,340
4,335
4,330
4,325
4,320
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Station (ft)

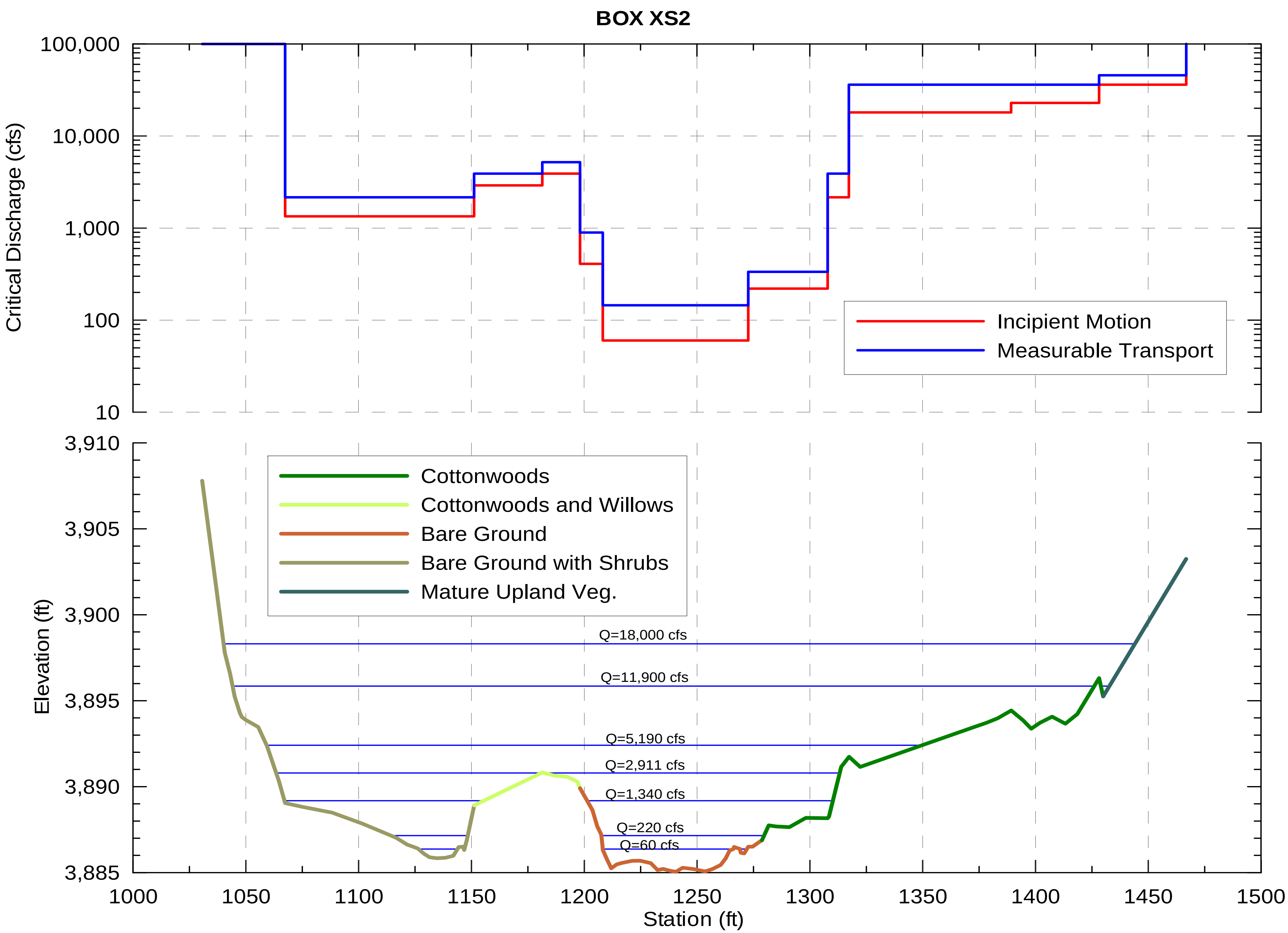


BIRDS XS9
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
4,340
4,335
4,330
4,325
4,320
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
Cottonwoods
Shrubs and Grasses with Bare Ground
Bare Ground
Bare Ground with Shrubs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Station (ft)

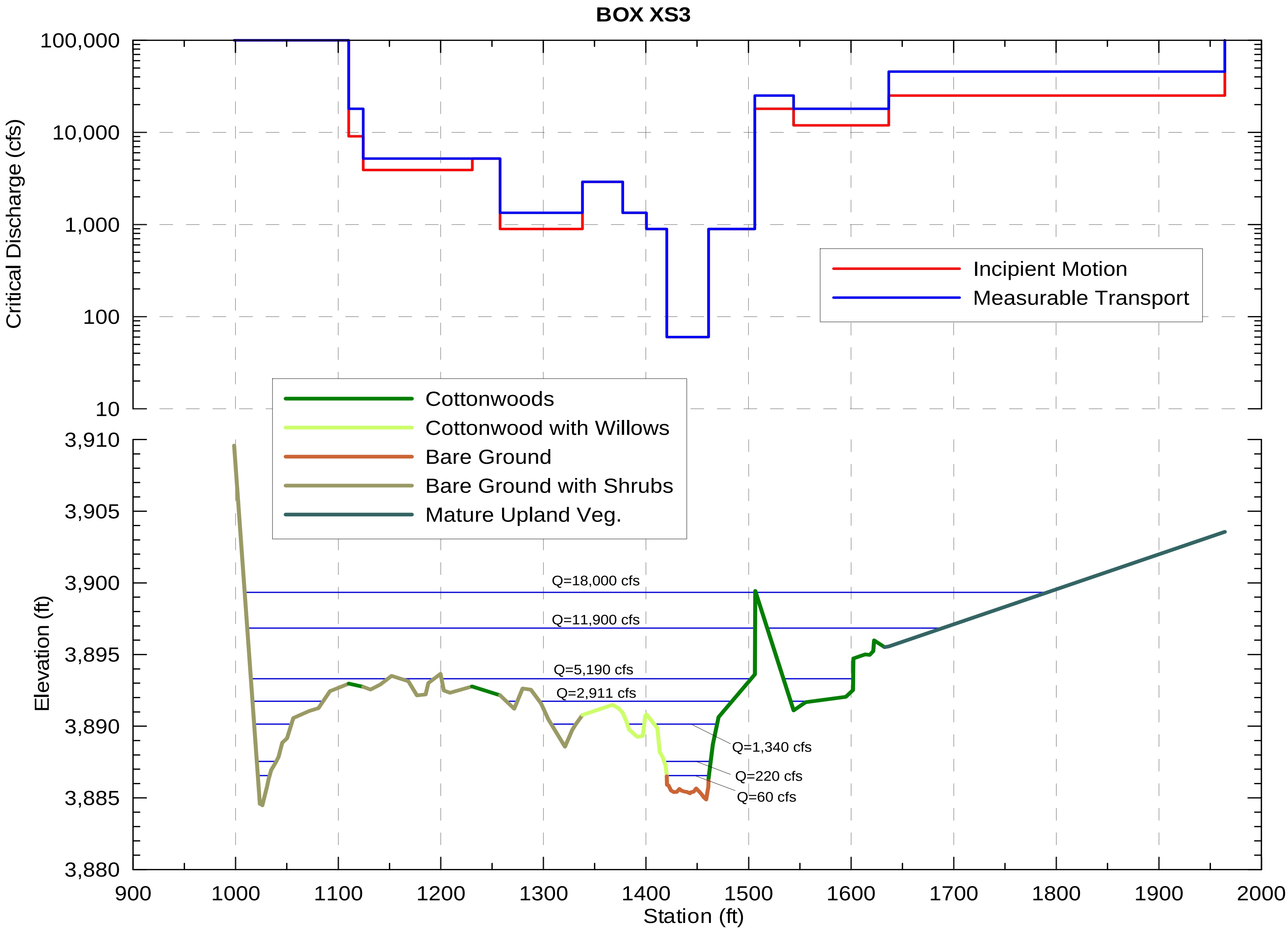

BIRDS XS10
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Cottonwoods
Cottonwoods and Willows
Shrubs and Grasses with Bare Ground
Bare Ground
Elevation (ft)
4,345
4,340
4,335
4,330
4,325
4,320
Q=19,300 cfs
Q=13,000 cfs
Q=5,930 cfs
Q=3,265 cfs
Q=1,640 cfs
Q=230 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Station (ft)



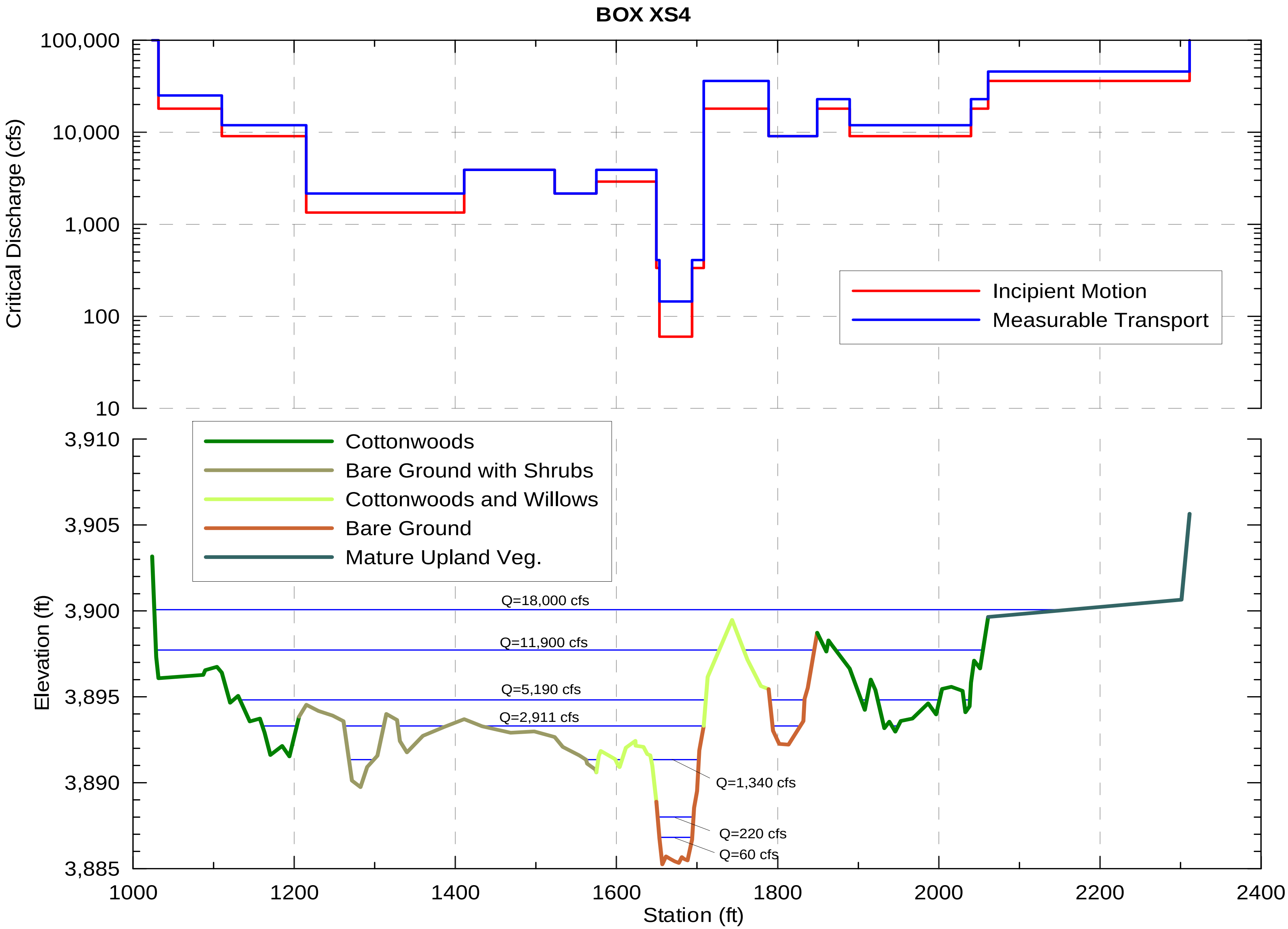
BOX XS1
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Bare Ground
Mature Upland Veg.
Willows
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1050
1100
1150
1200
1250
1300
Station (ft)

