LOWER PROVO RIVER ECOSYSTEM FLOW RECOMMENDATIONS FINAL REPORT

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FOREWORD

Thank you for taking the time to read this report. Its purpose is to summarize and in some instances re-examine prior data, reports, and recommendations regarding instream flow regimes for the lower Provo River in Utah County, Utah. Together with new information and analyses, we present a thorough report on findings and recommendations relative to instream flow regimes for various important components of the lower Provo River ecosystem. The lower Provo River has been the focus of numerous studies and interagency efforts over the past two decades, primarily due to the listing of the June sucker (*Chasmistes liorus*), a lake sucker endemic to Utah Lake, as an endangered species by the U.S. Fish and Wildlife Service in 1986. The lower 4.9 miles of the Provo River were designated as critical habitat in the listing, as the June sucker spawns in the lower Provo River. Therefore most of the monitoring, studies, interest, and extensive cooperative efforts among many agencies and water management entities involving the lower Provo River since that time have focused on the goal of recovering the June sucker.

The Central Utah Project Completion Act (CUPCA) authorized the Central Utah Water Conservancy District, with funding provided by the Utah Reclamation Mitigation and Conservation Commission, to acquire water supplies with the goal of establishing a year-round minimum flow of 75 cfs on the lower Provo River. In addition, several environmental commitments of those two agencies and the Department of the Interior – CUPCA Office for completing the Diamond Fork System and the Utah Lake Drainage Basin Water Delivery System (ULS) of the Central Utah Project's Bonneville Unit involve water acquisition and management on the lower Provo River in support of June sucker recovery objectives. When completed in about 2021, the ULS will provide additional water for year-round instream flow purposes in the lower Provo River that, with water supplies acquired to date together with those anticipated in the future, should provide for substantial improvement of the lower Provo River ecosystem, including June sucker.

In this report we promote the concept that a healthy and naturally functioning riverine ecosystem in the lower Provo River is supportive of and not at odds with the goal of June sucker recovery. However, recognizing the special emphasis on June sucker, we provide information about various aspects of the recommended streamflow regimes and attempt to prioritize selected components with respect to their relative importance for June sucker spawning, larval transport, and other life history requirements. This is intended to help managers as they consider and make critical decisions to develop streamflow regimes for the lower Provo River on an annual basis, especially for those times when water supplies available for instream flows might be more limited than in some other years. This is true under existing conditions as well as when the ULS will be providing additional water supplies for instream flow purposes. Presently, in accordance with the June Sucker Recovery Implementation Program (JSRIP) Program Document, the JSRIP Administration Committee finalizes annual instream flow recommendations on the lower Provo River system for June sucker recovery. Those recommendations are presented to the Administration Committee by the JSRIP Technical Committee, for which the June Sucker Flow Workgroup serves as a subcommittee.

As explained in this report, the role of streamflow and the effects of various changes in streamflow regimes are important components of riverine ecosystems. But streamflow is not the only factor that influences ecosystem health or function. Other factors can be as important or more important, and may serve as limits or constraints on the ability to achieve naturally functioning and sustaining riverine communities. For example, the lower Provo River ecosystem, especially the lowest several miles that comprise the designated critical habitat for the June sucker, is substantially compromised by the alteration of its physical environment characteristics due to channelization and the influence of Utah Lake backwater. We recognize that restoring the lower Provo River ecosystem to a high-functioning level, and recovering the June sucker, will not be achieved by manipulation of streamflow regimes alone. We strongly encourage the continued pursuit of habitat restoration efforts on the lower Provo River and Utah Lake interface.

The recommendations and guidelines presented in this report are based on sound ecological principles. In this regard, we relied heavily on the work of the Instream Flow Council as presented in their 2004 book *Instream Flows for Riverine Resource Stewardship*. Where available, information, data, and reports specific to the lower Provo River were examined and incorporated. Nonetheless, some caution should be exercised when applying these guidelines and recommendations. Since 1994 cooperative efforts among many agencies and partners to manage flows in the lower Provo River have been directed primarily to the spawning requirements of June sucker and, more recently, also the transport requirements for newly hatched June sucker larvae. Attempts have generally not been made to provide year-round flows. The effects of providing year-round flows on non-target, non-native fishes that use the lower Provo River are not well-studied although they may be somewhat predictable. The potential exists for non-native species to benefit from year-round flows, possibly to the detriment of June sucker, especially larvae, which may be preyed upon or competed with for food resources by the non-native species. This represents a line of inquiry that might be pursued by the JSRIP prior to implementing year-round instream flows on a permanent basis.

We also recognize that inter-specific interactions among the fish community present in the lower Provo River and Utah Lake interface are complex and may affect especially the efforts to recover June sucker in other ways. For example, making changes to the lower Provo River streamflow regime could hypothetically attract increased numbers of June sucker spawners to the river, which could lead to increased spawning activity and increased numbers of larval June sucker produced. There might not be a corresponding increase in recruitment of those larval fish (arguably one of the main biological objectives of the JSRIP) to the juvenile and subsequent life stages because of other factors such as predation by other fishes in the lower river and Utah Lake interface (lack of suitable rearing habitat, and/or failure of larvae to reach rearing habitats may also be factors).

For these reasons, the JSRIP is a multi-faceted program that attempts to address all factors that constitute a threat to the existence of June sucker. Similarly, we encourage a multi-faceted approach to restoring functions and improving the lower Provo River ecosystem. Although streamflow regime is a critical component of riverine ecosystems, it is only one of several vital components, and all limiting constraints should continue to be addressed in order to achieve successful ecosystem recovery.

Finally, we acknowledge and appreciate the efforts and input of many individuals, organizations, and agencies in the development of this report. Russ Findlay, June Sucker Flow Workgroup leader, provided valuable comments on the revised final draft of the report, and Ralph Swanson, former Chair of the JSRIP Technical Committee, provided helpful review and comments on the initial draft. Many personnel from the Central Utah Water Conservancy District provided thoughtful comments and constructive suggestions for the report. The Acknowledgements section of this report recognizes several other individuals, and we also express appreciation to the many others who contributed to this effort, especially those involved with June sucker recovery efforts.

Sincerely,

Mark Holden, Projects Manager
Utah Reclamation Mitigation and Conservation Commission
August 2008

SECTION 1. INTRODUCTION

The Provo River is a highly significant water resource within the State of Utah. The river is a major source of drinking water for residents along the Wasatch Front, and is also heavily used for agricultural and recreational purposes. To put the importance of this water body in perspective, Provo River is used to supply drinking water to more than 50 percent of Utah's population. In addition, the section of the Provo River between Deer Creek Reservoir and Olmsted Diversion is known nationally as a blue-ribbon trout fishery. The section of the Provo River between Jordanelle Dam and Deer Creek Reservoir is rapidly achieving that same status, in response to minimum stream flows and habitat restoration projects made possible through the Central Utah Project in combination with other projects, agencies, and organizations.

This report describes the process and products of developing a suite of year round instream flow recommendations for the lower Provo River in Utah County, Utah. This project was undertaken by the Utah Reclamation Mitigation and Conservation Commission, a Federal agency established by the Central Utah Project Completion Act (CUPCA [Titles II through VI of Public Law 102-575]). The Utah Reclamation Mitigation and Conservation Commission (Mitigation Commission) is responsible for mitigating impacts of the Bonneville Unit of the Central Utah Project (CUP) on fish, wildlife, and related recreation resources. The Mitigation Commission is required to include in its fish and wildlife mitigation plans measures that it determines will ". . . restore, maintain, or enhance the biological productivity and diversity of natural ecosystems within the State and have substantial potential for providing fish, wildlife, and recreation mitigation and conservation opportunities," and ". . . be based on, and supported by, the best available scientific knowledge".[1]

The goal of this report is to make instream flow recommendations specific to the lower Provo River. In order to achieve that goal, this report starts by briefly reviewing the history and features of the Bonneville Unit (Section 1), one of the water development projects that affects flows on the lower Provo River. Various flow-dependent riverine processes and ecological functions are described (Section 2), and the background and framework for the approach we used to develop the comprehensive instream flow recommendations are described as an "idealized" approach (Section 3). We then review specific technical methods for determining instream flow requirements (Section 4). Then by applying site-specific information (Sections 5 – 7), the report integrates that information into a suite of recommendations for the lower Provo River (Section 8). Several appendices are included that provide data, context, and additional details regarding the basis for the flow recommendations.

This report and the process of developing it builds upon the prior efforts of many parties to develop instream flow regimes for the lower Provo River, for the benefit of the endangered June sucker. Without the insight, excellent technical analyses, and above all, spirit of cooperation that those prior efforts established, this report would be a lesser product and would have been more difficult to develop. For more than a decade, cooperative management among the Central Utah Water Conservancy District, Reclamation, the State of Utah, Provo River Water Users

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[1] From CUPCA, Sections 301(g)(4)(A) and (B)

Association, U.S. Fish and Wildlife Service and many other water users has been successful in making water available for lower Provo River instream flow purposes, especially for June sucker, while protecting the rights of other parties. As additional water becomes available for instream flow purposes, whether through water conservation programs or acquisition of water supplies, and as the existing water development projects that use the Provo River fully utilize their water resources in the near future, it will be important to identify how both stored and natural flows can be managed to meet all user and environmental needs.

Purpose and Need

The recommended flow regime for the lower Provo River should protect the entire riverine ecosystem year-round. The flow regime(s) should be scientifically derived, ecologically defensible and hydrologically feasible. A critical aspect of this effort is the need to provide habitat for June sucker (*Chasmistes liorus*) spawning and recruitment. The June sucker was listed as an endangered species in 1986. It resides in Utah Lake and uses the lower Provo River for spawning. The June Sucker Recovery Plan (USFWS 1999) lists habitat alteration through alteration of the natural flow patterns as one of the human-induced changes affecting the Utah Lake drainage and June sucker. Long-term protection and eventual recovery of the June sucker is dependent on several critical factors, of which water management is only one. This report provides recommendations and considerations regarding the management of water to maintain sufficient flows in the Provo River in the quantity, quality and pattern necessary to support the aquatic ecosystem that will help recover the species. Flow maintenance is particularly important within designated critical habitat (Tanner Race Diversion on Columbia Lane to Utah Lake) during important life stages of the fish.

Background

The Background section of this report describes the various interconnected water development projects that affect the lower Provo River. Irrigation and hydroelectric power generation have been a part of the lower Provo River history for more than a hundred years. The earliest efforts to utilize Provo River waters were by individuals and small companies. One of the largest projects is the CUP. The CUP was authorized by Congress through enactment of the Colorado River Storage Project Act of 1956 (43 U.S.C. 620 et seq.). The CUP is intended to develop a portion of Utah’s share of water from the Upper Colorado River system, according to interstate compact. Even before the Central Utah Project was built, water storage and diversion features involving the Provo River were developed to provide municipal and irrigation water to portions of the Wasatch Front. These efforts, collectively known as the Provo River Project, were authorized and constructed with the approval of the federal government beginning in 1933. Most features of the Provo River Project were built by or under the supervision of the Bureau of Reclamation from 1938 to 1958. These included the building of (1) Deer Creek Dam, first completed in 1941, (2) the Salt Lake Aqueduct transferring water stored in Deer Creek Reservoir to the Salt Lake Valley, also completed in 1941, (3) the Duchesne Tunnel to transfer water from the headwaters of the Duchesne River to the Wasatch Front via the Provo River, completed in 1952, and (4) enlargement of the Weber-Provo Diversion and Canal to transfer water from the

Weber River to the Provo River, completed in 1948. Other important features of the Provo River Project include the Murdock Diversion and Murdock Canal.

The Bonneville Unit is the largest unit of the CUP. It is a system of reservoirs, aqueducts, pipelines, pumping plants, and conveyance facilities that develop water supplies for use in the Uinta Basin, and primarily transport water from the Uinta Basin to the Bonneville Basin in Utah. It is composed of the Starvation Collection System, the Strawberry Aqueduct and Collection System (SACS), the Diamond Fork System, the Municipal and Industrial (M&I) System, and the Utah Lake Drainage Basin Water Delivery System (ULS or Utah Lake System) (Figure 1.1). This unit includes facilities to collect water from Duchesne River system streams and release it through the Wasatch Mountains as needed in the Bonneville Basin and Wasatch Front. The SACS diverts flows from nine Duchesne River tributaries through approximately 40 miles of tunnels and aqueducts for storage in Strawberry Reservoir. That water is then carried to Utah Lake through the Diamond Fork System and the Spanish Fork River in Utah County. The water delivered from Strawberry Reservoir to Utah Lake is used as replacement water, allowing for the exchange and/or storage of Provo River flows in Jordanelle Dam, located on the Provo River in Heber Valley, approximately 10 miles upstream of Deer Creek Reservoir. Jordanelle Dam and Reservoir on the Provo River are the principal features of the M&I System, providing municipal and industrial water to Salt Lake, Utah, and Wasatch Counties, and supplemental irrigation water to Summit and Wasatch Counties. Upon completion of the Utah Lake System in about 2021, additional water will be made available within the Bonneville Basin for environmental and municipal needs.

In 1992 Congress enacted CUPCA (Titles II through VI of Public Law 102-575). Among other things CUPCA raised the Bonneville Unit appropriations ceiling, required local cost-sharing of project capital costs, authorized various water conservation and wildlife mitigation projects, and allowed local entities to construct certain project features under the direction of the Secretary of the Interior. Under section 301 of CUPCA, the Mitigation Commission was created to plan and administer the fish and wildlife mitigation and conservation program for the Bonneville Unit.

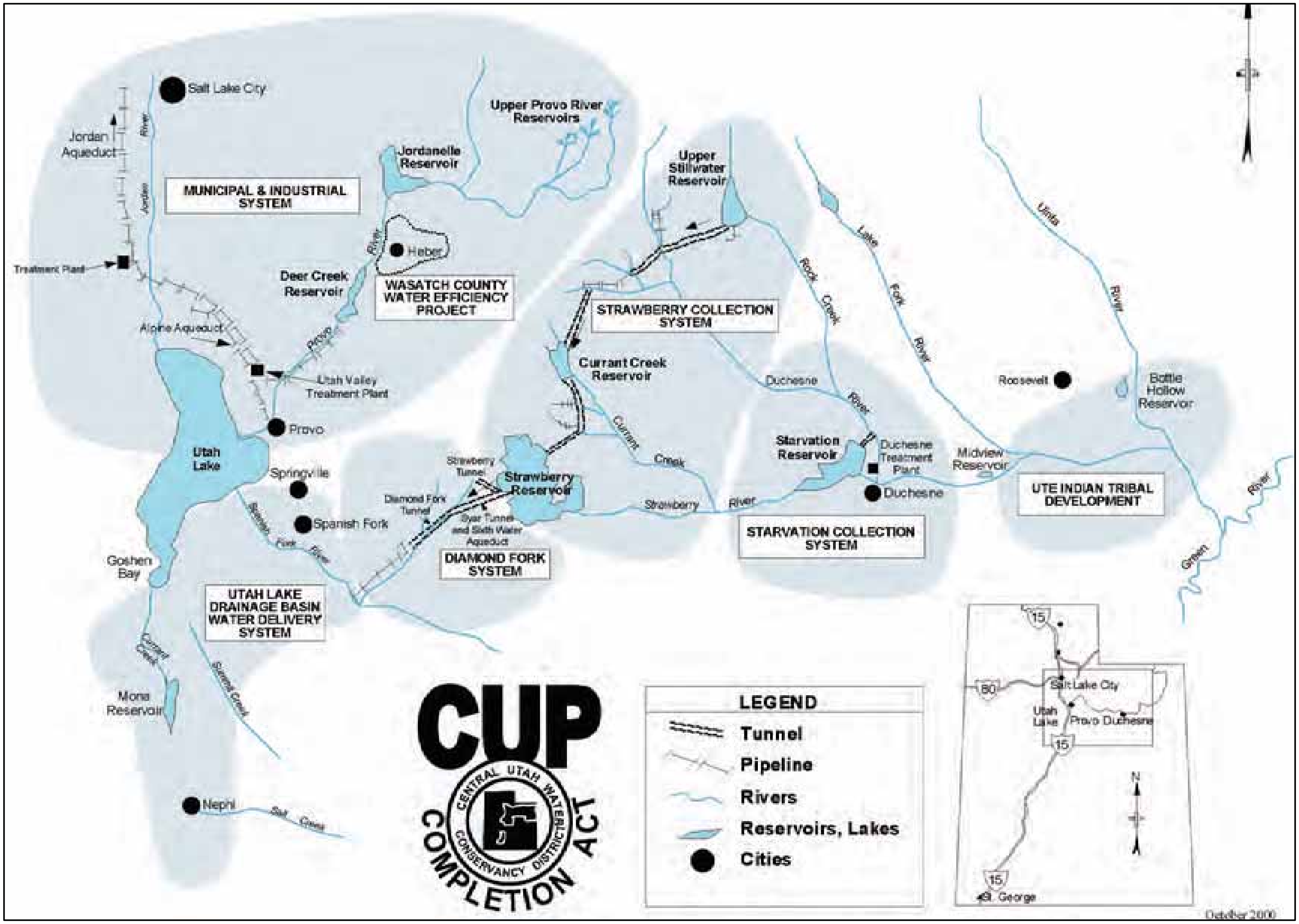

Figure 1.1. Features of the Bonneville Unit, Central Utah Project.