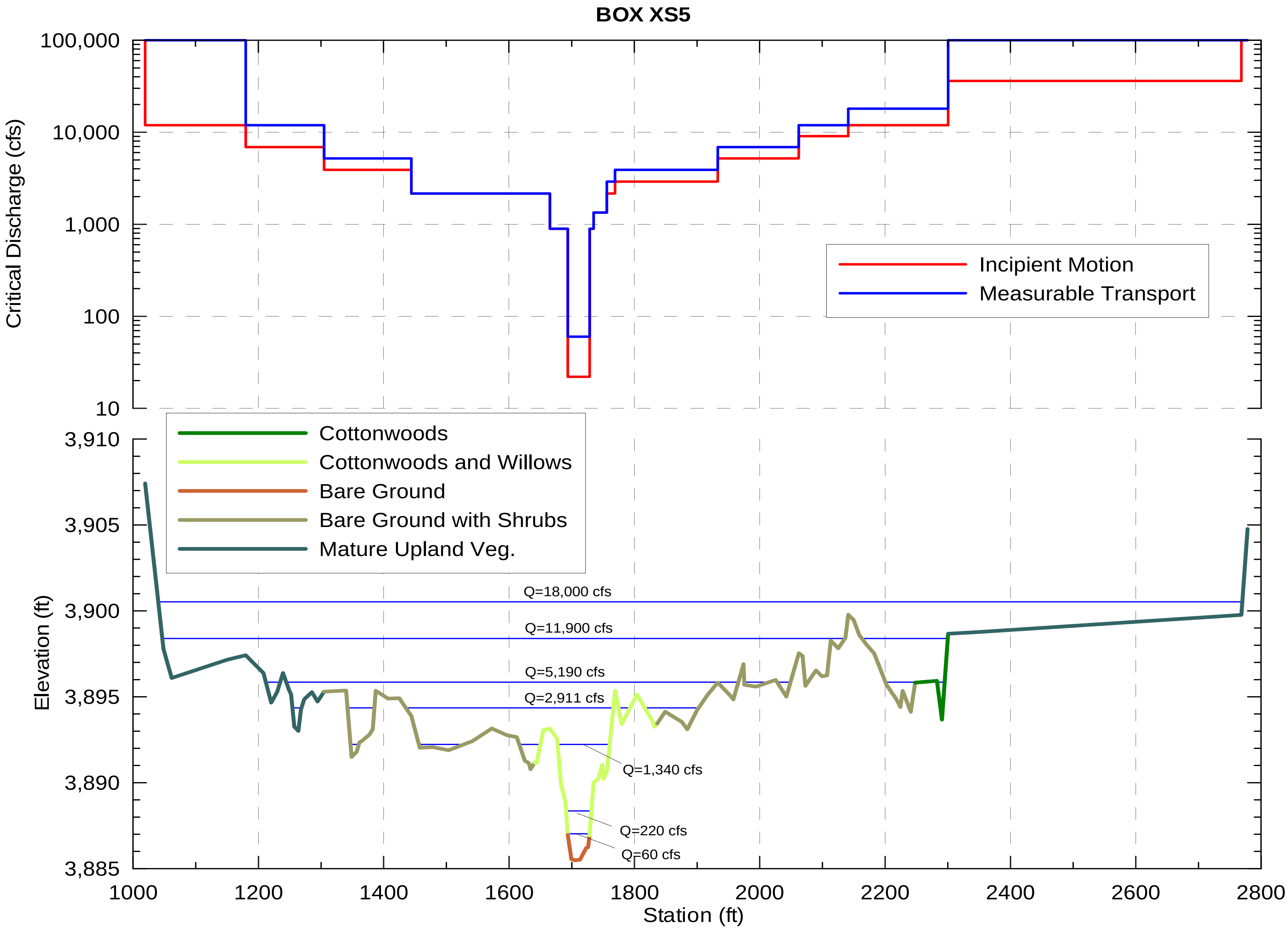


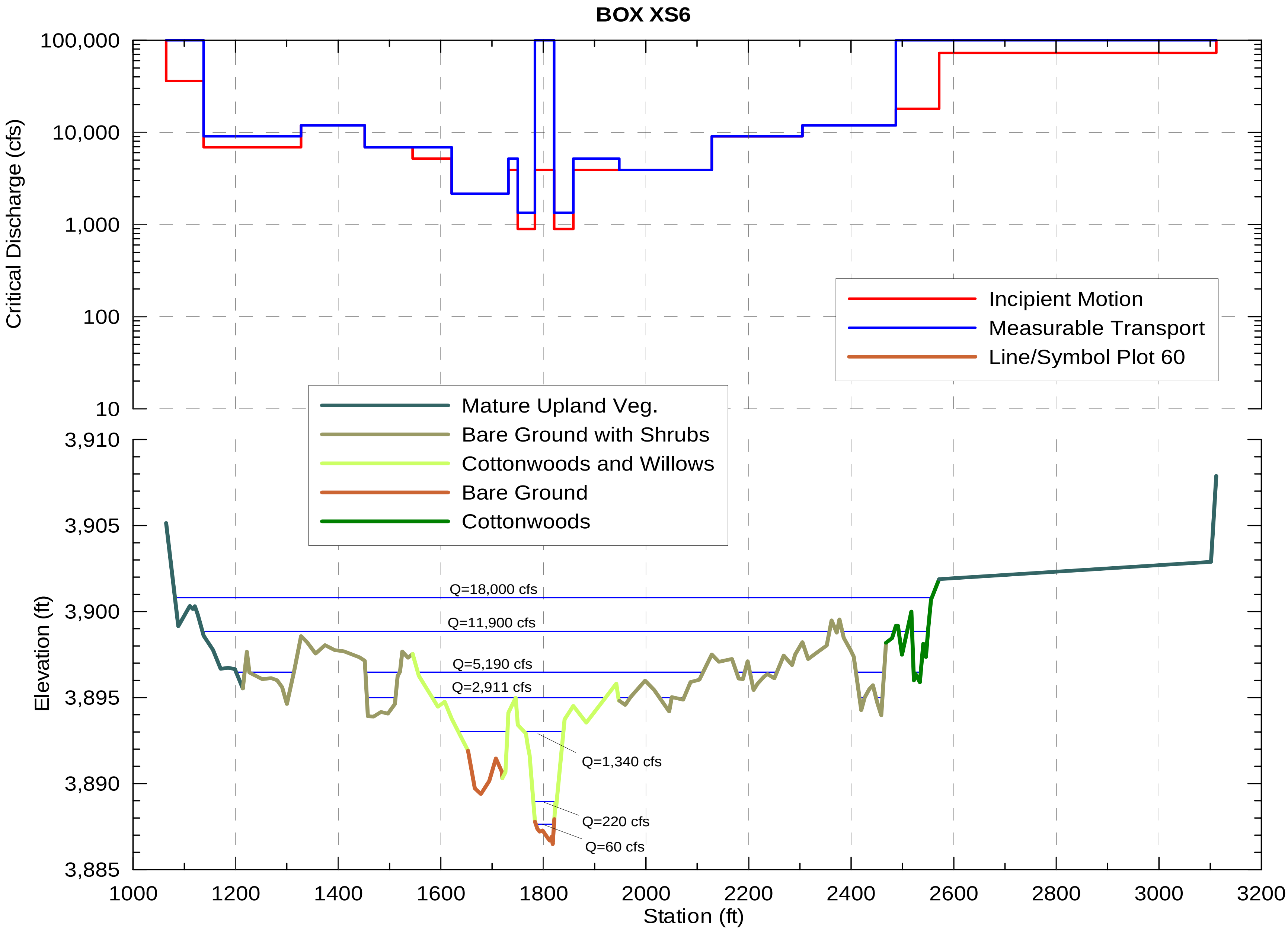
BOX XS2
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Mature Upland Veg.
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
Station (ft)



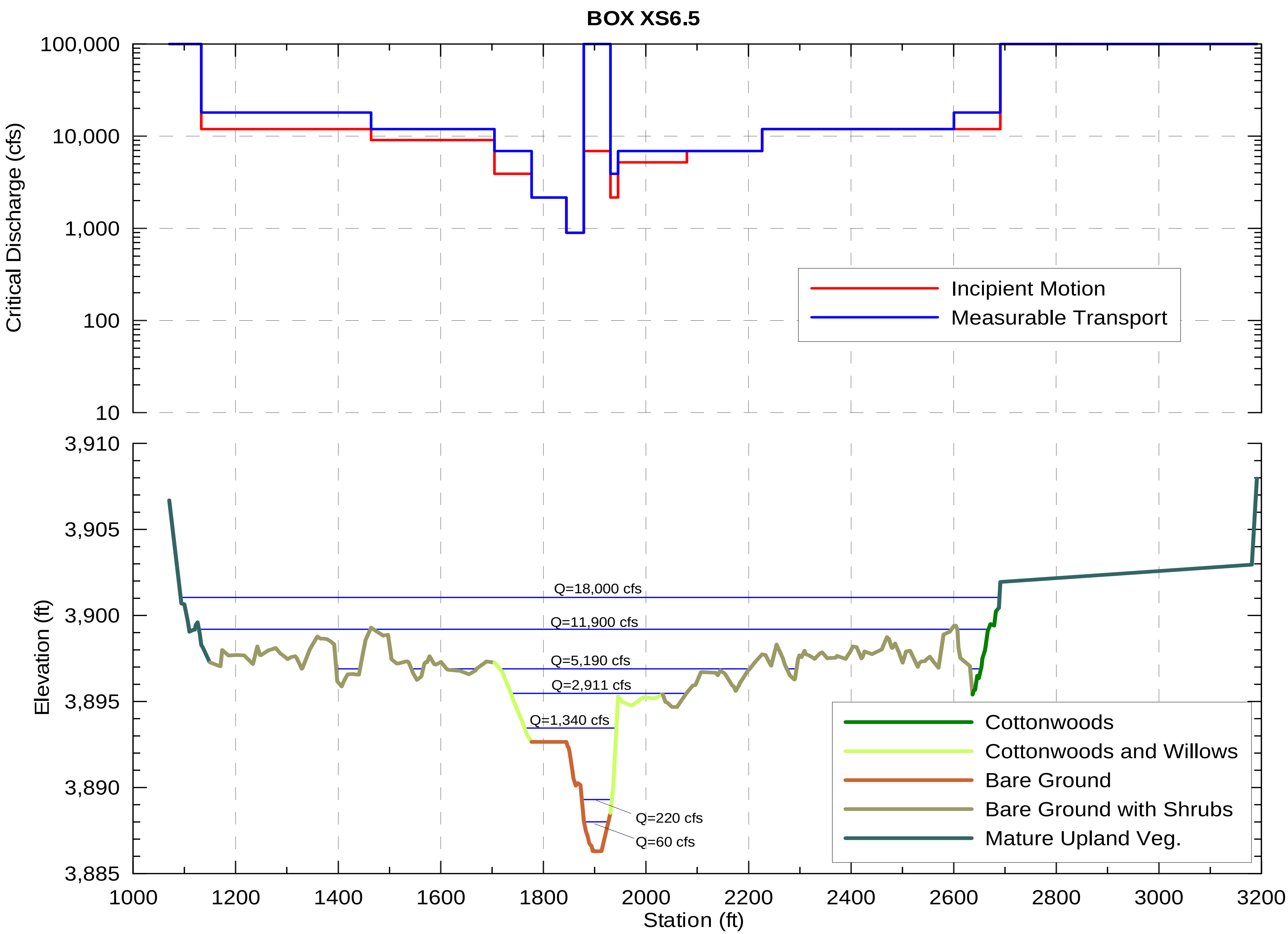
BOX XS3
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Cottonwoods
Cottonwood with Willows
Bare Ground
Bare Ground with Shrubs
Mature Upland Veg.
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
3,880
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Station (ft)


BOX XS4
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Cottonwoods
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Mature Upland Veg.
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1200
1400
1600
1800
2000
2200
2400
Station (ft)

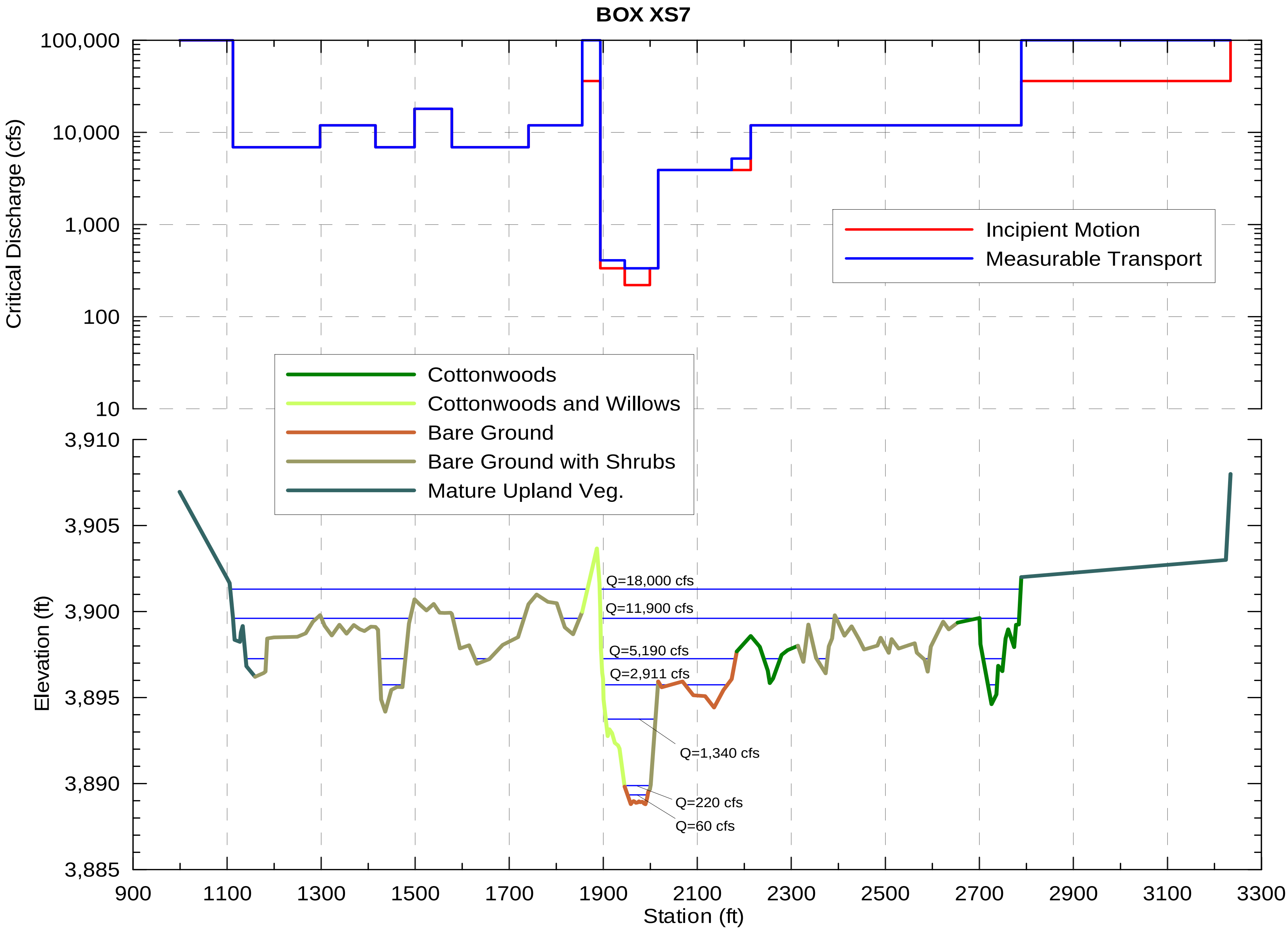

BOX XS5
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Mature Upland Veg.
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Station (ft)



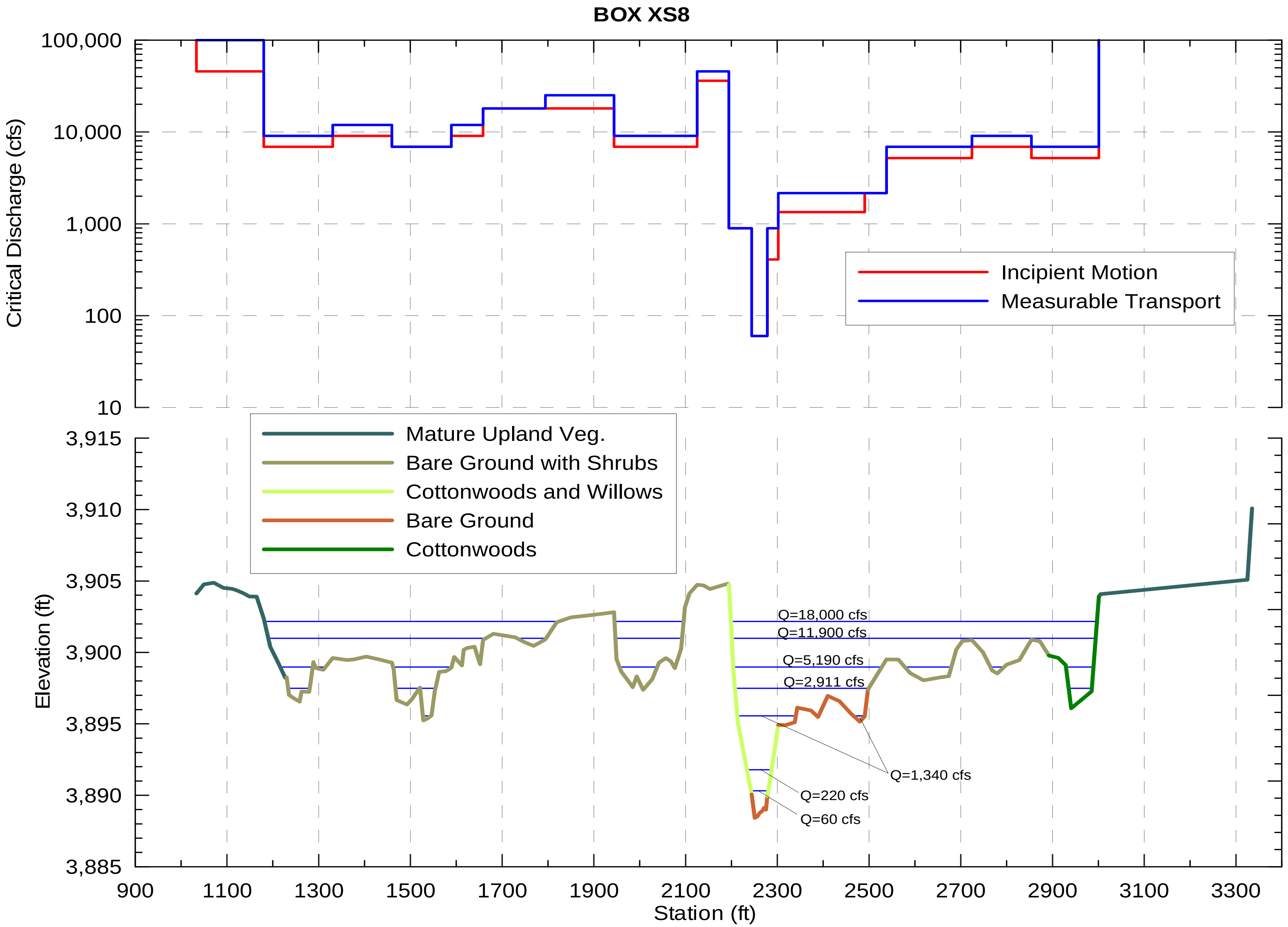
BOX XS6
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Line/Symbol Plot 60
Mature Upland Veg.
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Cottonwoods
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
Station (ft)



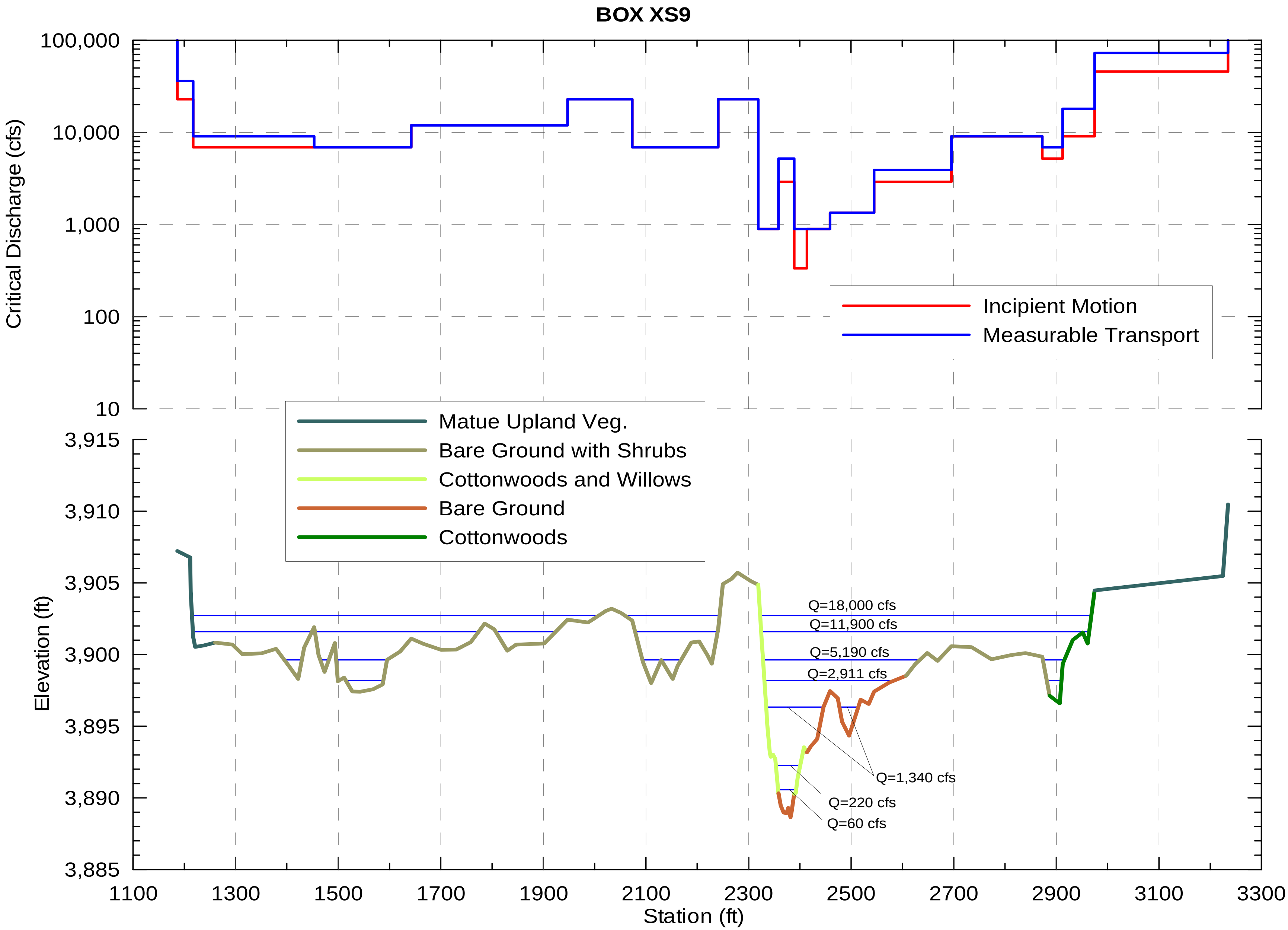
BOX XS6.5
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Mature Upland Veg.
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
Station (ft)