SECTION 2. HYDROLOGIC ALTERATIONS and THEIR EFFECTS ON FLOW-DEPENDENT ECOLOGICAL FUNCTIONS

Dams and diversions are common features on rivers throughout the western United States, and their impacts on streamflow and riverine habitat have been recognized for several decades. After environmental concerns led to the passage of the National Environmental Policy Act (NEPA) in 1969, the need to mitigate for the impacts of dams and provide instream flows began to be recognized (Annear et al. 2004, NRC 2005).

The dam, diversion, and pipeline facilities that have been built as part of the Bonneville Unit of the CUP have substantially altered the flow volume, timing, duration, frequency, and flood characteristics of several rivers and streams, including the lower Provo River. These flow regime alterations may have broad-reaching effects on the health and sustainability of the affected riverine ecosystems and the native species that depend upon them. Conversely, the design, construction, and operation of some CUP facilities have been specifically intended to provide opportunities to restore, augment, or otherwise improve instream flow management on several creeks and rivers affected by the CUP and by other non-CUP projects, including the lower Provo River and Hobble Creek, both important streams for the recovery of June Sucker.

Although minimum instream flow requirements have been established on some sections of the Provo River and CUPCA authorized acquisition of water rights with the an objective of establishing a minimum flow of 75 cfs on lower Provo River, broader-based flow regime recommendations for the lower Provo River have not been prepared. Initial efforts at flow management were focused on providing suitable habitat for June sucker spawning.

Since that time the scope of instream flow science has expanded beyond a single-species/life stage focus to more comprehensive protection of complete aquatic communities. The focus has also moved beyond the low-flow river channel to include the riparian corridor, floodplain, and associated geomorphic processes (NRC 2005). With this broadening of scope, instream flow development has become an interdisciplinary science requiring contributions from biologists, geomorphologists, water quality/chemistry specialists, and hydrologists, as well as policy specialists. As these disciplines have become increasingly integrated, the focus of instream flow recommendations has broadened. It is now recognized that single-flow requirements do not adequately protect the full range of riverine ecosystem functions or ensure sustainable, long-term habitat quality (Annear et al. 2004). More sophisticated, “modern” instream flow prescriptions include a comprehensive flow regime, with recommendations for base flows, overbank flows, high pulse flows, and subsistence flows, among possibly others (NRC 2005). The importance of seasonal and inter-annual flow variability is also becoming increasingly recognized.

Developing holistic, ecologically based instream flow prescriptions that account for streamflow variability would allow for improved management of the Bonneville Unit for healthier riverine ecosystems. One of the purposes of this report is to describe the relationships among streamflow and various ecological processes and conditions of riverine ecosystems and to develop an approach to determine ecologically based streamflow regimes. Those ecological components include aquatic habitat, channel processes, sediment transport, riparian vegetation, water quality, and recreational usability.

Not all of the ecological functions that are presented in the following pages will apply to the lower Provo River, for various reasons that are explained thoroughly in Section 5 where specific details of the Provo River are presented. A brief but thorough review of those processes and functions is nonetheless provided as a primer for better understanding of natural river system processes that can be important on lower Provo River in the future, especially if habitat restoration efforts are implemented. Starting development of specific recommendation for the lower Provo River by applying a broadly based, ecologically comprehensive template to the lower Provo River system helps assure that potentially important ecological components will not be overlooked.

Ecological Importance of Instream Flows

Rivers are complex, dynamic systems that support myriad important ecological functions. Rivers transport water, sediment, nutrients, and energy downstream. As described in the river continuum concept (Vannote et al. 1980), rivers support a diversity of biological communities with distinct trophic organizations as they transition longitudinally from headwater to mouth. Individual communities depend on this downstream transfer of sediment, water, organic matter, nutrients, and food. Rivers also provide longitudinal movement corridors for terrestrial and avian wildlife. Dams and water diversions interrupt the longitudinal connectivity of rivers by creating physical instream barriers and altering the downstream transfer of water and sediment.

Riverine ecosystems also provide lateral transfer and cycling of water, sediment, nutrients, and energy between the stream channel and floodplain/valley areas. Healthy floodplains act as "sponges" that store water during high-flow events and release it back to the channel during low-flow periods. This function serves to dampen downstream flood peaks (and associated flood damages) and helps ensure that adequate base flows are available to aquatic communities during seasonal dry periods. Floodplains and associated riparian vegetation also help filter nutrients, contaminants and improve surface water and ground water quality. When dams or water diversions reduce the magnitude, frequency and/or duration of overbank flooding events, the lateral connectivity of the system and associated ecological functions are compromised. Other human activities, such as levee construction, river channelization/straightening, riparian vegetation removal, draining of floodplain wetlands, and urbanization, can also compromise the lateral connectivity of rivers by restricting floodplain inundation.

Streamflow acts as a "master" variable that directly and indirectly influences the full range of riverine resources and functions including aquatic habitat, riparian vegetation, sediment transport, channel morphology, and water quality (Figure 2.1). The individual riverine components also influence each other either directly or indirectly (Figure 2.1). Therefore, ignoring a particular riverine component when developing instream flow requirements could ultimately result in the failure to adequately protect another riverine component, perhaps even one that may be of primary interest. For example, ensuring that a minimum spawning flow is

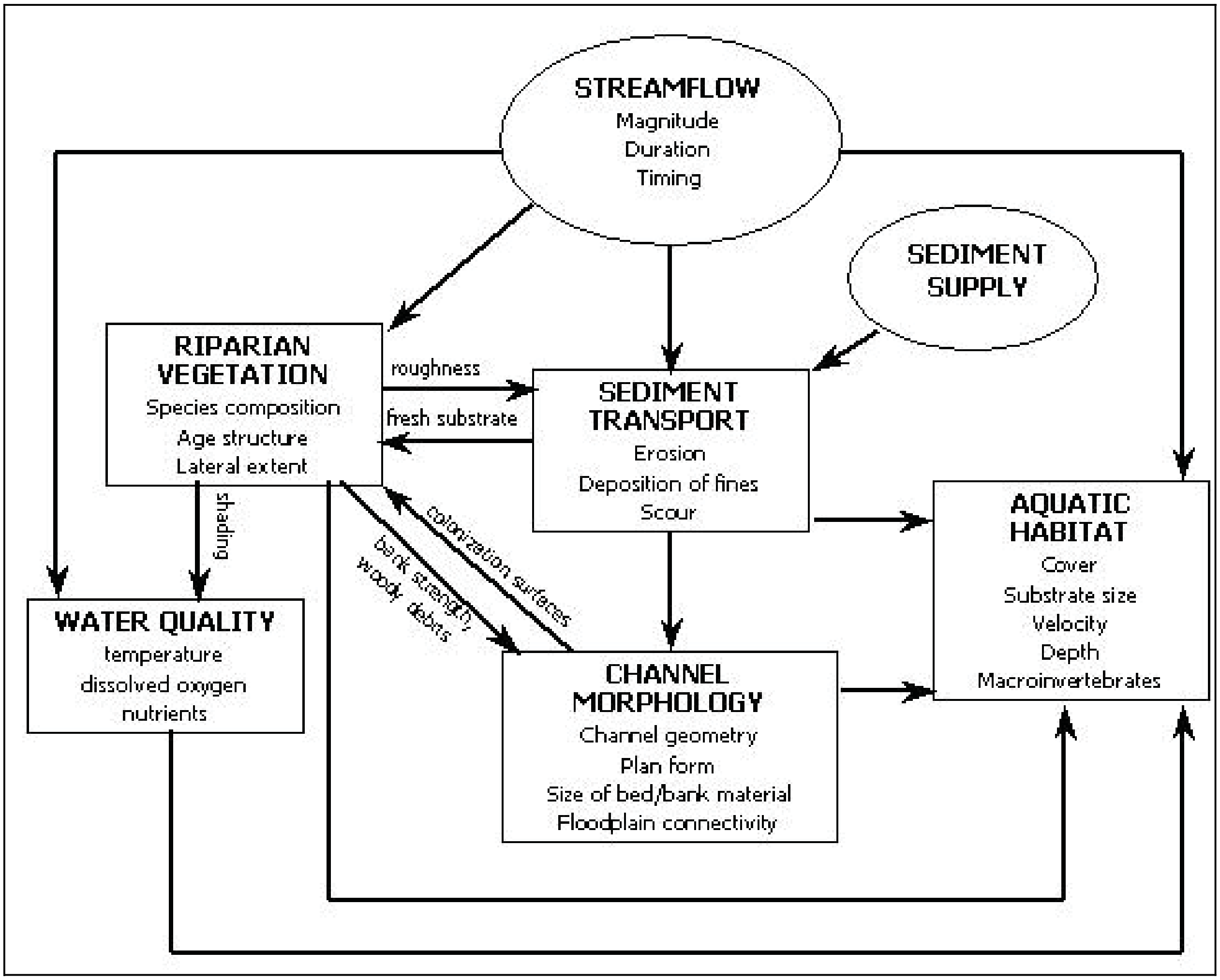

Figure 2.1. Schematic illustration of major interactions among riverine resources and processes.

provided may not protect spawning habitat over the long term unless the flood flows that create, clean, and maintain spawning gravels (i.e., geomorphic processes/channel morphology) are also protected on a periodic basis. The June Sucker Flow Workgroup, for example, has recognized this and for many years has recommended periodic higher flows on lower Provo River to cleanse the spawning substrate prior to initiation of the June sucker spawning run. Similarly, in recent years the June Sucker Flow Workgroup has recommended higher flows following the spawning period to help transport the hatched June sucker larvae downstream towards Utah Lake. Because of the interdependence among the various resource components and processes, the full range of flow regime components should be considered when developing instream flow prescriptions.

Individual Ecological Functions

Hydrology

Natural streamflow regimes display diurnal, seasonal, and inter-annual variability, and native aquatic and riparian biota are adapted to this variability. For example, seed dispersal by native riparian cottonwoods (*Populus* spp.) is timed to coincide with the typical springtime high-flow/ snowmelt-runoff period. Seasonal flow patterns may also cue spawning for various fish species.

Year-to-year hydrologic variability is also important. For example, wet years that produce large overbank floods are important for creating habitat complexity and promoting lateral and longitudinal nutrient cycling. However, if major flooding occurred every single year, the frequent disturbance would prevent riparian communities from becoming established and compromise the stability of aquatic communities. Because different ecological functions are served by dry, wet, and average water years, inter-annual hydrologic variability should be considered when developing instream flow prescriptions.

Geomorphology

Together with streamflow, the physical channel form provides important hydraulic habitat features such as pools, riffles, and backwaters. The morphology of river-floodplain systems is dynamic. Geomorphic variables, including channel width, depth, bed material characteristics, plan form, and slope, are all potentially adjustable and controlled by the influx of water and sediment against the backdrop of a particular geologic/physiographic setting. Classic geomorphic theory suggests that streams tend toward a state of "dynamic equilibrium" in which, over a period of time, channel size, shape, and slope adjust to the dominant sediment and flow regime (Mackin 1948, Leopold et al. 1964). In a stream that is in equilibrium, features like pools that are lost due to in-filling tend to be replaced by new pool features that are created by scour elsewhere in the system. Over time, the distribution of habitat features in an equilibrium channel is maintained.

When streamflow or sediment supply is altered by dams, diversions, or other factors, channel equilibrium may be disturbed. A channel may begin to downcut, aggrade, narrow, or widen as it responds to changes in the flow and/or sediment regime (Schumm 1969, Williams and Wolman 1984). If an instream flow prescription is developed based on an analysis of existing hydraulic habitat in a rapidly widening or incising river, habitat will not be effectively protected over the long term. Therefore, geomorphic trends in the river reaches of interest should be considered when developing instream flow recommendations.

Channel morphology and processes are a function of a wide spectrum of different flow regime parameters. Much attention is paid to the "bankfull channel," which empirical research has found to correspond with discharges with recurrence intervals between 1.2 and 4 years (Leopold et al. 1964). These moderate-magnitude, bankfull floods are effective at flushing accumulated fine sediments from gravels, scouring pools, building riffles, removing vegetation from active channel areas, inundating bars, and maintaining channel capacity. Bankfull discharge also corresponds with effective discharge, which is the flow that transports the largest amount of sediment when averaged over a long period of time (Wolman and Miller 1960, Andrews 1980, Leopold 1992, Andrews 1994).

Less frequent, higher-magnitude floods that overtop the streambanks also perform important geomorphic functions. Overbank floods can create new side channels, form or erode islands, build log jams, cut off meander bends, and deposit fresh sediment on the floodplain. These processes increase channel complexity and habitat diversity, as well as provide the disturbance that forms germination sites needed for recruitment of certain riparian plants.

Water Quality

Streamflow volume directly influences water quality parameters including temperature, sediment and nutrient concentrations, dissolved oxygen, and pollutant concentrations. Dams and diversions that impound water and/or alter downstream flow release volumes can significantly alter the downstream temperature regime. Diverted streams with reduced, shallow summertime base flows are very susceptible to solar heating and can experience lethally warm water temperatures. High water temperature, especially if combined with stagnant flow velocities, can also lead to lethally low dissolved oxygen levels in streams where base flows have been reduced. Artificially high temperatures may also be seen in streams where flow regime alterations have limited the recruitment of woody riparian vegetation, thereby reducing the amount of streamside shading.

Reservoirs increase surface area and water depth, and may lead to increased or decreased downstream water temperatures depending on when flows are released and whether flows are released from the top or bottom portion of the impoundment. Altered water temperature regimes can have important effects on the aquatic community because of the influences of temperature on spawning, swimming efficiency, egg incubation, growth, and other biotic factors.