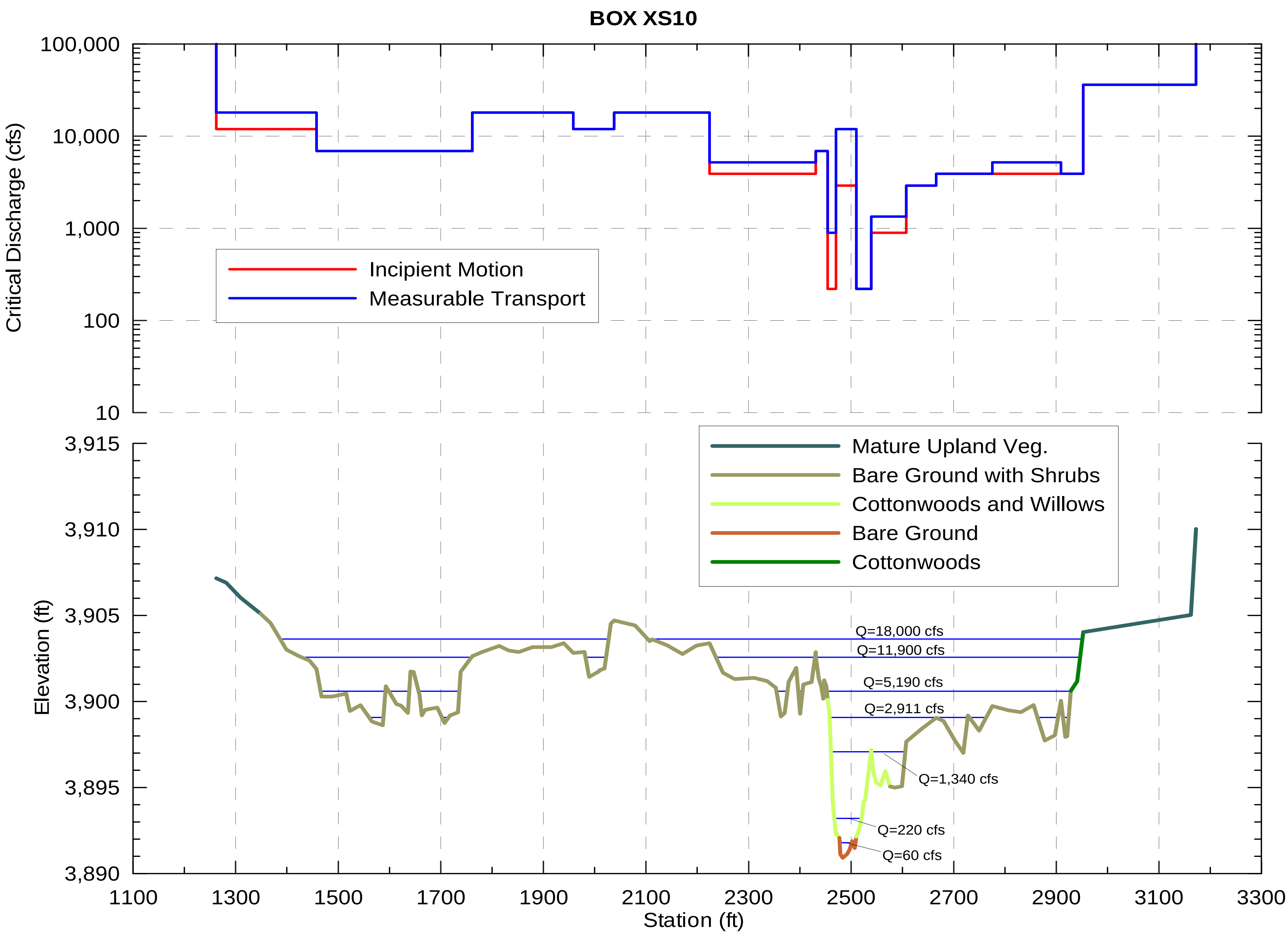
BOX XS7
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Mature Upland Veg.
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
3,885
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
Station (ft)

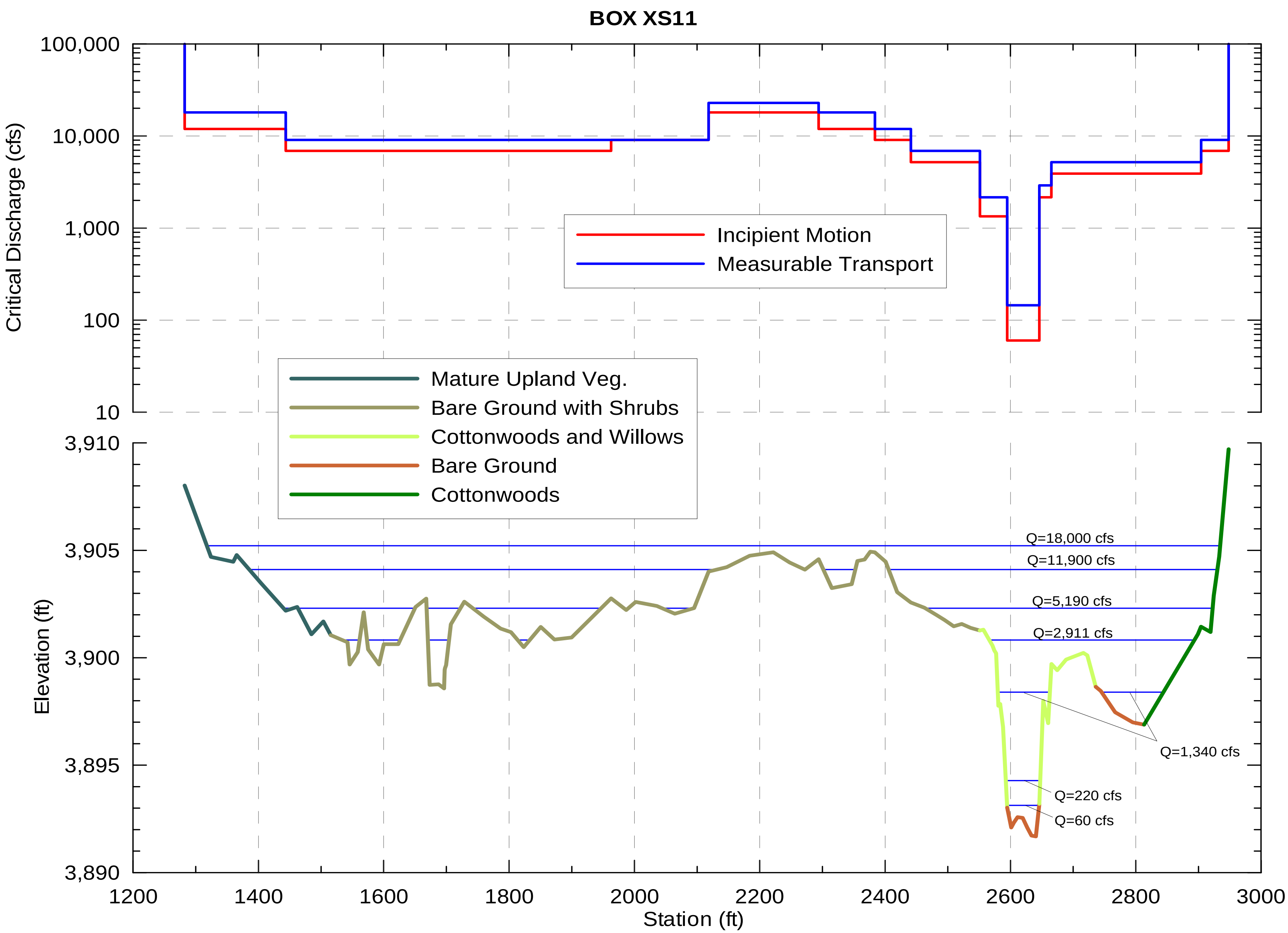


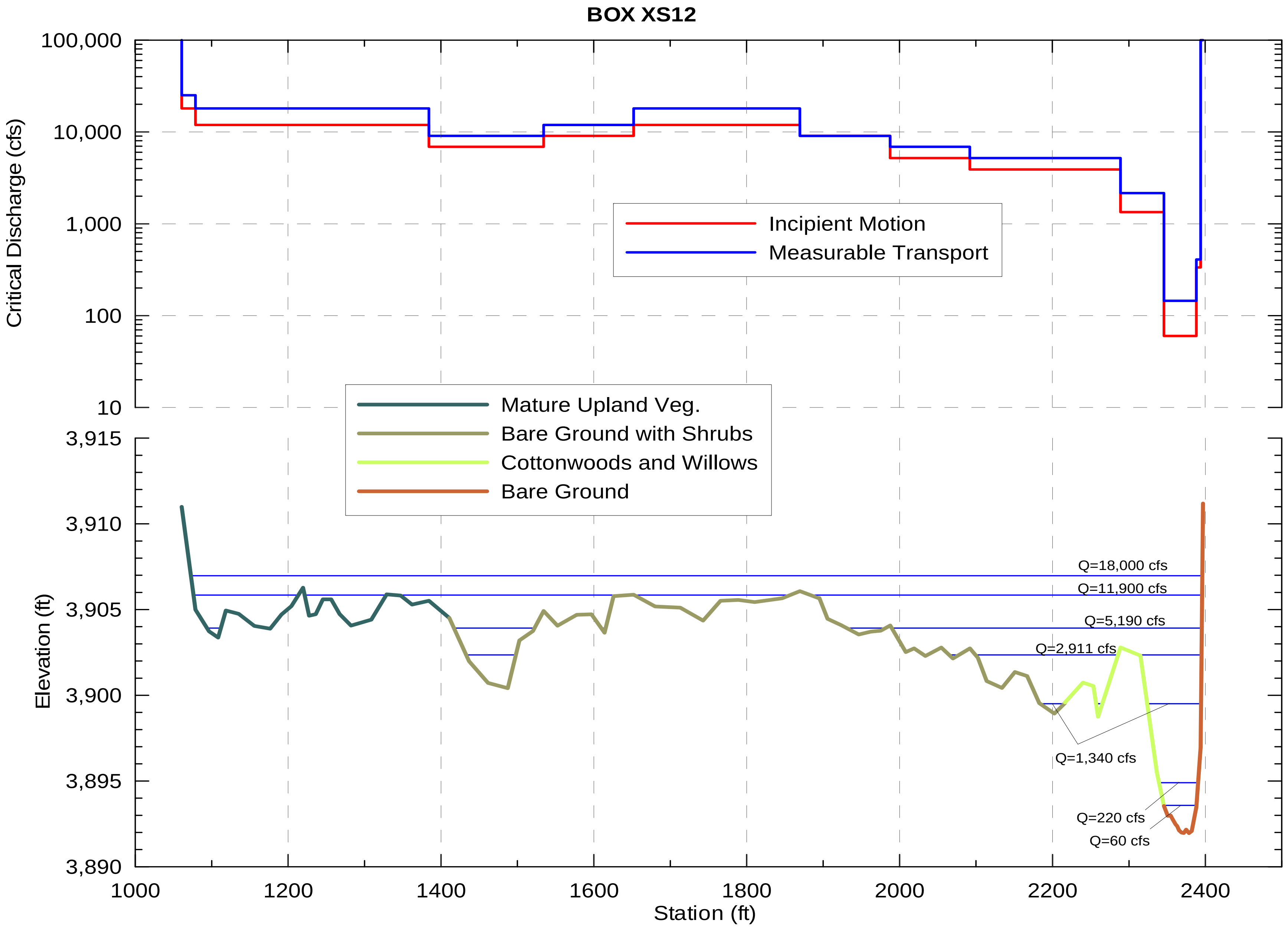
BOX XS8
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,915
3,910
3,905
3,900
3,895
3,890
3,885
Mature Upland Veg.
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
900
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
Station (ft)