Although not a problem on lower Provo River, flow regime alterations that increase bank erosion rates, such as hydropower peaking releases, can adversely affect water quality by increasing input of fine sediments and attached nutrients and contaminants. In general, water quality is a sensitive riverine component that responds to changes in land use, groundwater recharge, and channel morphology, as well as instream flows.

Aquatic Biology

The life histories of native aquatic species are adjusted to and evolved with the variability and seasonal pattern of natural flow regimes. In the Intermountain West, many fish species cue their timing of spawn on the flow and water quality conditions that occur during spring snowmelt runoff. Spawning by species whose fry require low-velocity habitat may be timed to hatch later in the summer, when flows are typically lower than in the spring (Annear et al. 2004). Flow regime alterations that reduce springtime peak flows and/or increase summertime flow releases can have detrimental effects on native species. In addition, the geomorphic effects from flow alteration or other activities, such as river straightening, can degrade or limit the availability of spawning, staging, and rearing habitats critical to the life histories of aquatic species.

Hydraulic habitat (flow depth and velocity) is another riverine component that is dependent upon the flow regime. Individual aquatic communities may be adapted to a particular hydraulic environment such as backwaters or riffles. Other species may require a variety of hydraulic habitats for feeding, resting, and reproductive activities. Altered flow regimes may significantly reduce the availability of preferred hydraulic habitats for certain species, resulting in shifts in aquatic community composition or diversity. Changes in channel morphology, such as reduced diversity in bed and bank topography, can also limit the availability and diversity of hydraulic habitat.

Riparian Biology

The streamflow regime, together with channel morphology, largely controls the composition, distribution, and extent of riparian vegetation on streambank and floodplain areas. Different vegetation types have different inundation tolerances and water requirements. Grasses and other herbaceous species often occupy wet areas close to the channel while species with lower inundation tolerances, such as willows or cottonwoods, occupy higher-elevation surfaces. The hydrologic associations of different riparian types in terms of inundation depth, frequency, timing, and duration can be used to analyze and predict riparian community shifts resulting from flow regime alterations (Auble et al. 1994).

Altered flow regimes can limit or prevent recruitment of native woody riparian species, such as cottonwoods, which require a specific combination and sequence of fluvial surfaces and hydrologic patterns for successful seed-based reproduction (Scott et al. 1993). Specifically, the four conditions that must be met for successful cottonwood recruitment include:

1. presence of a bare surface with freshly deposited sediments at the time of seed dispersal,

2. transport and deposition of seeds onto the surface,

3. post-germination decline in water levels at a rate slow enough that seedlings do not desiccate, and

4. absence of post-germination floods that would scour seedlings.

Because of these flow-specific requirements, changes in flood magnitude, timing, frequency, or recession rate all have the potential to compromise the reproductive success of cottonwoods. Altered flow regimes may tend to instead favor nonnative riparian species such as tamarisk (*Tamarix* spp.) or Russian olive (*Elaeagnus angustifolia*), which can reproduce under a wider range of flow patterns.

Highly variable flow-release patterns, such as hydropower peaking releases, may destabilize streambanks and prevent establishment of any type of riparian vegetation. Flood-control dams that eliminate high-magnitude, overbank floods will limit the outward lateral extent of riparian vegetation along the affected river corridor.

Low-flow characteristics are also important for riparian vegetation. The inundation width of flows during the summertime growing season defines the inward lateral extent of riparian vegetation. Vegetation tends to encroach onto surfaces that remain dry during the growing season. In systems altered by artificially high summertime irrigation flow releases, the inward extent of vegetation is limited relative to streams with naturally lower summertime flows. In systems where summertime base flows are reduced or eliminated by diversions, vegetation tends to encroach inward into the active channel. If the encroaching vegetation is not scoured away by floods, channel capacity and aquatic habitat are reduced over time.

SECTION 3. IDEALIZED GENERAL APPROACH TO INSTREAM FLOW RECOMMENDATIONS

The ideal approach to instream flow recommendations would take into account all the types of riverine processes and ecological functions supported or affected by streamflows. This idealized approach is promoted by several of the Instream Flow Council's Policy Statements (Annear et al. 2004):

> *IFC Riverine Components Statement:* Instream flow studies must evaluate flow needs and opportunities in terms of hydrology, geomorphology, biology, water quality, and connectivity.
>
> *IFC Riverine Resource Stewardship Policy Statement:* All streams and rivers should have instream flows that maintain or restore, to the greatest extent possible, ecological functions and processes similar to those exhibited in their natural or unaltered state.
>
> *IFC Flow Variability Statement:* Instream flow prescriptions should provide inter- and intraannual variable flow patterns that mimic the natural hydrograph (magnitude, frequency, duration, timing, rate of change) to maintain or restore processes that sustain natural riverine characteristics.

The idea of a comprehensive framework that includes all riverine components is also suggested in the principles of effective instream flow science outlined in a recent National Research Council report (NRC 2005). These principles are as follows:

- Preserve whole functioning ecosystems rather than focus on single species.
- Mimic, to the extent possible, the natural flow regime including seasonal and inter-annual variability.
- Expand the spatial scope of instream flow studies beyond the river channel to include the riparian corridor and floodplain systems.
- Conduct studies using an interdisciplinary approach. Instream flow studies need hydrologists, biologists, geomorphologists, and water quality experts all working together. Experts can come from academic, public, and private sectors.
- Use reconnaissance information to guide choices from among a variety of tools and approaches for technical evaluations in particular river systems.
- Practice adaptive management, an approach for recommending adjustments to operational plans in the event that objectives are not being achieved.
- Involve stakeholders in the process.

As a way to incorporate the ideas promoted by these principles and policy statements, we have listed the recognized riverine processes and ecological functions and the flow regime component(s) (i.e., type of instream flow prescription) that need to be provided in order to support the ecological function (Table 3.1). This table provides a starting point for developing a specific approach to instream flow recommendations for an individual river reach of interest.

Table 3.1. General types of riverine processes and ecological functions supported by instream flows.

CATEGORY	ECOLOGICAL FUNCTION	PURPOSE/ISSUES	GENERAL TYPE OF FLOW REQUIRED
Water Quality	Maintenance of water temperature below harmful/lethal levels.	When summertime flows become too low, temperatures can exceed harmful/lethal levels.	Adequate summertime base flow.
Water Quality	Nutrient cycling.	High, overbank flows that inundate the floodplain provide lateral connectivity between the channel and floodplain and allow for nutrient cycling.	High magnitude, low frequency flood flows.
Biology: Aquatic	Spawning: attraction flows.	Spring-spawning species may cue their timing of spawn on water temperature/chemistry conditions associated with spring snowmelt runoff.	Flows patterned/ timed to coincide with natural springtime snowmelt runoff.
Biology: Aquatic	Spawning: flushing of gravels.	Adequate flows are needed to flush accumulated fine sediment/algae and maintain clean, loose spawning gravels and cobbles.	Regularly occurring flows of sufficient magnitude/duration to flush fine sediments.
Biology: Aquatic	Hydraulic habitat availability.	Flows affect the availability of habitats with different depths/velocities required by various aquatic species and life stages.	Flow regime that provides an appropriate mix of hydraulic habitats during critical life stage periods.
Biology: Riparian	Cottonwood/willow recruitment.	Seed-based recruitment of native woody riparian species requires a specific combination of flows and fluvial surfaces.	Flows that inundate an appropriate germination surface during the seed dispersal window and then decline slowly enough for root growth to keep up with groundwater recession.
Biology: Riparian	Prevention of vegetation encroachment/channel narrowing.	Low-flow or dry conditions during the summer growing season allow vegetation to encroach into the active channel and can lead to channel narrowing.	Adequate summertime base flow.
Geomorphology	Channel maintenance.	Moderate-magnitude (bankfull) floods are needed to maintain channel capacity and form (pools/riffles) and transport sediment.	Regularly occurring flows of sufficient duration and magnitude to fully mobilize the streambed and transport the incoming sediment load.
Geomorphology	Channel complexity creation/maintenance.	Large, overbank floods create and maintain complex habitat such as side channels and backwaters.	Occasional large, overbank flood flows.
Hydrology	Inter- and intra-annual flow variability.	Native plants and aquatic species are adapted to natural flow variability at short and long term time scales.	Mimicry of natural inter- and intra-annual flow variability (duration, magnitude, rise and fall rates, etc.).

SECTION 4. METHODS FOR DETERMINING INSTREAM FLOWS

A wide variety of techniques and tools have been developed to quantify instream flow prescriptions (Annear et al. 2004). Individual techniques fall into different categories, which are described in the subsections below.

Base Flow/Minimum Flow Setting Techniques

A number of different techniques can be used to set base flow or minimum instream flow requirements (Table 4.1). The techniques included in Table 4.1 generally require a low level of effort and can be done either entirely in the office or with a relatively small amount of fieldwork. However, because they only set a single minimum flow value, they do not provide inter- or intra-annual flow variability. In addition, they do not address the role of moderate or high flows important for resource components such as riparian vegetation, channel morphology and substrate, and nutrient cycling. Therefore, these tools should be used only in conjunction with other techniques to establish a comprehensive flow-protection strategy that meets the needs of the full range of riverine components and ecosystem functions.

Many of the techniques included in Table 4.1 rely on assumptions about the hydraulic habitat needs of aquatic species and use flow as a surrogate for habitat conditions. A specific technique may only be appropriate to apply to a particular geographic region, stream type, or fish species/life stage. The assumptions that underlie a given technique should be assessed and validated for the specific stream reach and species of interest before it is applied.

Hydraulic Modeling (Incremental) Techniques

Hydraulic modeling techniques are often referred to as “incremental” techniques (Annear et al. 2004). They involve detailed field data collection to develop quantitative models that predict hydraulic habitat variables (primarily depth and velocity) for a given flow condition. While they can be used to set a single minimum-flow requirement, these techniques are flexible, powerful tools that can be used to evaluate and compare entire annual flow regimes or hydrograph time series. Because they require substantial fieldwork, hydraulic modeling techniques are expensive relative to the predominantly office-based minimum-flow techniques described in the previous section. A variety of different hydraulic modeling methods have been developed (Table 4.2).

Incremental techniques are most commonly used to evaluate the availability of preferred hydraulic habitat based on input habitat suitability indices (HSIs) for fish species or life stages of interest. However, the underlying physical hydraulics models also have the potential to be used to evaluate other hydraulics-dependent resources such as sediment transport and riparian vegetation.

Table 4.1. Comparison of techniques for setting base flows/minimum instream flows (based on descriptions in Annear et al. 2004; for complete methodology reference information see Annear et al. 2004).

METHOD/ REFERENCES	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
New England Aquatic Base Flow Standard (ABF) *Larsen (1981)*	Recommends the August median flow as the minimum instantaneous flow during the low-flow season; the April/May median flow for the spring season; and the February median flow for the fall/winter seasons.	Gage data representing "natural" flow regime, or drainage area to input into default equations.	Office technique. Requires little effort.	Default equations only applicable to New England streams. Data representing "natural" hydrology may be difficult to obtain.
Flow-Exceedance Percentile Techniques *Bounds and Lyons 1979*; *Northern Great Plains Resource Program (NGPRP, unpublished)*	Recommends a specific percentile value derived from a flow-duration curve as a minimum instream flow such as Q_{90} (NGPRP) or 60% of Q_{50} (Lyon's method, summer season).	Gage data representing "natural" flow regime.	Office technique. Requires little effort.	Data representing "natural" hydrology may be difficult to obtain. Applicable only to geographic region where developed. Selection of percentile value somewhat arbitrary.
Single-Transect Hydraulic-Habitat Method (R2-Cross) *Rose and Johnson 1976*	Uses a stage-discharge relation at a single riffle transect to recommend a minimum flow that provides adequate wetted perimeter, depth, and velocity conditions.	Transect (distance/ elevation) data, estimates of slope and roughness, minimum hydraulic criteria.	Based on site-specific physical characteristics. No gage data needed. Requires only moderate amount of field data.	Requires selection of appropriate transect location, roughness inputs, and hydraulic criteria.
Tennant (Montana) Method *Tennant 1976; modifications by Tessman (1980), Estes 1984, Estes and Orsborn 1986)*	Recommends a percentage of the average annual flow (Q_{AA}) as an instream flow requirement for a given 6-month period of the year.	Gage data representing "natural" flow regime, field calibration to establish appropriate percentage/time period.	Office technique. Requires little effort. If field-calibrated/ validated, relatively few data are required.	Data representing "natural" hydrology may be difficult to obtain. Applicable only to geographic region(s) where relationships are validated. Selection of percentage value somewhat arbitrary.
Wetted-Perimeter/ Inflection-Point Method *Annear and Conder 1984*	The inflection point (breakpoint) on a plot of wetted perimeter vs. discharge is selected as the minimum low-flow period instream flow prescription.	Transect (distance/ elevation) data at a riffle crest, discharge measurements or slope/roughness inputs for Manning's equation.	Based on site-specific physical characteristics. No gage data needed; requires only moderate amount of field data.	Selection of inflection point is somewhat subjective. Protection of wetted perimeter may not necessarily provide adequate hydraulic habitat.

METHOD/ REFERENCES	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
7-Day, 10-Year Low Flow ($7Q_{10}$) *Reiser et al. 1989*	Sets the $7Q_{10}$ (lowest average flow expected to occur for 7 consecutive days with a frequency of 1 in 10 years) as a minimum instream flow. This technique was originally developed to set wastewater dilution standards.	Gage data with period of record sufficient to determine $7Q_{10}$ statistic.	Office technique. Requires little effort.	$7Q_{10}$ drought flow is inadequate to protect aquatic life or ecological integrity. Not recommended for use in prescribing instream flows.
Empirical Water Temperature-Flow Evaluation	Analyzes the relationship between Flow and water temperature during a critical season to select the minimum flow needed to ensure that temperature does not exceed standards.	Gage and water temperature data for study site/time period of interest.	Based on actual study site data. Temperature effects on aquatic life typically well established.	Streamflow and temperature data not always available. Does not explicitly address physical habitat protection
Hatfield-Bruce Western Salmonid Regressions *Hatfield and Bruce (2000)*	Mean annual discharge, latitude, and longitude values are entered into equations that estimate the flow that maximizes weighted usable habitat area (WUA) for various salmonid species/guilds/ life stages. Equations are based on 127 western PHABSIM study results.	Discharge and latitude/longitude data.	Office technique. Requires little effort and little data.	Setting the flow that maximizes WUA as a minimum flow requirement may not be realistic. Application limited to western region and salmonid species only.
Dimensionless Flow Duration Curve Approach *Gourley and Allred 2000; Allred and Gourley 2002*	Annual and/or monthly dimensionless flow duration curves are developed and compared using daily flow gage records from natural streams similar to the stream of interest; results are used to develop flow recommendations ranked by percentile (i.e. wet- vs. dry year recommendations).	Daily flow data for area streams with similar physical setting as target stream and that have minimal watershed or hydrologic alteration.	Office technique; specifically provides for flexibility and year-to year-variability in flow prescriptions depending on anticipated climatic conditions (i.e., acceptable minimum flow for a “10% driest” year).	May be difficult to find “natural” gage data; selection of appropriate reference streams requires sound scientific judgment.
Demonstration Flow Assessment *Swales and Harris 1995*	A team of experts views and evaluates a number of specific flows and uses professional judgment to set a minimum instream flow value.	Experts’ field evaluation results for multiple flow levels.	Requires little data analysis. Requires moderate field effort. Useful for streams that are unsafe or difficult to model.	May be logistically difficult to schedule evaluations of specific flow increments. Technique is subjective and not necessarily repeatable.

Table 4.2. Comparison of hydraulic modeling/incremental methods (based on descriptions in Annear et al. 2004; for complete methodology reference information see Annear et al. 2004).

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
PHABSIM (Physical Habitat Simulation) *Bovee 1986. Milhous et al. 1989*	This computer program uses topography (transect), substrate (roughness), and habitat suitability inputs to simulate hydraulic conditions and WUA for a given discharge.	Transect and substrate data; water surface elevation, depth, and velocity measurements to calibrate/ verify hydraulics model; habitat suitability index (HSI) criteria.	Well-established, tested model. Software is well-documented and readily available. Requires less topographic data/computational power than two-dimensional hydraulics models.	One-dimensional model may not accurately represent hydraulic conditions in complex channels.
MesoHABSIM *Parasiewicz 2001*	Similar to PHABSIM, but on a different scale. Mesohabitat units (riffles, runs, pools etc) are mapped at multiple flow levels; maps are combined with habitat suitability criteria to model usable habitat area at different flow increments.	Mesohabitat maps at multiple flows, fish sampling to establish biological criteria/mesohabitat use.	Field measurements are simpler and less intensive than PHABSIM. Surveys encompass entire area of interest rather than a single “representative” study site.	Requires access to entire river reach and availability of accurate base maps or air photos. Designation of mesohabitat types is somewhat subjective and may be inconsistent among mappers.
Two-Dimensional Hydraulic Models *Ghanem et al. 1994, Leclerc et al. 1995*	A 2D hydrodynamics model uses detailed stream bed topography and substrate (roughness) data to generate detailed depth/ velocity information; results are combined with habitat criteria to simulate WUA for different discharges.	Detailed channel and floodplain topography data, substrate/ roughness data, water surface elevation measurements for model calibration, HSI criteria.	Fewer field measurements of velocity required than for PHABSIM. Able to simulate unsteady flow conditions, better representation of velocities in complex channel and floodplain areas.	Requires intensive, detailed field collection of topographic data. Requires more modeling expertise and computational power than one-dimensional models.
Instream Flow Incremental Methodology (IFIM) *Stalnaker et al. 1995, Bovee et al. 1998, Armour and Taylor 1991*,	Consists of a suite of linked computer models (one of which is PHABSIM) that address hydrology, biology, sediment transport, and water quality based on site-scale hydraulics models and reach-scale data.	Depends on modules used but may include transect, topography, and substrate data; water surface, depth, and velocity measurements; HSI criteria; temperature and water quality data; geomorphic reach and mesohabitat mapping; hydrologic data; substrate size measurements.	Provides a way to integrate evaluations of multiple resource components. Many of the individual models used are well documented and validated. Highly flexible tool. Incorporates seasonal and inter-annual flow variability recommendations.	Highly data-intensive technique. Requires multi-disciplinary expertise. Susceptible to misuse by inadequately trained practitioners. Often incorrectly equated with the PHABSIM method.

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Biological Response to Flow-Correlation Method *McKernan et al. 1950, Anderson and Nehring 1985*	Statistical correlations are established between biological data, habitat quality, hydrology, hydraulic habitat or water quality; these correlations are used to predict biological response to flow changes.	Biological data such as population size, year-class strength, condition; flow and/or habitat statistics for same time period as biological data.	Based on actual study site biological data.	High level of effort to gather data with adequate statistical power. Correlations may not be valid for other streams/ regions. Correlations may not account for all sources of variability.
Feeding Station Method *Fausch 1984, Beecher 1987*	Uses hydraulic modeling to relate flow to a feeding-habitat index based on areas of slow water adjacent to faster water that meets or exceeds depth thresholds.	Transect and substrate data; water surface elevation, depth, and velocity measurements to calibrate/ verify hydraulics model.	Relates flow and hydraulic conditions to a specific biological activity (feeding) rather than more generally to "habitat."	High level of effort to review individual hydraulic cells. Validity of method highly dependent on size/ scale of hydraulic cells. Not as well validated as PHABSIM. Feeding station criteria may not be available for species of interest.
Riverine Community Habitat Assessment and Restoration Concept (RCHARC) *Nestler et al. 1993, 1996*	Uses transect data to compare the spatial and temporal distribution of depth and velocity between a reference river and a target river or proposed flow alternative.	Transect data; monthly hydrologic data; water surface elevation, depth, and velocity measurements to calibrate/ verify hydraulics model.	Does not require biological (HSI) criteria. Useful as a monitoring tool to track changes through time. Straightforward way to compare flow alternatives.	May be difficult to identify an appropriate reference reach or reference flow regime. Use of monthly average flow does not account for altered daily flow-release patterns.

There are several limitations of incremental techniques, one of which is scale. Because detailed topographic data input is needed, study sites are usually limited to relatively short stream reaches. Study site results are then "scaled up" and applied to the full length of stream for which flow recommendations are being developed. This extrapolation will only be valid if the habitat/channel features encompassed within the detailed study site are representative of conditions throughout the entire reach.

Another limitation of incremental techniques is that they are based on a "one-point-in-time" survey of channel conditions and do not specifically take into account the dynamic nature of channel morphology. If a stream is out of equilibrium and is actively incising, aggrading, or widening, the results of a physical survey-based hydraulics model quickly become obsolete as site topography changes.

A final consideration when using hydraulic modeling techniques is that the ability of the model to accurately predict fish population distribution and response depends on the accuracy of the habitat suitability information used in the model. For some species and locations, depth and velocity preferences may not be known, or a species may be more responsive to factors other than hydraulic habitat. Therefore, hydraulic modeling results should be interpreted within the context of the certainty (or uncertainty) of the habitat preference assumptions used.

Spawning Flow Determination Techniques

Various techniques have been developed to determine flows needed for successful spawning by various fish species of interest. The office techniques described in Table 4.3 require little effort, but they will be reliable only if used for the species and stream type/region where the techniques were developed. Hydraulic modeling methods can be implemented anywhere, but they require collection of intensive site-specific topographic data and spawning preference data for the species of interest. None of these three methods specifically takes into account factors such as annual climatic variability or specifies the timing or falling limb pattern needed for spawning success. The biological response to flow-correlation method could be used to address these issues, but this method entails a very high level of effort to collect and analyze an adequate amount of data. Using a combination of techniques and data sources to generate a comprehensive spawning-flow recommendation may be the best way to ensure that spawning is adequately protected.

Channel Maintenance and Flushing Flow Determination Techniques

A variety of methods have been developed to determine instream flow prescriptions that protect geomorphic functions such as flushing of accumulated fine sediments, floodplain inundation, and channel maintenance. The office-based hydrologic techniques (i.e., Tennant method, flow exceedance methods) listed in Table 4.4 require little effort but will only be applicable to the region where they were developed; use of these techniques elsewhere would require field data for verification. Sediment transport models use site-specific channel geometry and substrate data, but they can provide widely variable results depending of the transport equation used. Transport models can be used to determine the flow needed to initiate transport of certain particle sizes, but they do not specify the duration of needed flows.

The effective discharge technique is particularly useful for comparing alternative proposed flow regimes, but it is subject to the same limitations as transport modeling methods unless field samples are used to generate a bedload rating curve. The U.S. Forest Service Channel Maintenance Method relies on direct field-based transport measurements, and it specifies a complete range of flows for protection; however, it requires a high level of effort and is only applicable to gravel-bed mountain streams. The empirical/test flow method is a thorough and defensible technique that uses site-specific field data (e.g., tracer rock studies, bedload sampling) to determine the magnitude and duration of flows needed to mobilize particles, maintain channel geometry, and/or flush accumulated sediments. However, it is an expensive method that requires a high level of effort. In general, appropriate implementation of any channel maintenance/ flushing-flow method will require a high level of geomorphic expertise.

Table 4.3. Comparison of spawning-flow methods (based on descriptions in Annear et al. 2004; for complete methodology reference information see Annear et al. 2004).

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Migration-Cue Method *B. Winter, pers. comm., NMFS Seattle*	Identifies a 20% flow increase in a regulated stream as the flow needed to stimulate salmon and steelhead spawning migration in the absence of a natural flood event.	Flow value before migration; application to other regions/ species would require data on spawning migration cue thresholds.	Office technique. Requires little effort.	Only applicable to regulated streams. 20% pulse value is somewhat subjective/arbitrary. Not applicable to other regions or species without validation.
Flow-Exceedance Percentile Methods for Spawning Flows *Hoppe (unpublished paper), Bounds and Lyons 1979*	Designates a specific percentile value derived from a flow-duration curve as a spawning flow recommendation such as the Q_{40} (Hoppe) or 60% of the Q_{50} (Lyons).	Gage data representing "natural" flow regime.	Office technique. Requires little effort.	Data representing "natural" hydrology may be difficult to obtain. Applicable only to geographic region where developed. Selection of percentile value somewhat arbitrary.
Hydraulic-Modeling Methods for Spawning Flows *See references in Table 4.2*	Combines spawning depth and velocity preference criteria with hydraulic model results (such as PHABSIM or a 2-D Model) to determine the flow that maximizes spawning habitat.	Inputs for selected hydraulics model (see Table 4.2), spawning depth/velocity criteria, also possible to incorporate spawning substrate preference criteria.	Quantitative technique. Based on site-specific conditions. Easy to evaluate and compare a range of flow alternatives.	High level of effort. If intensive modeling site is not representative of larger reach, results may be skewed when extrapolated. Hydraulic variables may not be main control on spawning success.
Biological (Spawning) Response to Flow-Correlation Method *McKernan et al. 1950, Anderson and Nehring 1985*	Statistical correlations are established between data on spawning success and hydrology or hydraulic habitat; these correlations are used to predict biological response to flow changes.	Biological data on timing and success of spawning, flow and/or habitat statistics for same time period as biological data.	Based on actual study site biological data.	High level of effort to gather data with adequate statistical power. Correlations may not be valid for other streams/ regions. Correlations may not account for all sources of variability.

Table 4.4. Comparison of channel-maintenance and flushing-flow methods (based on descriptions in Annear et al. 2004; for complete methodology reference information see Annear et al. 2004).

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Flow-Exceedance Percentile Methods for Flushing Flows *Hoppe (unpublished paper), Beschta and Jackson (1979)*	Designates a specific percentile value derived from a flow duration curve as a flushing flow recommendation, such as the Q_{17} for 48 hours (Hoppe) or the Q_5 (Beschta and Jackson)	Gage data representing “natural” flow regime.	Office technique. Requires little effort.	Data representing “natural” hydrology may be difficult to obtain. Applicable only to geographic region where developed. Selection of percentile value somewhat arbitrary.
Tennant Method for Flushing Flows *Tennant 1976; modifications by Tessman (1980), Estes 1984, Estes and Orsborn 1986)*	Recommends 200% of the average annual flow (Q_{AA}) for 48-72 hours as a flushing or maximum flow	Gage data representing “natural” flow regime.	Office technique. Requires little effort. Would require field data for verification of appropriateness for use in a different region.	Data representing “natural” hydrology may be difficult to obtain. Applicable only to geographic region(s) where relationships are validated. Selection of percentage value somewhat arbitrary.
Empirical/Test-Flow Method *Reiser et al. 1988*	Sediment transport and channel condition data are collected before and after test flow releases to assess changes and determine the threshold discharge for sediment movement	Bedload and suspended load transport rates; streamflow data; transect (elevation) data; substrate size/composition; tracer rock data.	Based on site-specific data and channel conditions. Thorough and defensible method.	High level of effort requiring intensive field data collection and a high level of geomorphic expertise. If study site is not representative, results may be inaccurate when “scaled up” to entire reach of interest.
Sediment Transport Modeling Methods *Meyer-Peter Mueller 1948, Einstein 1950, Parker 1982, 1990*	Established sediment transport equations are used to determine the flow at which a certain bed particle size is mobilized or the flow at which substantial bedload transport begins	Streambed particle size distribution, transect and slope data.	Less field work required than empirical/ test flow techniques. More quantitative and physically based than office/ hydrology-based techniques.	Different transport models can provide highly variable results. Expertise required to select appropriate model for study area. Potential for gross inaccuracies if results not verified. Method does not address flow timing or duration.

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Effective-Discharge Method *Wolman and Miller 1960, Andrews and Nankervis 1995*	This uses a bedload rating curve in conjunction with flow duration data to determine the effective discharge - the flow that moves the greatest amount of sediment over time; it can also estimate using general/regional relationships (e.g., effective Q = bankfull Q=1.5 yr Q).	Transect, roughness, slope, and particle size data; long-term flow data, documented regional relationships.	Useful for comparing effective discharge under alternative flow regimes. Low level of effort if regional empirical relationships used instead of bedload transport model or sampling data.	Protection of single-value effective discharge may not protect full range of flows important for sediment transport Use of regional relationships or transport model results subject to inaccuracies if not verified.
U.S. Forest Service Channel-Maintenance Method *Schmidt and Potyondy 2004*	Establishes that flows between the “trigger” discharge (flow at which Phase 2 bedload transport is initiated, often approximately bankfull discharge) and the 25-year flood should be protected for channel maintenance in gravel-bed rivers.	Bedload particle size distribution; direct bedload transport measurements (ideally, 80 samples); flood frequency analysis of long-term flow data.	Based on strong empirical evidence. Quantitative technique based on site-specific data and channel conditions. less subjective than some other techniques	Only applicable to gravel-bed streams. High level of effort/data collection required.
Floodplain Inundation Method *Benke et al. 2000*	Uses stage-discharge relations to identify discharge that substantially inundates and maintains the floodplain.	Transect data; stage-discharge data (field surveys, model outputs, or gage records); inundation needs of target species; historical high flow data.	Technique links lateral connectivity with biology. Relatively little effort if data are available and field surveys not required.	High effort if transect/stage-discharge data not available. Requires subjective interpretation of species’ inundation needs.
Hydraulic Engineering Center-6 Model (HEC-6) *USACE 1991*	This 1-D flow and sediment transport model simulates changes in river profiles due to scour and deposition; outputs can be used to determine flows needed to maintain channel equilibrium.	Reach geometry, roughness, substrate size, sediment inflow rate, hydrology, and water surface data.	Well-established, tested model. Software is well-documented and readily available. Easy-to-adjust variables to calibrate/validate model results.	Subject to widely variable results if inappropriate sediment transport function used or if input data are inaccurate.

Riparian Vegetation Techniques

Several of the methods developed to prescribe instream flows to protect fisheries can also be modified for use in prescribing riparian vegetation flows (Table 4.5). One- or two-dimensional hydraulic modeling approaches can be used to determine flows that meet designated floodplain inundation or riparian recruitment criteria. Use of these techniques requires that the inundation-duration and recruitment requirements of the target riparian species are well understood for the region of interest. The wetted perimeter/inflection point method, which identifies the flow below which the streambed begins to substantially dry out, could be used to identify a minimum-flow requirement to prevent encroachment of riparian vegetation into the streambed.

Table 4.5. Comparison of riparian vegetation flow-determination methods (based partly on descriptions in Annear et al. 2004; for complete methodology reference information see Annear et al. 2004).