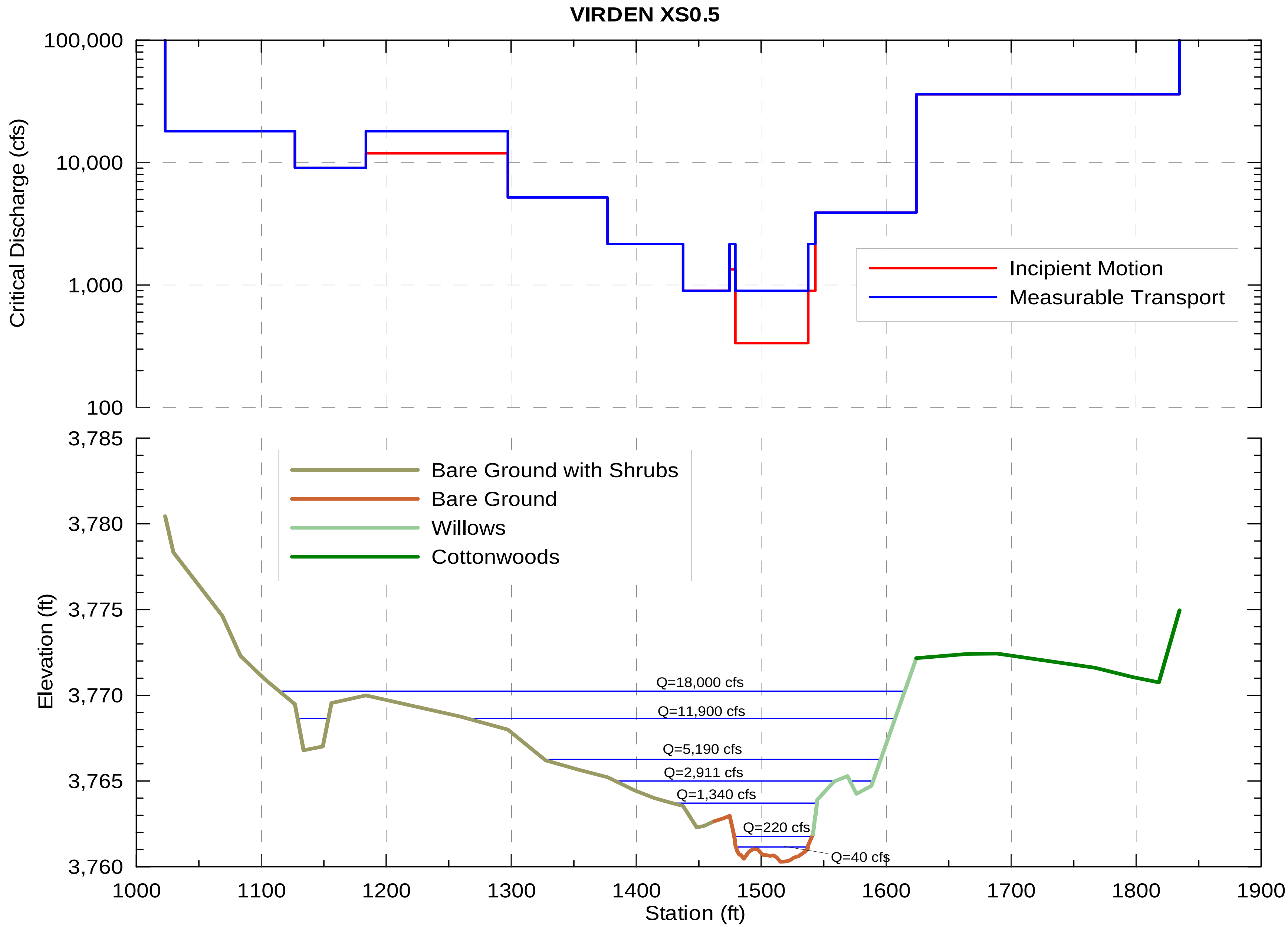


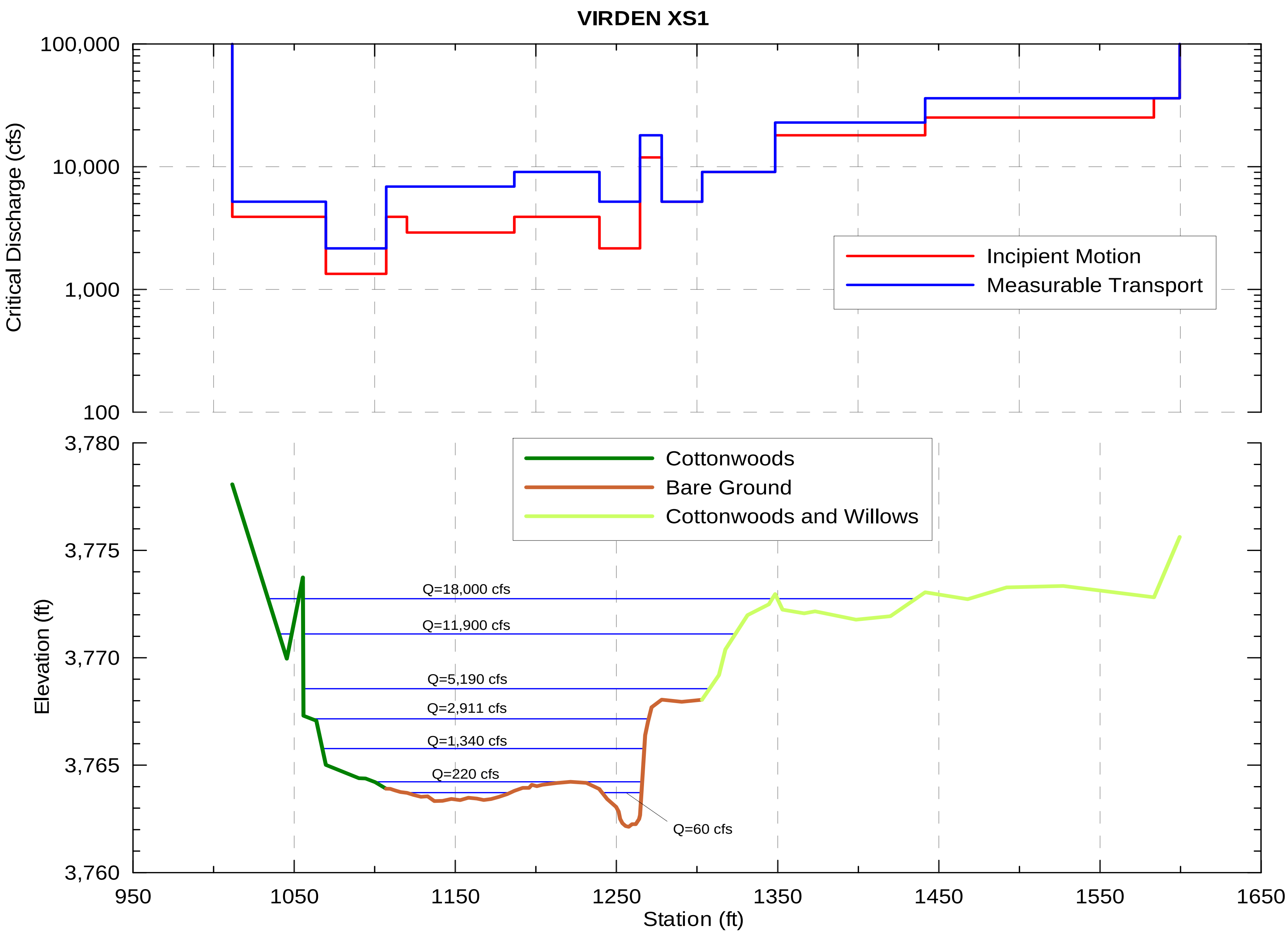
BOX XS9
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,915
3,910
3,905
3,900
3,895
3,890
3,885
Matue Upland Veg.
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
Station (ft)

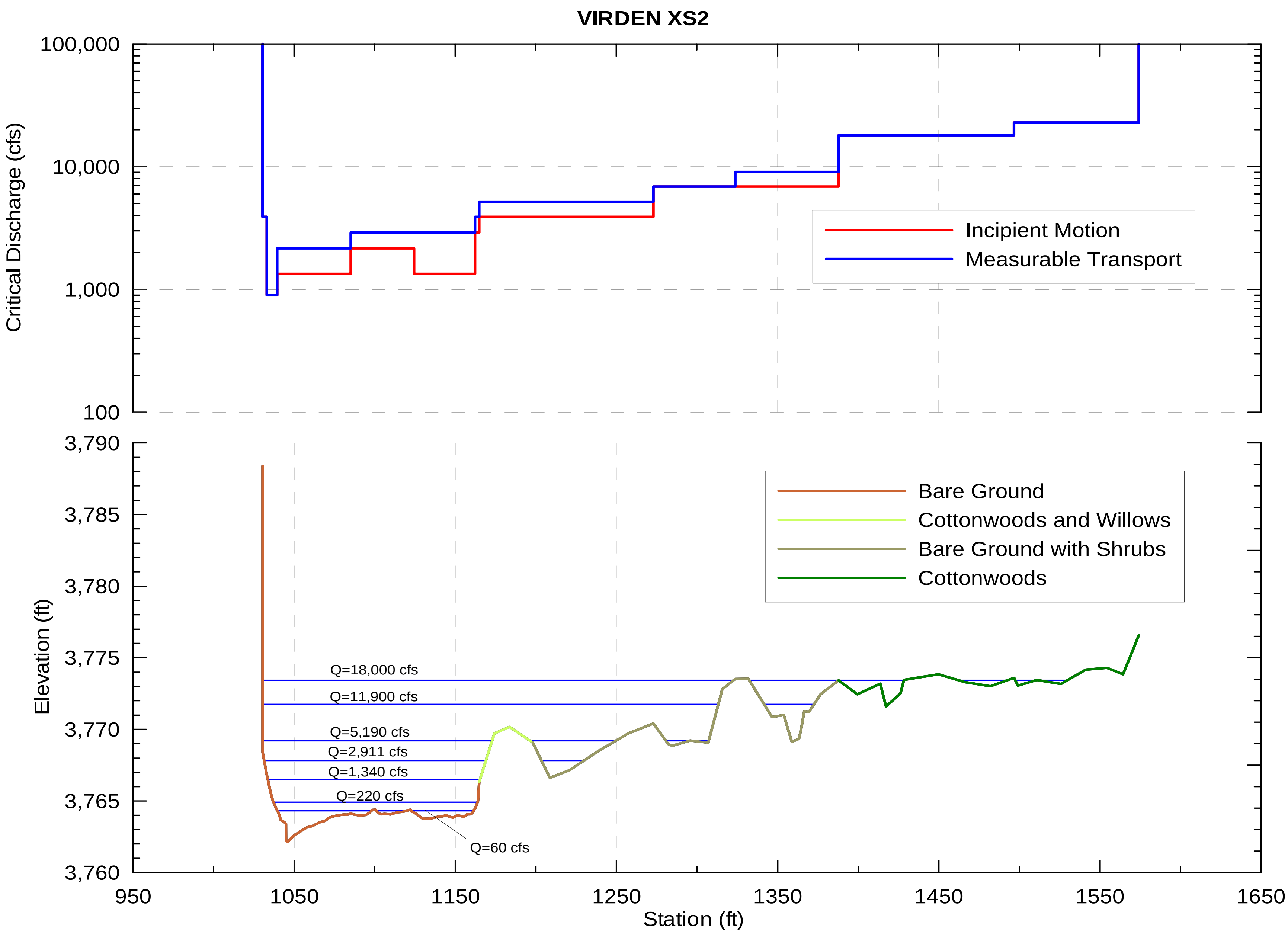

BOX XS10
100,000
10,000
1,000
100
10
Critical Discharge (cfs)
Incipient Motion
Measurable Transport
3,915
3,910
3,905
3,900
3,895
3,890
Elevation (ft)
Mature Upland Veg.
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1100
1300
1500
1700
1900
2100
2300
2500
2700
2900
3100
3300
Station (ft)