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Floodplain Inundation Method *Auble et al. 1994*	Uses a stage-discharge model, such as HEC-RAS, to identify the inundation frequency/duration of different floodplain surfaces and riparian communities; the flow-riparian relationships are then used to predict changes under alternative flow scenarios.	Transect and substrate data; water surface elevation, depth, and velocity measurements to calibrate/ verify hydraulics model; elevation and composition of riparian communities.	Directly links riparian communities to hydrologic conditions. Allows comparison of resulting riparian communities/areas under alternative flow regimes.	Flow-riparian relationships may be unclear/difficult to establish. Relatively high level of effort required.
Hydraulic Modeling Methods for Riparian Recruitment Flows *Mahoney and Rood 1998, Rood et al. 2003, Olsen 2004, Stamp et al. 2005.*	Uses recruitment criteria (timing of inundation, flow recession rate, final groundwater elevation) in conjunction with a 2D hydrodynamics model to predict amount and distribution of cottonwood recruitment under different flow scenarios.	Two-dimensional hydraulic model data inputs (see Table 4.2); specific riparian recruitment criteria.	Allows comparison of recruitment success under alternative flow regimes. Easy-to-adjust/calibrate recruitment criteria model parameters.	High level of effort to set up model. Recruitment criteria may not be well established for some species.
Wetted Perimeter/ Inflection Point Method for Anti-Encroachment Flows *Adaptation of Annear and Conder 1984*	The inflection point (breakpoint) on a plot of wetted perimeter vs. discharge is selected as minimum flow prescription during the growing season to prevent vegetation encroachment into the active channel.	Transect (distance/elevation) data at a riffle crest; discharge measurements or slope/ roughness inputs for Manning's equation.	Based on site-specific physical characteristics. No gage data needed. Requires only moderate amount of field data.	Selection of inflection point is somewhat subjective.

Hydrologic Variability Assessment Techniques

Several methods for determining hydrologic variability have been developed (Table 4.6). Any of these methods can be used in conjunction with other instream flow techniques to help specify the appropriate timing, duration, frequency, and pattern of recommended flows, and to stratify requirements according to year-to-year flow variability (i.e., modify recommendations for wet, dry, or average water years). In cases where ecological data are unavailable, these techniques can be used to establish instream flow requirements that meet natural hydrologic criteria. All of these techniques require the availability of daily streamflow data with a sufficient period of record and the availability of hydrologic data representing "natural" flow conditions. Because it uses a compilation of regional streamflow gage data, the dimensionless flow-duration curve approach can be particularly useful for highly regulated/diverted streams for which historical/natural flow hydrologic records are unavailable.

Table 4.6. Comparison of hydrologic-variability methods (based partly on descriptions in Annear et al. 2004; for complete methodology reference information see Annear et al. 2004).

METHOD/ REFERENCE	DESCRIPTION	DATA REQUIRED	ADVANTAGES	DISADVANTAGES
Indicators of Hydrologic Alteration (IHA) *Richter et al. 1996*	This computer program uses stream gage records to generate 32 ecologically relevant hydrologic parameters that address magnitude, frequency, duration, timing, and rate of change	Daily flow data	Office technique; can be used to identify temporal trends or compare pre- and post-impact (e.g., pre- and post-dam) flow regime characteristics	Daily flow data with an adequate period of record may not be available for area of interest
Range of Variability Approach (RVA) *Richter et al. 1997*	This extension of IHA identifies an appropriate range of variation in each of the 32 IHA parameters to determine target instream flows for river management	Daily flow data reflecting a natural hydrological regime	Office technique; tool for setting flow targets when adequate ecological data are unavailable; can be used to evaluate how often variability goals are met	Does not specifically address geomorphic condition of channel; "natural" flow regime data with a sufficient period of record may not be available
Dimensionless Flow Duration Curve Approach *Gourley and Allred 2000; Allred and Gourley 2002*	Annual and/or monthly dimensionless flow duration curves are developed and compared using daily flow gage records from natural streams similar to the stream of interest; results are used to develop flow recommendations ranked by percentile (i.e. wet vs. dry year recommendations)	Daily flow data for area streams with similar physical setting as target stream and that have minimal watershed or hydrologic alteration	Office technique; specifically provides for flexibility and year-to year-variability in flow prescriptions depending on anticipated climatic conditions (i.e., acceptable minimum flow for a "10% driest" year)	May be difficult to find "natural" gage data; selection of appropriate reference streams requires sound scientific judgment

SECTION 5. APPROACH TO INSTREAM FLOW RECOMMENDATIONS, LOWER PROVO RIVER

Study Area/Watershed Overview

The remaining sections of this report apply the general instream flow approach described in Section 3 to the portion of the lower Provo River between Murdock Diversion and Utah Lake (Figure 5.1).

The Provo River originates in the Uinta Mountains of Utah at an elevation of approximately 10,800 feet and flows through Jordanelle Reservoir, Heber Valley, Deer Creek Reservoir, and Provo Canyon before reaching the Study Area. Within the Study Area, the Provo River flows through the cities of Orem and Provo before it outlets into Utah Lake. Average precipitation within the Study Area ranges from about 20 inches at the Olmsted Power Plant near the mouth of Provo Canyon to about 13 inches near Utah Lake (NOAA 2001, Utah Climate Center 2006). The majority of this precipitation comes in the form of snow during the winter months, which melts and runs off during the spring and early summer months. The annual hydrograph in the Study Area is driven by the amount of wintertime snow accumulation and the rate and timing of snowmelt throughout the watershed, especially in the Uinta Mountains, and the operation of water development facilities and features.

The hydrologic, geomorphic, and biological characteristics of the Provo River system have been greatly altered by a variety of historical anthropogenic influences. Flows are affected by a complicated network of dams, water imports, and water diversions constructed for hydropower, irrigation, and water-supply purposes. In addition to the natural runoff of the Provo River basin, there are two transbasin diversions that import water into the basin above Jordanelle Reservoir: the Weber-Provo Canal and the Duchesne Tunnel (Figure 5.1). Other important water development features include Deer Creek Dam and Reservoir, Olmsted Diversion, Murdock Diversion, and Provo Reservoir (Murdock) Canal. Eight additional diversion structures are present in the Study Area below Murdock Diversion (Figure 5.2).

Existing Conditions

Hydrology

Water operations have altered the streamflow hydrograph within the Study Area from natural historical conditions. In addition to the hydrologic alterations caused by Jordanelle Dam, Deer Creek Dam, and Olmsted Diversion, the lower Provo River is affected by diversions at nine additional locations (Figure 5.2). Murdock Diversion is the largest of these and commonly diverts more than 300 cfs from the river during the height of the summer irrigation season.

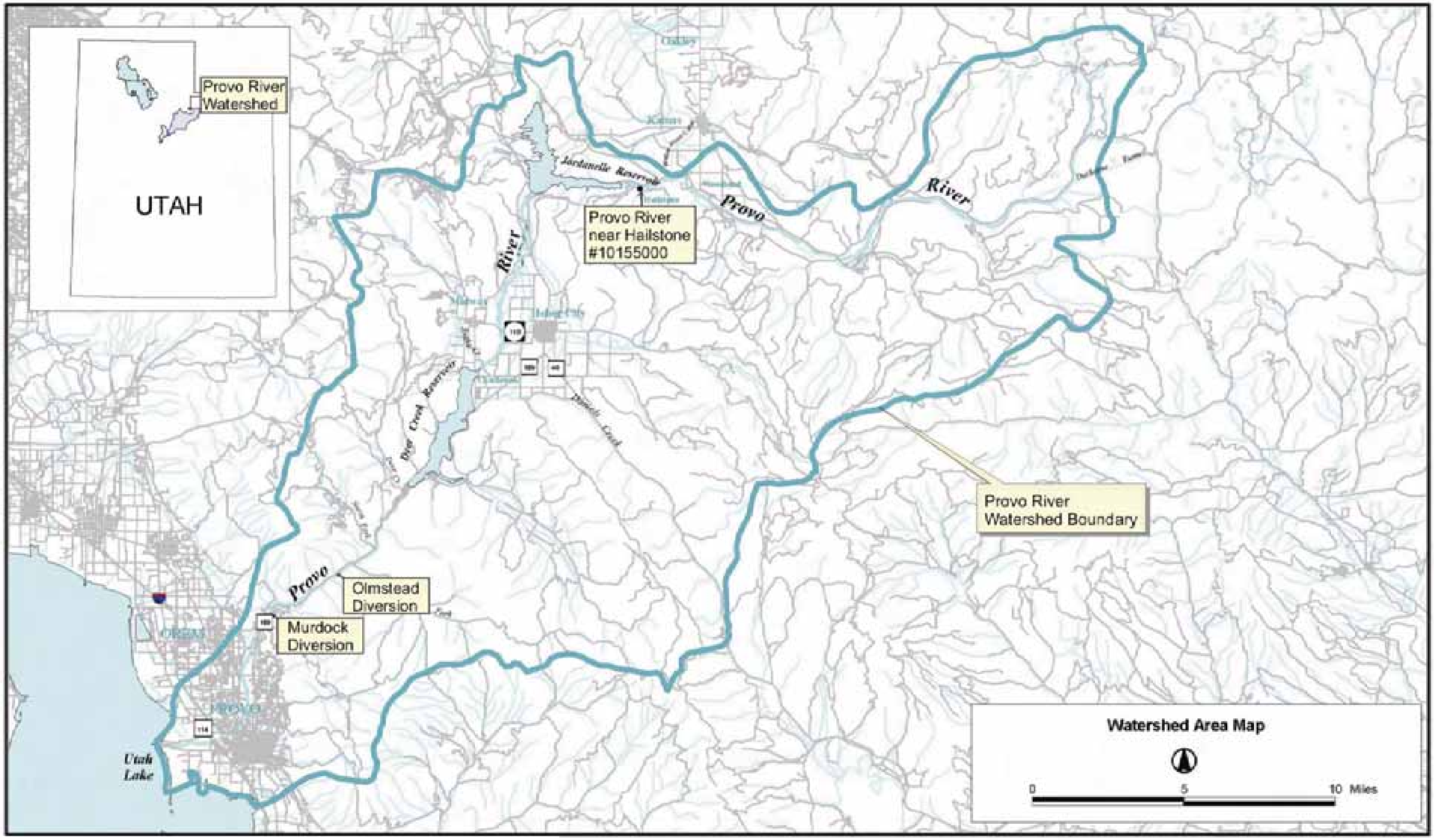

Figure 5.1. Location and watershed area map.

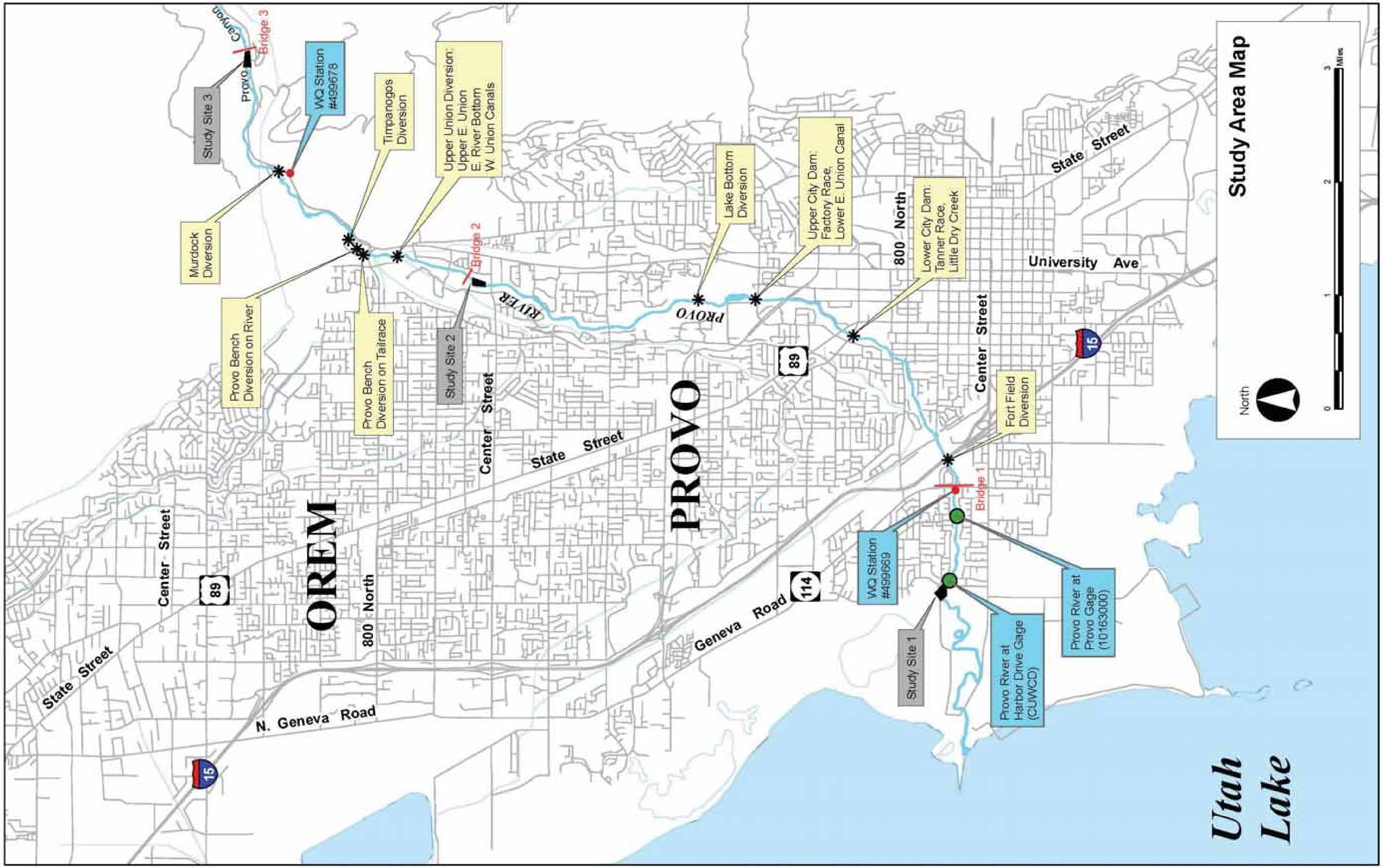

Figure 5.2. Study Area map.

Cumulatively, the eight diversions on the lower Provo River divert between 50 and 700 cfs from the river between May and September (BIO-WEST 2001).

The effects of these diversions and upstream water operations are illustrated by data from the U.S. Geological Survey (USGS) gage at Provo, which is located downstream of all the diversions (Figure 5.3). Peak flows at this gage site have been reduced by approximately 66% and occur approximately 2 weeks later than they would have naturally (UDWR 1999).

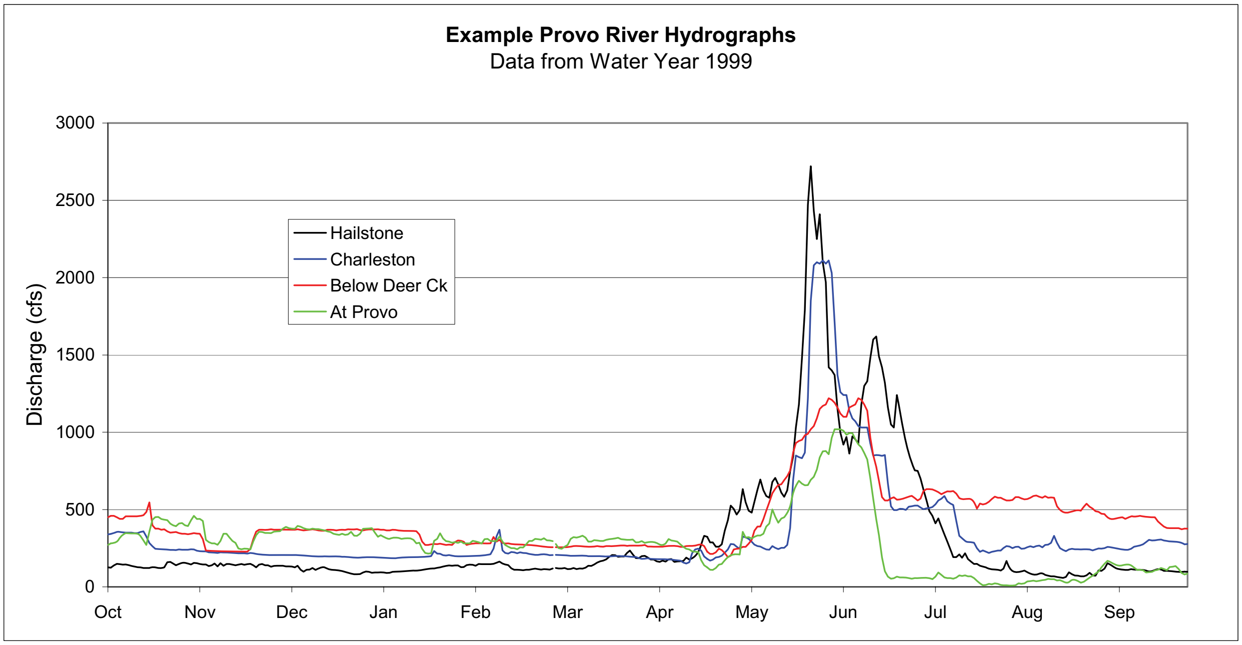

Figure 5.3. Example Provo River hydrographs.