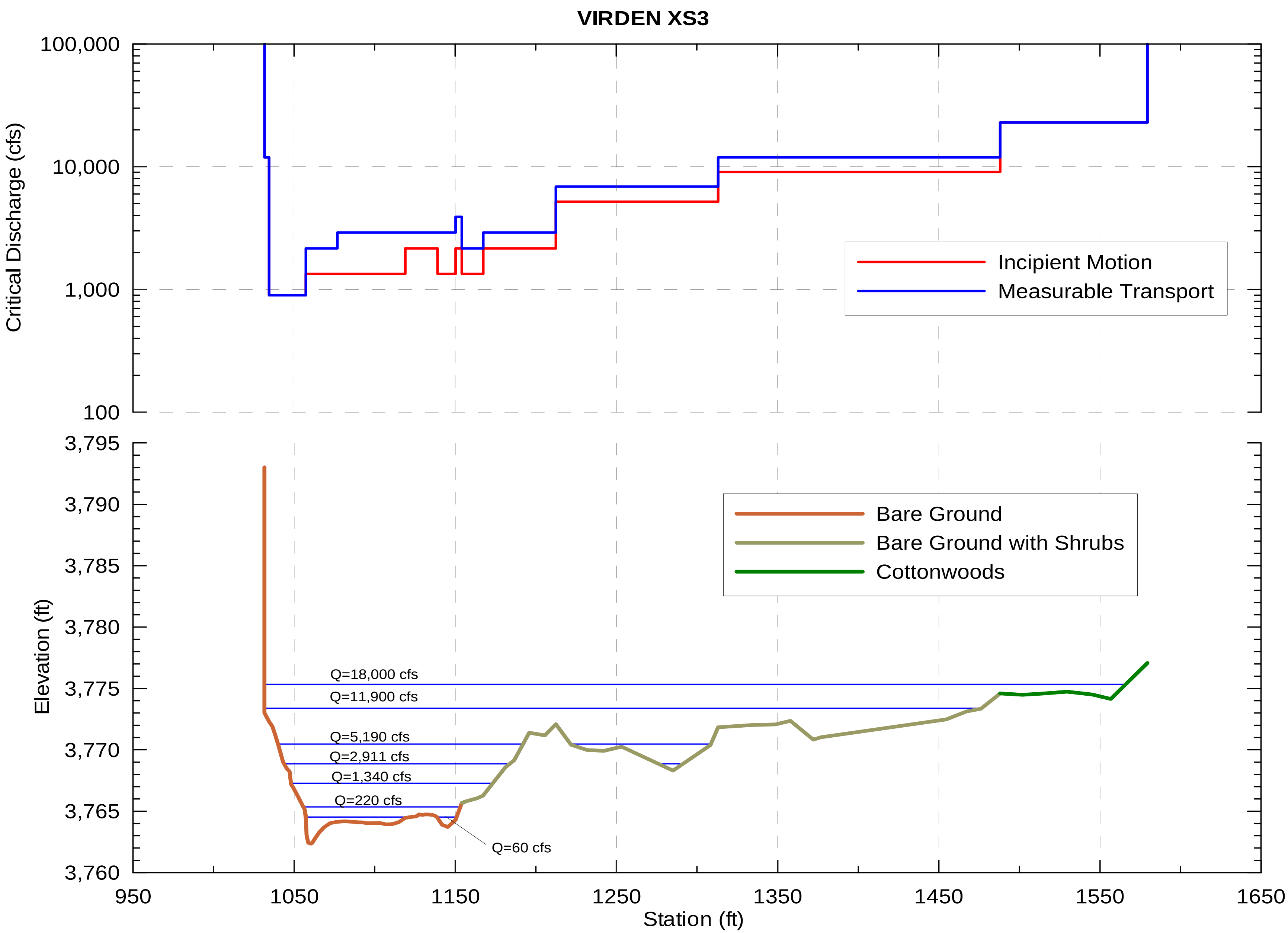

BOX XS11
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Elevation (ft)
3,910
3,905
3,900
3,895
3,890
Mature Upland Veg.
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Station (ft)

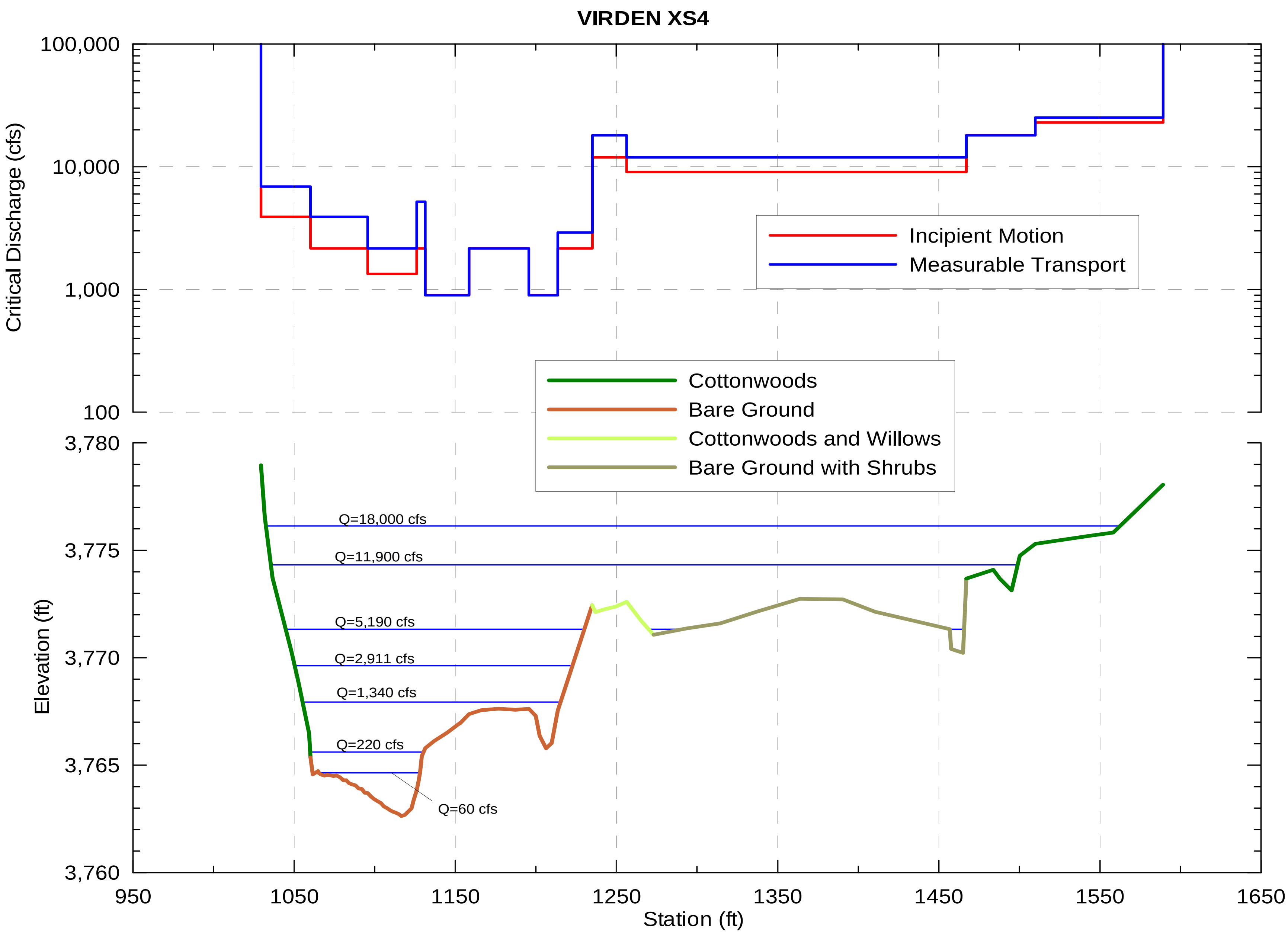

BOX XS12
Critical Discharge (cfs)
100,000
10,000
1,000
100
10
Incipient Motion
Measurable Transport
Mature Upland Veg.
Bare Ground with Shrubs
Cottonwoods and Willows
Bare Ground
Elevation (ft)
3,915
3,910
3,905
3,900
3,895
3,890
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1200
1400
1600
1800
2000
2200
2400
Station (ft)

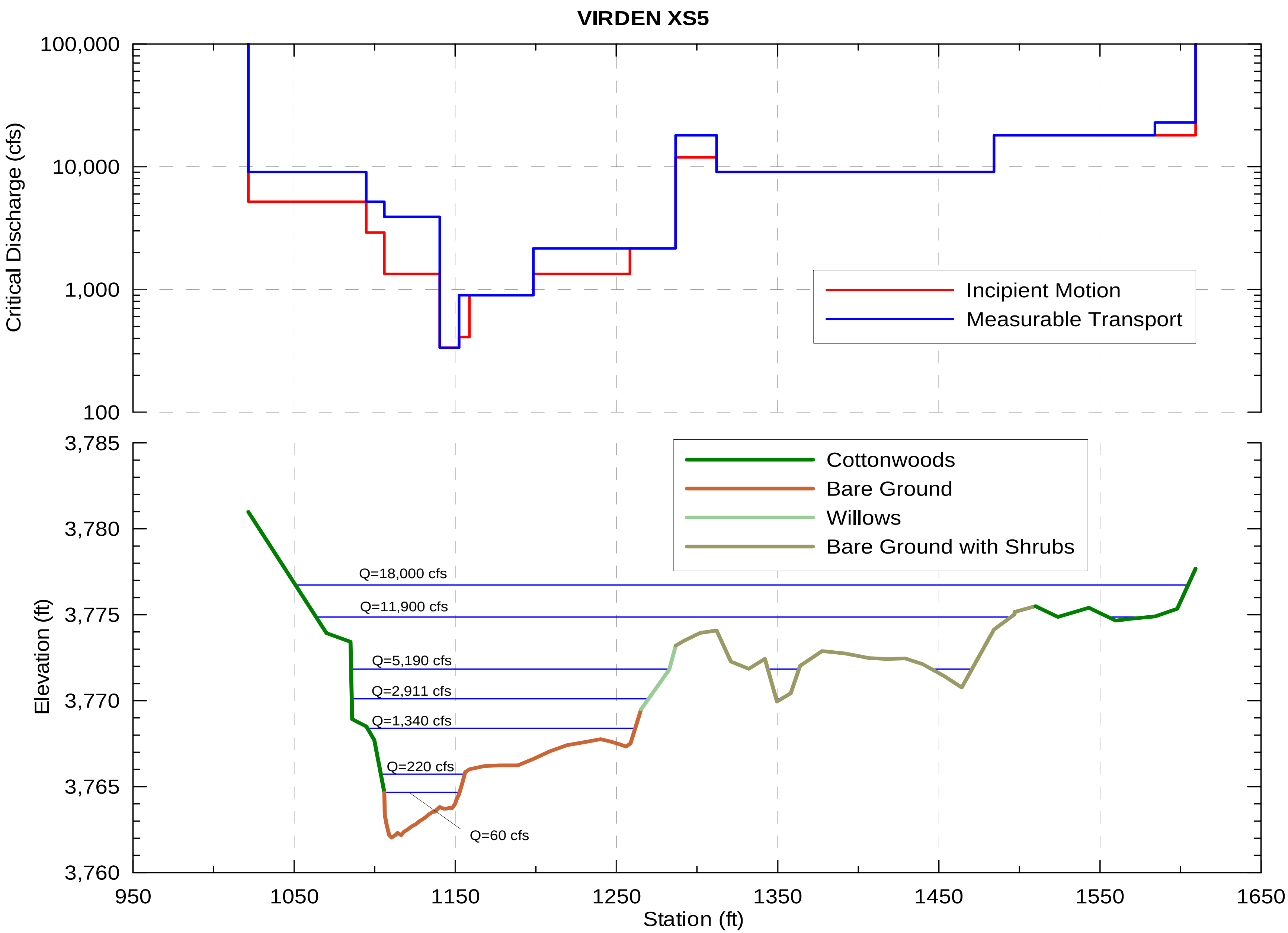

VIRDEN XS0.5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,785
3,780
3,775
3,770
3,765
3,760
Bare Ground with Shrubs
Bare Ground
Willows
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=40 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Station (ft)