Attempts to operate the Provo River system to provide flows more suitable for June sucker (*Chasmistes liorus*) spawning and recruitment have been ongoing since 1994, and attempts to manage streamflows to match "target" hydrographs have been implemented since 1997. However, streamflows outside the spring period targeted by the June Sucker Flow Workgroup are intermittent, at best. Summer flows as low as 2 cfs were recently recorded at the Provo USGS gage, and portions of the lower river between diversion structures are commonly dewatered (BIO-WEST 2001). In the summer of 2007, experimental releases of 40 cfs were delivered to the lower river and water temperature was monitored in an attempt to maintain better water quality during the summer base flow period (see Appendix G for details). Similar releases are planned for summer 2008.

Geomorphology

The lower Provo River is highly urbanized and flows through the cities of Orem and Provo (Figure 5.2). Within the Study Area, the river has been extensively channelized and straightened, and levees have been constructed to protect residential, commercial, industrial, and agricultural land uses. Because of these channel modifications, a floodplain is generally nonexistent, streambanks are overly steep and tall, and natural geomorphic processes, such as point bar deposition and channel avulsion, are limited. Flood flows are fully contained between the levees. The lack of large, functional, connected floodplain areas severely reduces the spatial and temporal diversity of in-stream habitat and limits natural recruitment and extent of riparian vegetation.

Sediment supply to the lower Provo River has been reduced by the presence of dams and diversions that trap sediment. Sediment inputs are limited to bank and bed erosion and nonpoint source inputs. The diversion structures within the Study Area also create “knick points” in the channel profile that artificially flatten channel gradient both upstream and downstream, and lead to deposition of fine-grained sediment (e.g., sand and silt) within the substrate material. In general, substrate in the upstream portion of the Study Area is coarse, consisting primarily of cobble material. In the lower portion of the Study Area, stream gradient flattens and gravel comprises a larger proportion of the bed material.

River channelization, straightening, and dredging at the mouth of Provo River have compromised the longitudinal connectivity between the river and Utah Lake. The lowermost 1.6 miles of Provo River have been converted to “lake habitat,” where conditions are controlled more by the Utah Lake backwater than by actual river flows. Velocities are slow to stagnant, with water depths of 6 to 10 feet depending on the Utah Lake level. Substrate consists of silty material, and the straightened, steep-banked trapezoidal channel shape severely limits aquatic and riparian habitat availability. Few emergent or submergent aquatic plants are present (Olsen et al. 2002).

Under historical, unaltered conditions, the lower Provo River at its interface with Utah Lake would most likely have behaved as a delta, with a multi-threaded channel pattern. This area would have historically provided considerably more complex, off-channel, low-velocity habitat than the current (2008) river-lake interface does in its channelized condition. River flows would have been distributed among multiple channel threads, adding complexity to the depth and velocity conditions available at a given total streamflow rate. If physical habitat restoration measures are pursued on the lower Provo River in the future, the relationships among streamflow, geomorphology, and depth/velocity conditions would be anticipated to change.

Water Quality

Water quality data are collected by the Utah Division of Water Quality (DWQ) at its station near Geneva Road/U-114 (Station #499669), and by the CUWCD at its gage at Harbor Drive (Figure 5.2). While streamflows are maintained by releases specifically to achieve June sucker target flows in the Spring, water quality is high and would not appear limiting to aquatic flora and fauna. However water quality is typically poor in the river’s lower reaches during summer low flow periods due to low dissolved oxygen levels and elevated temperatures. Below Upper City Dam, polluted storm water runoff from urbanized areas contributes a large portion of the streamflow during storm events. Fish kills associated with polluted runoff are possible in the lower reaches of the river if these storm events occur during low-flow periods (USFWS 1999).

Nutrient and sediment inputs, combined with warm temperatures and shallow water depths, contribute to summertime build-ups of algae and macrophytes within the channel. This aquatic vegetation can cause armoring of spawning gravels and accumulations of fine sediments that degrade spawning habitat quality.

Riparian Vegetation

The width and overall density of riparian vegetation in the lower Provo River are low relative to upstream portions of the watershed. As previously discussed, channelization and bank armoring (i.e., rip rap) are extensive in the lower river, and flat vegetation establishment surfaces are therefore very limited. Common species include willow (*Salix* sp.), cottonwood, box elder (*Acer negundo*), and various grasses. Exotic invasive species, including tamarisk, Russian olive, and common reed (*Phragmites australis*) are also present at various locations within the Study Area. Plant diversity is artificially increased in the lower river because of the proximity of landscaped, stream-side residential and commercial properties. These landscaped areas are often irrigated, supplying an additional source of water that alters riparian vegetation patterns from what would occur naturally if the river were the only water source. Cottonwood recruitment occurs to a limited extent on localized bar and bank surfaces within the lower river.

Fisheries

The lower Provo River downstream of Murdock Diversion can be divided into two sections in terms of habitat conditions available to fish. The differences in habitat affect the community composition in these areas, as indicated by fish sampling efforts in the Lower Provo River conducted annually by the Utah Division of Wildlife Resources (UDWR).

The upstream half of the Study Area (Murdock Diversion to Lower City Dam) has nearly constant depth and substrate, which limits habitat diversity available to fish. However, some cover is present that provides habitat for a persistent population of larger brown trout (*Salmo trutta*). The densities of brown trout are not as high in this section of river as in areas above Murdock Diversion, but the two sites sampled by UDWR in 2004 still had 1,590 and 2,058 fish per mile (Hepworth and Wiley 2004). Few rainbow trout (*Oncorhynchus mykiss*) or cutthroat trout (*Oncorhynchus clarki*) persist in this reach. Mountain whitefish (*Prosopium williamsoni*) and mottled sculpin (*Cottus bairdi*) occur in this reach but are also uncommon (Hepworth and Wiley 2004).

The downstream half of the Study Area (the last 4.9 miles below Lower City Dam) is designated as Critical Habitat for June sucker and management focuses on conservation and enhancement of the species relative to guidelines outlined in the June Sucker Recovery Plan (USFWS 1999). The June sucker was Federally listed as an endangered species in 1986. The documented wild population size at time of listing was less than 1,000 individual spawning adults (USFWS 1999); a more recent estimate is 393 individual spawning adults UDWR (2004a). Historically, spawning, rearing, and nursery habitats may all have been available in whole or in part within the Provo River. In its current condition, this section of the lower Provo River provides the greatest, though limited, habitat suitable for spawning, as well as very limited rearing or nursery habitat (Radant et al. 1987). The Provo River is used by adult June sucker for spawning in late May and June. After 7-10 days, larvae hatch and drift downstream to Utah Lake. Fort Field Diversion is located approximately 3miles upstream of the mouth of the Provo River and is likely a migration barrier during some spawning seasons (C. Thompson 2000, pers. comm.). Tanner Race (Lower City) Diversion is a barrier to migration at any flow due to a drop in streambed elevation of approximately 8 feet at the diversion structure.

In addition to providing the only known spawning habitat for June sucker, the lowermost portion of the Study Area (i.e., lake habitat) is managed as a Wildfish Water for white bass (*Morone chrysops*), black bass (*Micropterous* sp.), walleye (*Sander vitreus*), channel catfish (*Ictalurus punctatus*), and brown trout. Wildfish Waters are those waters that can be naturally sustained, and the fishery is maintained via natural reproduction. Electrofishing samples by UDWR (Hepworth and Wiley 2004) revealed that brown trout are the most common species in this segment of the river. The high relative abundance of nonnative fishes is a threat to the continued existence of June sucker.

In the downstream half of the Study Area, the river is largely influenced by Utah Lake and has many transient species that move upstream from the lake including most of the nonnative species managed as part of the Wildfish Water designation. Here deeper habitats and cover along the shoreline, including overhanging riparian vegetation and large woody debris, provide high-quality habitat for large brown trout as well as species that are more typically associated with lake habitat. Although the UDWR conducts sampling in a few sites in this lower section of the river using its standard electrofishing techniques, habitat that is closer to the lake is often too deep to sample this way. In these areas sampling is conducted primarily by snorkeling and spotlighting (June sucker), as well as drift netting and light traps (for larvae) (UDWR 2002, 2003, 2004b, 2004c, 2005). Trap netting is conducted annually in Utah Lake, and during 1999-2001 nets were set near the mouth of the Provo River. The results of these efforts give an indication of which fish species are associated with the most downstream section of the lower Provo River (though not all species captured in the river mouth travel up into the river in significant numbers). The species abundance data from these efforts were virtually all non-native species, primarily black bullhead (*Ameiurus melas*) (28%, 40%, and 43% in 1999, 2000, and 2001, respectively) and common carp (*Cyprinus carpio*) (29%, 18%, and 31%, respectively). Other non-natives included bluegill sunfish (*Lepomis macrochirus*), black crappie (*Pomoxis nigromaculatus*), white bass, and yellow perch (*Perca flavescens*). June sucker captures amounted to only 0.2%, 0.3%, and 0.002% of the catch in 1999, 2000, and 2001, respectively. Other native fish species included Utah sucker (*Catostomus ardens*) (one individual in each of 1999 and 2000) and redside shiner (*Richardsonius balteatus*) (one individual in 2000). Placement of trapnets near the mouth of the Provo River has been sporadic due to ineffectiveness at sampling the spawning run of June sucker (UDWR 2002), but Utah State University again began placing trapnets in 2004.

June Sucker

As discussed above, the documented wild population size at the time June sucker was Federally listed was less than 1,000 individual spawning adults (USFWS 1999). Since 1994 supplemental June sucker raised in hatchery and refuge facilities have been stocked into Utah Lake nearly every year (Table 5.1). These fish have been propagated in captivity from brood stock developed to represent, to the greatest extent possible, the genetic composition of the wild population. The current population of June sucker in Utah Lake is a mix of wild and stocked individuals.

Table 5.1. Summary of annual June sucker stocking efforts. [a]

YEAR	SOURCE POPULATIONS						TOTAL
	Red Butte Reservoir	Camp Creek	Fisheries Experiment Station	Rosebud	Springville	Net-Pens	
1994	0	0	1,557	0	0	0	1,557
1995	0	0	1,221	0	0	0	1,221
1996	0	0	312	0	0	0	312
1997	0	0	0	0	0	0	0
1998	0	0	0	0	0	0	0
1999	0	0	692	0	0	0	692
2000	0	0	0	0	0	0	0
2001	700	939	1,056	0	0	0	2,695
2002	0	0	0	0	0	0	0
2003	0	0	3,384	0	0	0	3,384
2004	1,600	1,069	23,333	0	0	0	26,002
2005	9,165	880	3,562	0	0	0	13,607
2006	0	336	1,473	1,901	0	0	3,710
2007	0	0	52,956	7,000	1,100	5,319	66,375
Total	**11,465**	**3,224**	**89,546**	**8,901**	**1,100**	**5,319**	**119,555**

[a] Fish size upon stocking varied from 3 to 8 inches.

The UDWR (2004a) estimated that the total number of adult June sucker in the Provo River during the 2004 spawning season was 393 individuals. The report does not differentiate population estimates by wild and stocked fish, but spotlighting efforts (upon which the estimates are based) resulted in 20 wild June sucker, 130 wild Utah or hybrid sucker, and 141 stocked June sucker. More recent spotlight sampling efforts caught only seven suckers (six Utah sucker and one hybrid) in 2005 (UDWR 2006), and 16 suckers (eight June suckers, seven hybrid, one Utah sucker) in 2006. Five of the eight June sucker captured in 2006 were stocked fish from Red Butte Reservoir, and the other three were of unknown origin (UDWR 2007). Part of the reason few fish were caught in 2005 and 2006 was that high flow conditions limited the ability to sample the river in those years. Flows were lower in 2007, allowing for a greater amount of sampling time. A total of 271 individual suckers (237 June sucker, 21 Utah sucker, 13 hybrid sucker) were captured in 2007 (UDWR 2008b). Of the 237 June sucker, 172 were from Red Butte, 10 were from Camp Creek, 7 were from the Fisheries Experiment Station hatchery in Logan, 47 were of unknown origin, and 1 was wild (UDWR 2008b). Also in 2007, 167 June sucker were captured in trap and trammel nets near the mouths of the Provo and Spanish Fork Rivers, and in Provo Bay near the mouth of Hobble Creek (UDWR 2008a); information as to the origin of these suckers is not yet available. Overall, based on the most currently available data, it appears that the June sucker population remains quite low and that the wild proportion of the population is small. However, significant numbers of June sucker larvae (823 in 2005; 486 in 2006; 31 in 2007) continue to be caught annually in drift nets in the lower Provo River (see Appendix E for additional details), suggesting that successful spawning is occurring (UDWR 2006, UDWR 2007, UDWR 2008a). Lack of recruitment from the larval to adult life stages appears to be the primary limitation on the population numbers. Monitoring efforts planned for 2008 will include use of a stationary antenna in the lower Provo River, which will allow for continuous "sampling" of fish even during periods of high flow. This planned monitoring should provide more accurate information about the June sucker population numbers in Utah Lake.

Spawning

Although is it believed that river flow is the primary factor influencing the cue for June sucker to initiate the spawning migration (USFWS 1999), a similar species, the cui-ui (*Chasmistes cujus*), is believed to be cued by water temperatures in addition to flow characteristics (Scoppettone et al. 1983, Sigler et al. 1985, Scoppettone et al. 1986). Peak migrations for cui-ui occur in river temperatures varying from 9°C to 17°C and mean daily temperatures from 12°C to 15°C (Scoppettone et al. 1986). Hatching success is highest at temperatures lower than 17°C (Coleman et al. 1987). In addition to the apparent importance of temperature, Scoppettone et al. (2000) suggest that "sufficient fresh turbid flow" is also required to stimulate migration of that species. However, it remains unclear how readily the spawning requirements for cui-ui translate to the requirements for June sucker.

Alterations to the historic Provo River hydrograph may have affected the timing of the June sucker spawn. Since 1997 the June Sucker Flow Workgroup has worked to manipulate reservoir releases in an attempt to mimic the natural lower Provo River spring hydrograph to help ensure spawning success. Although the target hydrographs established for low-, moderate-, and high-flow years (Keleher 1999) have not been matched perfectly in every year, light trap and drift net sampling data indicate that successful spawning has occurred each year since a "natural" hydrograph has been replicated in the lower Provo River system. Successful spawning also occurred prior to 1999, although less is known about that period of time because monitoring was not as intensive. Modde and Muirhead captured larval June sucker in the Provo River in 1987 and 1988 (Modde and Muirhead 1990), and Keleher captured larval sucker in 1997 (Keleher et al. 1998).

Buelow (2006) used radio telemetry to monitor the movement of 13 June sucker during the 2004 spawning season. Unfortunately, drought conditions during 2004 meant that no true, distinct snowmelt runoff peak of significant magnitude occurred. Flows in March 2004 averaged about 130 cfs, flows then dropped to an average of 70 cfs through April 25 and then rose to a "peak" of 148 cfs on May 4 before receding again. Buelow (2006) observed fish staging at the mouth of the Provo River throughout his monitoring period from April 1 through mid-June. The greatest congregation of fish at the mouth was observed during the first 2 weeks of April, prior to any increase in river flows. Eight tagged fish were observed entering the Provo River at various times. Fish first entered the Provo River for a few hours between 3 April and 8 April (prior to increased flows) and again between 15 May and 25 May (after flows receded) for a period of 1-3 days (Buelow 2006). Because of the low water conditions in 2004, it is difficult to conclusively determine a relationship between runoff patterns and spawning behavior. Other monitoring data in the lower Provo River are confounded by the inability to sample during high-flow conditions, making it difficult to relate spawning habits to flow conditions (see Appendix E). Therefore, it remains unclear precisely which factor (i.e., turbidity, temperature, flow volume) is the most critical in attracting June sucker up river to spawn. Results of monitoring planned for 2008 using a stationary antenna should provide new insights into this relationship.

In summary, in a natural setting, temperature and the associated flow pattern of inflow streams may influence spawning events. However, refuge populations have spawned in lake shore environments. A population of stocked June sucker in Camp Creek Reservoir has been spawning and recruiting with such success that the reservoir can not support the recruitment (Webber and Thompson 2008). The common factor seems to be use of a gravel/cobble substrate as the spawning bed. It may be that as long as the water temperature is within the optimum range of 12-17 °C (Keleher et al. 1998) and a suitable substrate for spawning is present, then spawning will occur independent of water velocity.

Radant et al. (1987) developed habitat suitability index (HSI) curves for preferred water depth and velocity for June sucker spawning. These curves indicate that June sucker spawn in areas with an average depth of 1.67 feet (ft) and average velocity of 1.2 feet per second (ft/s). Preferred substrate was described as ranging in size from 100-200 millimeters (mm). However, this substrate curve has been updated based on the observations of June sucker spawning over larger substrates in Red Butte Reservoir. These sources suggested that June sucker use larger substrates in addition to those identified in the Radant et al. (1987) curves. The larger substrates are also predominant in the section of river where June sucker spawn.

Larvae

Modde and Muirhead (1990) suggested that emergent June sucker larvae drifted downstream, primarily at night and shortly after hatching; these results were supported during the spawning seasons in 1996 (Crowl and Thomas 1997) and 1997 (Keleher et al. 1998). Keleher et al. (1998) also determined that changes in flow rate below 400 cfs in the lower Provo River have a more dramatic affect on velocity, and possibly drift rates of larvae, than higher flows. However, Wilson and Thompson (2001) found that neutrally buoyant beads were able to drift at sufficient speed when flows were 300 cfs to move from the spawning areas to the lake during one night (approximately 5 hours) and presumably avoid the high predation risk. At 100 cfs the researchers found that beads drifted only 30 meters (m) in approximately 30 hours, suggesting that this flow would not allow efficient transport to the lake. A study by Ellsworth et al. (forthcoming) suggests that recruitment failure may be related to larvae not being able to reach the higher zooplankton densities within the lake before they deplete their yolk reserves.

Wilson and Thompson (2001) estimated larval production in the 1998 spawning season at 93,675 larvae. This compares favorably to estimates from the previous year (16,315 total) but indicates a substantial decline from earlier years; Modde and Muirhead (1990) estimated 60,200 and 73,000 per day during peak spawning.

Adults

The June Sucker Recovery Implementation Program (JSRIP) has funded a project to evaluate adult June sucker movements in Utah Lake. From 2004 to 2006, 60 adult June sucker were implanted with radio transmitters and released into Provo River, Utah Lake (Provo Bay) and Spanish Fork River. Tracking occurred in 2004 through 2006. In 2006, fish were present in large numbers near the mouths of all major tributaries – Provo River, Hobble Creek, Spanish Fork, and American Fork – from March through July (Buelow 2006). This information suggests that adult fish engage in post-spawning aggregations near the mouths of these rivers, which is similar to pre-spawning behaviors when adult fish stage during April and May (Radant and Hickman 1984). Radio-tagged sucker showed highly mobile behavior between Provo Bay and several of the tributaries. Also, tagged fish exhibited highly mobile movement patterns utilizing large areas of the lake in addition to staging near the rivers (Buelow 2006). It is also possible that these fish spend the majority of the year in these areas; more data from the tagging effort will clarify this issue. Furthermore, Radant et al. (1987) believed that elevated zooplankton densities in Provo Bay significantly contribute to the post-spawn June sucker use of this area because this efficient food source meets the energy demands of the species.

In 2004 two June sucker were captured in trapnets in Utah Lake, an adult near the mouth of Provo Bay and a juvenile near Lincoln Point. Trapnets were set for a cumulative total of 460 hours with an average of 23 hours per net. These are the first known captures of June sucker during UDWR standardized annual trapnet surveys in nearly 30 years (UDWR 2005). Standard trapnet surveys captured no June sucker in 2005 (UDWR 2006), one June sucker in 2006 (UDWR 2007), and five June sucker (four of FES origin; one from Red Butte) in 2007 (UDWR 2008a).

Water Temperature Requirements

According to Kindschi et al. (2005), a laboratory evaluation of chronic lethal temperatures on 8-inch fish indicated that the LC50 (temperature at which there was 50% survival for 60 days) occurred between 27.9° C (actual mortality was 18.7%) and 29.7° C (actual mortality was 61.3%). Water temperatures that provided maximum weight gain and feed efficiency in these 8-inch fish was 21.9° C and 21.6° C, respectively. Although this study focused on a single life stage and was a laboratory-based study that did not account for interaction effects of other factors, the information nonetheless provides valuable guidance for managing water temperatures in the lower Provo River. In another study Shirley (1983) reported that June sucker eggs hatch faster at 21.1° C (4 days) than at 10.6° C (10 days).

Macroinvertebrates

The National Aquatic Monitoring Center has processed macroinvertebrate samples taken by the Utah Department of Environmental Quality (UDEQ) from a station near the U-114 (Geneva Road) crossing of the Provo River (M. Vinson 2002, pers. comm.) (Figure 5.2). The data from this site have shown lower taxonomic diversity than from sites upstream of the Murdock Diversion (National Aquatic Monitoring Center, unpublished data). No stoneflies were found in collections taken from this area in 1999-2001. Mayfly and caddisfly diversity also appears depressed at this site compared with upstream areas. The community here seems dominated by midges and more tolerant mayflies in the Baetidae family.

Lower Provo River Instream Flow Recommendations Framework

As discussed in Section 3, the ideal approach to instream flow recommendations would account for all riverine processes and ecological functions (Table 3.1). However, on the lower Provo River, protection of certain individual ecological functions is of higher priority than others. For example, protection of flow-dependent ecological functions for the endangered June sucker is of the highest priority since the Study Area includes the designated Critical Habitat for the species. Table 5.2 identifies some of the important flow regime components that support the June sucker life cycle. Additional, independent factors unrelated to flows that affect the ecological functions important for June sucker are also identified.

Table 5.2. June sucker life history stages supported by instream flows.

JUNE SUCKER LIFE HISTORY STAGE	DESCRIPTION	SUPPORTING DATA/RESEARCH	TYPE OF FLOW REQUIRED	OTHER FACTORS
Spawning: Attraction Flows	June sucker may cue their timing of spawn on water temperature/ turbidity/flow conditions associated with spring snowmelt runoff.	June Sucker Recovery Plan- USFWS 1999; Scoppettone et al. 1983, 1986, 2000; but it is uncertain whether the main spawning cue is water temperature, turbidity, flow magnitude, or some combination thereof.	flows patterned/timed to coincide with natural springtime snowmelt runoff	Tanner Race (Lower City) Diversion and Fort Field Diversion limit spawning access to the lower 3.0-4.7 miles of the Provo River.
Spawning: Flushing of Spawning Substrate	June sucker spawn in coarse gravel to small cobble-sized substrate and do not spawn in finer material.	Radant et al. 1987, Sigler and Sigler 1996	regularly occurring flows of sufficient magnitude/duration to flush accumulated fine sediment/algae and maintain clean, loose spawning substrate	Tanner Race (Lower City) Diversion and Fort Field Diversion limit spawning access to the lower 3.0-4.7 miles of the Provo River.
Spawning: Hydraulic Habitat	June sucker spawn in moderate-velocity riffles/runs 1 to 3 feet deep with gravel/cobble substrate adjacent to lower-velocity resting areas.	Radant et al. 1987, Shirley 1983	flows during the spawning period that maximize spawning habitat in terms of depth/velocity	Tanner Race (Lower City) Diversion and Fort Field Diversion limit spawning access to the lower 3.0-4.7 miles of Provo River; levees and channelization limit spawning/ staging habitat regardless of flow.
Larval Drift	June sucker larvae emerge from spawning beds and passively	Modde and Muirhead 1990, Crowl and Thomas	flows adequate to transport June sucker larvae from	The diked, flattened, straightened, and stagnant condition of

JUNE SUCKER LIFE HISTORY STAGE	DESCRIPTION	SUPPORTING DATA/RESEARCH	TYPE OF FLOW REQUIRED	OTHER FACTORS
	drift downstream during nighttime.	1997, Keleher et al. 1998, Wilson and Thompson 2001, Ellsworth et al. forthcoming.	spawning to rearing habitats	Provo River/ Utah Lake interface halts drift regardless of flow; predation by non-native fish further limits reproductive success.
Juvenile and Adult Life Stages	June sucker adults and juveniles live in Utah Lake and congregate at the mouths of tributaries during pre- and post-spawning periods; Provo River is the largest tributary to the lake and influences the lake level (and associated refuge habitat availability) and water quality.	Buelow 2006 (tracking study); Crowl and Thomas 1997; UDWR 2005; information regarding use of main part of lake remains limited	flows adequate to provide appropriate Utah Lake levels, temperature, nutrient, and water chemistry conditions that maximize habitat at the Provo River mouth during congregation periods	The diked, flattened, and straightened condition of the Provo River/ Utah Lake interface greatly limits juvenile rearing habitat regardless of flow; predation by non-native fish further limits reproductive success.

In Table 5.3 we incorporate some of the priorities on the lower Provo River with the full list of riverine components listed in Table 3.1 to generate a specific lower Provo River instream flow recommendation framework.

Table 5.3. Ecological functions supported by instream flows and their relative priority on the lower Provo River under existing (2008) conditions [a].

CATEGORY	ECOLOGICAL FUNCTION	PURPOSE/ISSUES	GENERAL TYPE OF FLOW REQUIRED	LOWER PROVO RIVER CONSIDERATIONS /RELATIVE PRIORITY
Water Quality	maintenance of water temperature below harmful/lethal levels	When summertime flows become too low temperatures can exceed lethal levels.	adequate summertime base flow	high priority
Water Quality	nutrient cycling	High, overbank flows that inundate the floodplain provide lateral connectivity between the channel and floodplain, and allow for nutrient cycling.	high-magnitude, low-frequency flood flows	low priority; only because levees and channelization limit floodplain inundation regardless of flows.

CATEGORY	ECOLOGICAL FUNCTION	PURPOSE/ISSUES	GENERAL TYPE OF FLOW REQUIRED	LOWER PROVO RIVER CONSIDERATIONS /RELATIVE PRIORITY
Biology: Aquatic	spawning: attraction flows	Spring-spawning species may cue their timing of spawn on water temperature/chemistry conditions associated with spring snowmelt runoff.	flows patterned/ timed to coincide with natural springtime snowmelt runoff and/or appropriate early spring flow patterns	high priority Additional research is needed to identify specific component(s) of flows that cue spawning.
Biology: Aquatic	spawning: flushing of gravels/ cleansing of substrate	Adequate flows are needed to flush accumulated fine sediment/algae and maintain clean, loose spawning gravels.	regularly occurring flows of sufficient magnitude/duration to flush fine sediments	high priority
Biology: Aquatic	hydraulic habitat availability	Flows affect the availability of habitats with different depths/velocities required by various aquatic species and life stages.	flow regime that provides an appropriate mix of hydraulic habitats during critical life stage periods	medium priority Levees and channelization limit availability of low-depth/velocity habitat at high flows.
Biology: Riparian	cottonwood/willow recruitment	Seed-based recruitment of native woody riparian species requires a specific combination of flows and fluvial surfaces.	flows that inundate an appropriate germination surface during the seed dispersal window and then decline slowly enough for root growth to keep up	low priority; only because levees and channelization limit available riparian recruitment surfaces regardless of flows.
Biology: Riparian	prevention of vegetation encroachment/ channel narrowing	Low flow or dry conditions during the summer growing season allow vegetation to encroach into the active channel and can lead to channel narrowing.	adequate summertime base flow	medium priority
Geo-morphology	channel maintenance	Moderate-magnitude (bankfull) floods are needed to maintain channel capacity and form (pools/riffles) and transport sediment.	regularly occurring flows of sufficient duration/magnitude to fully mobilize the streambed and transport the incoming sediment load	medium priority Sediment trapping by Murdock Dam and other lower river diversions alter sediment transport/ channel maintenance regardless of flows.

CATEGORY	ECOLOGICAL FUNCTION	PURPOSE/ISSUES	GENERAL TYPE OF FLOW REQUIRED	LOWER PROVO RIVER CONSIDERATIONS /RELATIVE PRIORITY
Geo-morphology	channel complexity creation/ maintenance	Large, overbank floods create and maintain complex habitat such as side channels and backwaters.	occasional large, overbank flood flows	low priority; only because levees and channelization limit floodplain inundation even during high flows.
Hydrology	inter- and intra-annual flow variability	Native plants and aquatic species are adapted to natural flow variability at short- and long-term time scales.	mimicry of natural inter- and intra-annual flow variability (duration, magnitude, rise and fall rates, etc.)	high priority

[a] The priorities listed in this table reflect the existing leveed condition of the lower Provo River and are not meant to imply that certain functions are unimportant in natural systems.

SECTION 6. AVAILABLE LOWER PROVO RIVER DATA SETS RELEVANT TO INSTREAM FLOWS

A large number of studies, data sets, and modeling tools has been developed for the lower Provo River. These data sets are useful in quantifying specific instream flow prescriptions and are listed below.

Hydrologic Data

A USGS streamflow gage (Provo River at Provo, #10163000) is located near the downstream end of the Study Area (Figure 5.2). Data from 1937 to present are available for this gage site and have been used to develop flood-frequency and flow-duration curves and determine average annual hydrograph conditions (Olsen et al. 2003). Flow diversion records for the diversions in the Study Area are available through the Utah Division of Water Rights flow records database (http://waterrights.utah.gov/distinfo/).

In addition, the CUWCD has developed a Provo River system hydrologic model (PROSIM) that uses historical flow data in conjunction with anticipated future water development and delivery scenarios to simulate monthly flows at various river nodes over a 50-year period. The model includes two nodes on the lower Provo River within the Study Area: one at its mouth at Utah Lake and one below Murdock Diversion. The PROSIM model was not specifically used for this study.