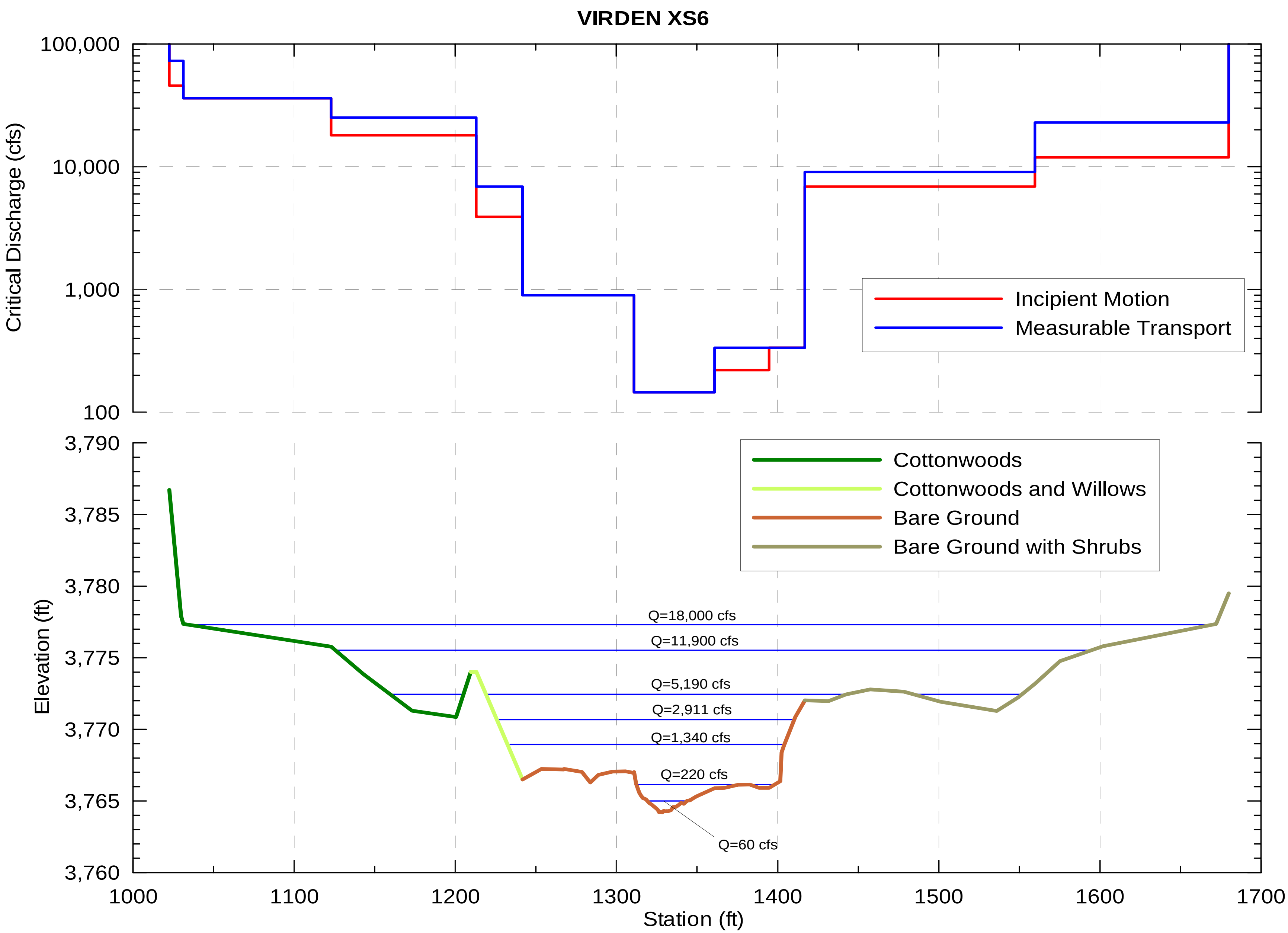

VIRDEN XS1
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,780
3,775
3,770
3,765
3,760
Cottonwoods
Bare Ground
Cottonwoods and Willows
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
950
1050
1150
1250
1350
1450
1550
1650
Station (ft)

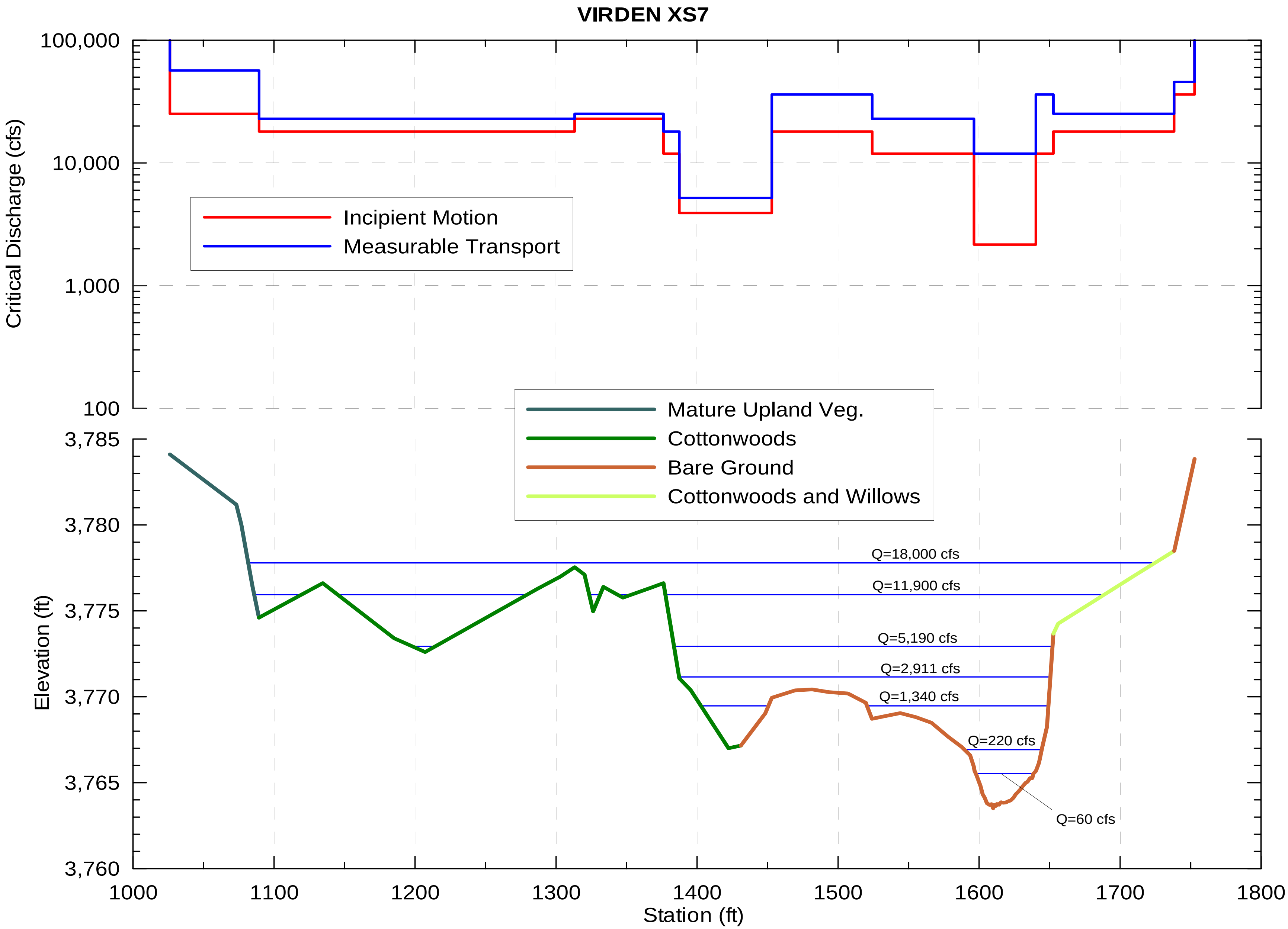

VIRDEN XS2
100,000
10,000
1,000
100
Critical Discharge (cfs)
Incipient Motion
Measurable Transport
3,790
3,785
3,780
3,775
3,770
3,765
3,760
Elevation (ft)
Bare Ground
Cottonwoods and Willows
Bare Ground with Shrubs
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
950
1050
1150
1250
1350
1450
1550
1650
Station (ft)


VIRDEN XS3
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,795
3,790
3,785
3,780
3,775
3,770
3,765
3,760
Bare Ground
Bare Ground with Shrubs
Cottonwoods
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
950
1050
1150
1250
1350
1450
1550
1650
Station (ft)

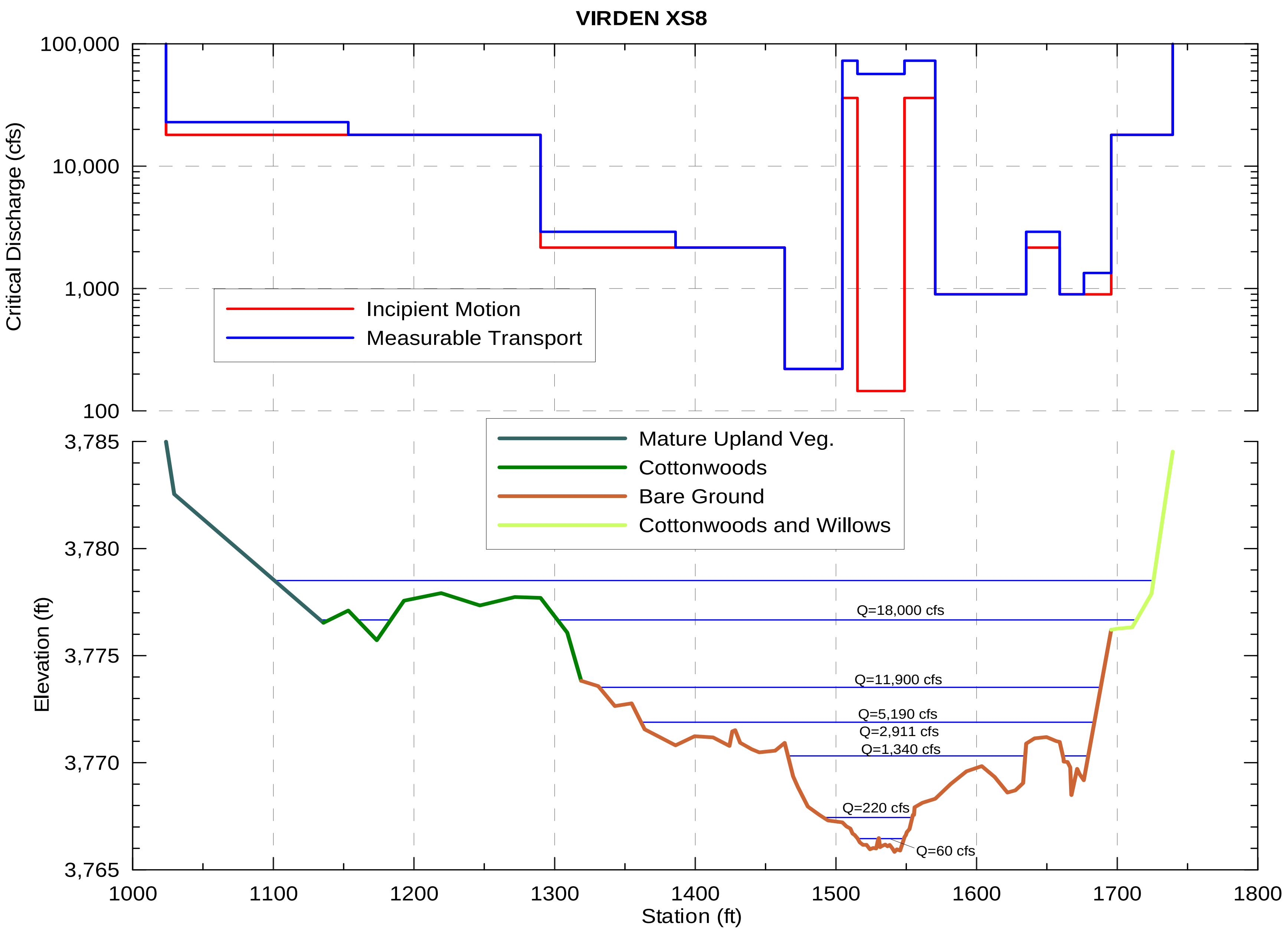

VIRDEN XS4
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Cottonwoods
Bare Ground
Cottonwoods and Willows
Bare Ground with Shrubs
Elevation (ft)
3,780
3,775
3,770
3,765
3,760
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
950
1050
1150
1250
1350
1450
1550
1650
Station (ft)

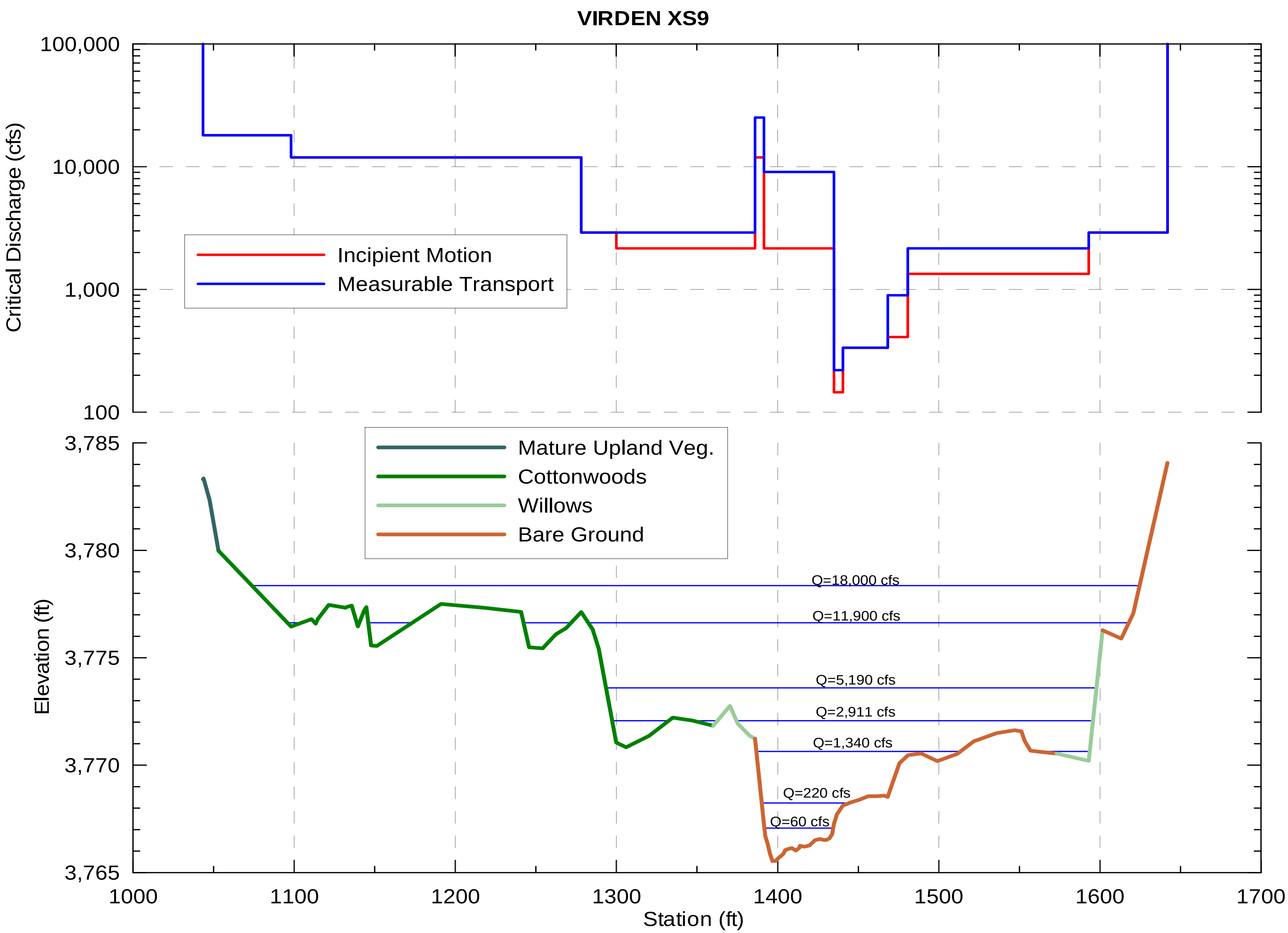

VIRDEN XS5
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,785
3,780
3,775
3,770
3,765
3,760
Cottonwoods
Bare Ground
Willows
Bare Ground with Shrubs
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
950
1050
1150
1250
1350
1450
1550
1650
Station (ft)


VIRDEN XS6
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,790
3,785
3,780
3,775
3,770
3,765
3,760
Cottonwoods
Cottonwoods and Willows
Bare Ground
Bare Ground with Shrubs
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
Station (ft)

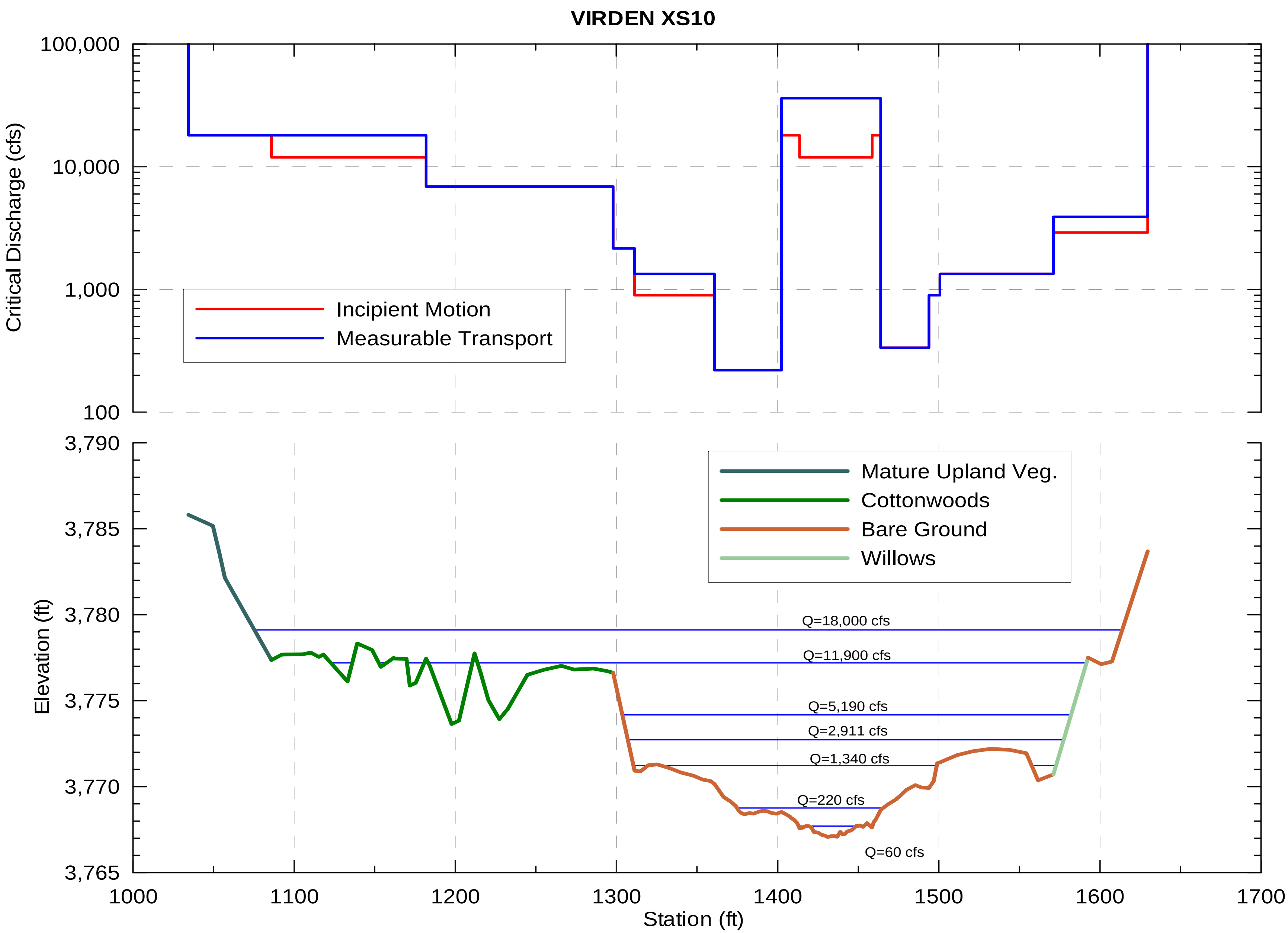


VIRDEN XS7
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Mature Upland Veg.
Cottonwoods
Bare Ground
Cottonwoods and Willows
Elevation (ft)
3,785
3,780
3,775
3,770
3,765
3,760
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
Station (ft)


VIRDEN XS8
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,785
3,780
3,775
3,770
3,765
Mature Upland Veg.
Cottonwoods
Bare Ground
Cottonwoods and Willows
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
1800
Station (ft)



VIRDEN XS9
Critical Discharge (cfs)
100,000
10,000
1,000
100
Incipient Motion
Measurable Transport
Elevation (ft)
3,785
3,780
3,775
3,770
3,765
Mature Upland Veg.
Cottonwoods
Willows
Bare Ground
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
Station (ft)



VIRDEN XS10
100,000
10,000
1,000
100
Critical Discharge (cfs)
Incipient Motion
Measurable Transport
3,790
3,785
3,780
3,775
3,770
3,765
Elevation (ft)
Mature Upland Veg.
Cottonwoods
Bare Ground
Willows
Q=18,000 cfs
Q=11,900 cfs
Q=5,190 cfs
Q=2,911 cfs
Q=1,340 cfs
Q=220 cfs
Q=60 cfs
1000
1100
1200
1300
1400
1500
1600
1700
Station (ft)