As part of this study, a dimensionless flow-duration technique was applied that has been useful in other river systems for determining a natural range of variability for periods of low streamflow. The technique uses a statistical analysis of the range of streamflow variability in nearby USGS gage sites with relatively minimal human alteration of the natural flow regime. Gages are selected that share similar climatic, geologic, and physiographic characteristics to the river system of concern, in this case the Provo River. All streamflow data are made dimensionless by simply dividing the "measured" discharge at the USGS gage by the mean discharge for the period of record at that gage. The result is a similarity collapse between the streamflow characteristics of drainages of all size, which is extremely helpful because it allows direct comparisons between basins to be made despite the differences in basin size. This technique is discussed further in subsequent sections of this report and in detail in Appendix A.

Also as part of this study, "naturalized" springtime flow records from the Provo River at Hailstone gage were analyzed to determine typical flow rise and recession rates, and examine and characterize the presence of "dual peaks" in streamflow, which often occur on the Provo River. The streamflow data used for these analyses were provided by Daryl Devey of the Central Utah Water Conservancy District and were adjusted to remove the effects of transbasin diversions that bring water into the Provo River Watershed. The results of these analyses were used to help define recommendations for springtime flow releases that mimic natural hydrograph patterns (see Appendix B for details).

Although the Hailstone gage is located a substantial distance upstream of the lower Provo River, it represents the best option for determining the current streamflow characteristics of the Provo River without the influence of the major dams. Although some attenuation of peak flows probably occurred historically between the Hailstone gage and the lower Provo River, there are no major storage areas in that section of the river, thus, large-scale attenuation would have been unlikely. The exact rates of change from the Hailstone gage were not used directly to determine flow recommendations, but rather they were used as a guide, assuming that the actual rates of change would have been somewhat smaller due to the attenuation that would have occurred within the reach. Although the naturalized Hailstone data serve as a valid guide for recommending total springtime flow release patterns for the lower river, it should be noted that under historical, unaltered conditions, the lower Provo River channel would likely have been multi-threaded, and the proportion of the total flow in each channel would have been variable.

Geomorphic/Hydraulic Data

As part of the Provo River Flow Study (Olsen et al. 2003), detailed topographic data and hydrodynamics models were developed for two sites within the Study Area (Study Sites 1 and 2 in Figure 5.2). The models provide two-dimensional depth and velocity information throughout the sites for a given streamflow input value. Maps of substrate and riparian vegetation types were also developed for each modeling site.

Sediment transport (bedload) data were collected at two bridges within the Study Area (Bridges 1 and 2 in Figure 5.2) as part of the Provo River Flow Study (Olsen et al. 2003). Suspended and bedload transport rating curves (transport rate vs. flow) were developed for each bridge site, and effective discharge was calculated. Bedload sampling and effective discharge calculations were also completed previously on the lower Provo River for the Lower Provo River Flushing Flow Study (Olsen et al. 1996). Results of these studies are summarized in Appendix C.

As part of this current study, calculations were recently completed to determine the flow magnitude needed to mobilize the coarsest fraction of the bed material at two cross sections previously surveyed as part of the Provo River Flow Study. These calculations are helpful in determining the flows needed to promote channel change and maintain physical habitat complexity (see Appendix C for details).

Biological/Habitat Data

Detailed information on aquatic habitat flow relationships was developed as part of the Provo River Flow Study (Olsen et al. 2003). Hydraulic habitat niches were developed that embodied depth/velocity preferences for different "guilds" of fish species and their life stages. Niche preferences were identified for sportfish, primarily brown trout, as well as various native species and life stages including June sucker, Utah sucker, mountain sucker (*Catostomus platyrhynchus*), and leatherside chub (*Gila copei*). The niches and preference information were used to determine weighted usable area for different flows at Study Sites 1 and 2. Individual habitat suitability curves were also developed for spawning June sucker and trout (Olsen et al. 2003). Results of these analyses are summarized in Appendix D.

Other researchers have also collected information on habitat use or usability in the Provo River (Belk and Ellsworth 2000, Olsen and Belk 2001, Buelow 2006). The UDWR collects fisheries data on the Provo River and conducts annual sampling during the June sucker spawning period as part of the June Sucker Recovery Implementation Program (UDWR 1976; UDWR 2000; UDWR 2002; UDWR 2003; UDWR 2004a, 2004b, 2004c; UDWR 2005; UDWR 2006; UDWR 2007). Results of springtime June sucker spawning and larval drift monitoring are summarized in Appendix E.

Macroinvertebrate data have been collected near the U-114 (Geneva Road) crossing within the Study Area (M.R. Vinson 2002, pers. comm.).

Riparian Vegetation Data

An evaluation was completed for the riparian surfaces at Provo River Flow Study Sites 1 and 2 that identified the discharge magnitude that inundates grass- and shrub-covered floodplain surfaces. A qualitative evaluation of cottonwood recruitment potential was also completed at the sites (Olsen et al. 2003). Riparian vegetation was mapped at a broad scale throughout the Study Area (Olsen et al. 2003). Riparian types were classified as wooded, scrub-shrub, herbaceous, or disturbed.

As part of this current study, the wetted perimeter/inflection point technique (Leathe and Nelson 1986) was applied to two cross sections previously surveyed as part of the Provo River Flow Study. This analysis identifies the flow below which wetted perimeter drops rapidly with discharge, which is an indication of minimum flows needed to limit vegetation encroachment (see Appendix F for details).

Water Quality Data

Water quality data are collected by the Utah DWQ near the Provo River at the USGS gage site near Geneva Road and by the CUWCD at the gage near Harbor Drive (Figure 5.2). These data are available from the CUWCD and through the Environmental Protection Agency's STORET database.

Water temperature thermistors were deployed at Provo River Flow Study Sites 1 and 2 during 2002. The data collected were plotted against streamflow for the same time period at Site 1, and the flow-temperature relationship was qualitatively assessed (Olsen et al. 2003).

As part of this study, hourly CUWCD water temperature and flow data for the 2002-2006 time period were compiled and analyzed to determine the relationship between streamflow and summertime water temperature. This analysis was used to identify a minimum flow range that is protective of water temperature standards for the lower Provo River. In July and August 2007, a test release was conducted with the goal of supplying 40 cfs to the lower river to determine whether that flow amount would maintain water temperature below the State standard. Temperature thermistors were deployed by UDWR at two locations on the lower river in summer 2007, and the CUWCD gage near Harbor Drive also collected temperature data during this time period. Results from the 2007 test release were used to modify the summer base flow recommendations (see Appendix G for details).

SECTION 7. INSTREAM FLOW DETERMINATION METHODS/DATA FOR LOWER PROVO RIVER RIVERINE COMPONENTS

Methods and analysis results used to develop lower Provo River flow recommendations are summarized in Tables 7.1, 7.2, and 7.3.

Table 7.1. Instream flow determination methods for the lower Provo River.

TYPE OF FLOW	QUANTIFICATION METHOD(S) USED	DATA SETS/ ANALYSIS TOOLS USED	IMPORTANCE FACTOR
Base Flows to Maintain Water Temperature	dimensionless flow duration curve approach; empirical temperature vs. flow evaluation; results of summer 2007 test releases	Provo Flow Study thermistor data; DWQ cold water fishery standard; DWR, DWQ and CUWCD temperature data; lab study of June sucker temperature requirements; 2007 summer test release results	June Sucker Habitat = low, given June sucker do not use the Provo River during the warm low-flow months Ecology of Provo River = high, given potential impacts to aquatic biota
Base Flows to Limit Vegetation Encroachment	wetted perimeter/inflection point method	Provo Flow study sites	June Sucker Habitat = medium, given potential impact to spawning habitat Ecology of Provo River = medium, given potential impacts to channel capacity and aquatic habitat
Base Flows for Aquatic Habitat	hydraulic habitat modeling	Provo Flow study sites/hydraulic modeling results; dimensionless flow duration curve analysis	June Sucker Habitat = unknown; however, probably high during the spawn and larval drift period Ecology of Provo River = high, given potential impacts to aquatic biota
Spawning Attraction Flows	mimicry of natural hydrograph	cui-ui research; UDWR monitoring data; analysis of natural springtime hydrograph patterns	June Sucker Habitat = unknown, yet there has to be something given the timing of the annual spawn Ecology of Provo River = unknown
Spawning Gravel Flushing Flows	empirical/test flow method	Lower Provo River Flushing Flow Study (Olsen et al. 1996); Provo River Flow Study (Olsen et al. 2003)	June Sucker Habitat = high during most years given need to maintain clean gravel/cobble spawning substrate Ecology of Provo River = high during most years given need to reduce embeddedness, flush pollutants that periodically build up, and scour algae and aquatic macrophytes

TYPE OF FLOW	QUANTIFICATION METHOD(S) USED	DATA SETS/ ANALYSIS TOOLS USED	IMPORTANCE FACTOR
Spawning Habitat Flows (Depth and Velocity)	hydraulic modeling	Provo River Flow Study (Olsen et al. 2003) with most up-to-date spawning habitat preference information	June Sucker Habitat = high during most years to provide adequate spawning habitat Ecology of Provo River = unknown
Flows to Promote Effective Larval Transport	field experiment	Bead study (Wilson and Thompson 2001)	June Sucker Habitat = high, given available rearing habitat Ecology of Provo River = low
Channel Maintenance Flows	effective discharge method; sediment transport modeling	Flushing Flow Study (Olsen et al. 1996); hydraulic information from Provo River Flow Study (Olsen et al. 2003)	June Sucker Habitat = high, given flushing flow needs Ecology of Provo River = high under natural conditions
Inter- and Intra-annual Flow Variability	dimensionless flow-duration curve approach	dimensionless flow-duration curve analysis	June Sucker Habitat = low, given June sucker do not use the Provo River during the low-flow months Ecology of Provo River = high under natural conditions
Channel Complexity Creation/Maintenance Flows (*note: levees, channelization, and urban development limit the magnitude of flood flows that can be released and the ability of flood flows to alter the configuration of the channel and floodplain*	sediment transport modeling and flow competence calculations	hydraulic information and substrate-size data from Provo River Flow Study (Olsen et al. 2003)	June Sucker Habitat = low under existing conditions; however, out-of-bank flows may be important to create and maintain rearing habitat if restoration of the river-lake interface occurs Ecology of Provo River = high under natural conditions
Overbank Flows to Promote Nutrient Cycling	*No instream flow recommendation was developed for this function because levees and channelization limit floodplain inundation regardless of flows. Overbank flow recommendations may be developed in the future if channel reconstruction/restoration activities are implemented on the lower Provo River.*		
Riparian Recruitment Flows	*No instream flow recommendation was developed for this function because levees and channelization limit available riparian recruitment surfaces regardless of flows. Riparian recruitment flow recommendations may be developed in the future if channel reconstruction/restoration activities are implemented on the lower Provo River.*		

Table 7.2. Summary of analysis results considered in determining lower Provo River flow recommendations.

TYPE OF FLOW	QUANTIFICATION METHOD(S) USED	RESULT
Base Flows to Maintain Water Temperature	empirical temperature vs. flow evaluation (Appendix G)	<40 cfs = frequent temperature problems 40 to 65 cfs = occasional temperature problems >65 cfs = rare temperature problems
Base Flows to Limit Vegetation Encroachment	wetted-perimeter/inflection-point method (Appendix F)	27 cfs (Site 1) 80 cfs (Site 2)
Base Flows for Aquatic Habitat	hydraulic habitat modeling (Appendix D); dimensionless flow duration curve approach (Appendix A)	between 40 and 70 cfs with inter- and intra-annual flow variability during non-runoff periods
Spawning Attraction Flows for June Sucker	analysis of natural hydrograph patterns (Appendix B); existing June sucker target hydrographs (Keleher 1999)	fall and rise rates of 20-45 cfs/day for flows below 400 cfs and 60-100 cfs/day for flows above 400 cfs
Spawning Gravel Flushing Flows	empirical/test flow method (Appendix C; Olsen et al. 1996)	flows ≥700 cfs for ≥3 consecutive days in 2 out of 3 years
Spawning Habitat Flows (Depth and Velocity)	hydraulic modeling (Appendix D; Olsen et al. 2003)	150-200 cfs (June sucker) 40-70 cfs (trout)
Flows to Promote Effective Larval Transport	bead study (Wilson and Thompson 2001)	300 cfs
Channel Maintenance Flows	effective discharge method; sediment transport modeling (Appendix C)	700-800 cfs (Site 1) 700 cfs (Olsen et al. 1996)
Inter- and Intra-annual Flow Variability during Non-Runoff Periods	dimensionless flow duration curve approach (Appendix A)	see table 7.3 and Appendix A
Channel Complexity Creation/ Maintenance Flows	mobilization calculations for coarsest fraction of bed material (Appendix C)	1,800-2,000 cfs (subject to adjustment based on flood risk considerations)

Table 7.3. Calculated natural average monthly flows for the lower Provo River based on median dimensionless values [a].

MONTH	WATER YEAR PERCENTILE		
	20	50	80
January	60 cfs	80 cfs	82 cfs
February	59 cfs	76 cfs	83 cfs
March	63 cfs	83 cfs	90 cfs
April	88 cfs	181 cfs	382 cfs
May	307 cfs	569 cfs	793 cfs
June	171 cfs	508 cfs	787 cfs
July	119 cfs	166 cfs	255 cfs
August	61 cfs	90 cfs	163 cfs
September	53 cfs	83 cfs	113 cfs
October	64 cfs	87 cfs	101 cfs
November	67 cfs	91 cfs	107 cfs
December	69 cfs	81 cfs	92 cfs

[a] See Appendix A for additional details on how these values were generated.

As previously mentioned, a dimensionless statistical technique was used to help determine a reasonable range of discharge for low-flow periods. This approach begins by selecting a group of gaged streams that have similar climatic, geologic, and physiographic characteristics to the stream of interest, in this case the lower Provo River. These streams are termed “reference” streams, because they are used as a reference for natural streamflow distribution. Streams are selected that have limited human alteration of the naturally variable temporal patterns of streamflow (e.g., streams without excessive alteration of the watershed, streams without large dams, streams with limited diversion capacity).

Seven streams were selected for use as reference streams. The streams that were chosen are:

1- Bear River near UT/WY State Line,
2- Hobble Creek near Springville, UT,
3- North Fork Provo River near Kamas, UT,
4- Payson Creek above Diversions near Payson, UT,
5- Spanish Fork above Thistle, UT,
6- Weber River near Coleville, UT,
7- Yellowstone River near Altonah, UT.

Although all these streams have some level of hydrologic alteration, they represent the natural distribution of streamflow in this area reasonably well.

Streamflow data from the selected group of reference streams can be plotted to create a standard flow duration relation, as shown in Figure 7.1. Notice that streams of different size are distributed vertically along the y-axis (discharge). Although the curves appear to have similar shapes, the vertical distribution makes it impossible to use the data from one stream to guide flow recommendations on another stream, unless they happen to be of exactly the same size. In order to use these data to guide flow recommendations, a way must be found to remove the effect of stream size on the data, which would allow basins of different sizes to plot in the same space. This can be accomplished by dividing all the measured discharges for the period of record by the mean flow for the same period, which produces the plots shown in Figure 7.2. The result is a dimensionless variable that we will call "dimensionless discharge." It is dimensionless because the units of discharge cancel out when dividing by the mean discharge. Notice that the plots that were previously distributed along the y-axis are now grouped much more closely. The new plots are quite useful for determining a natural range of discharge for other streams in the area.

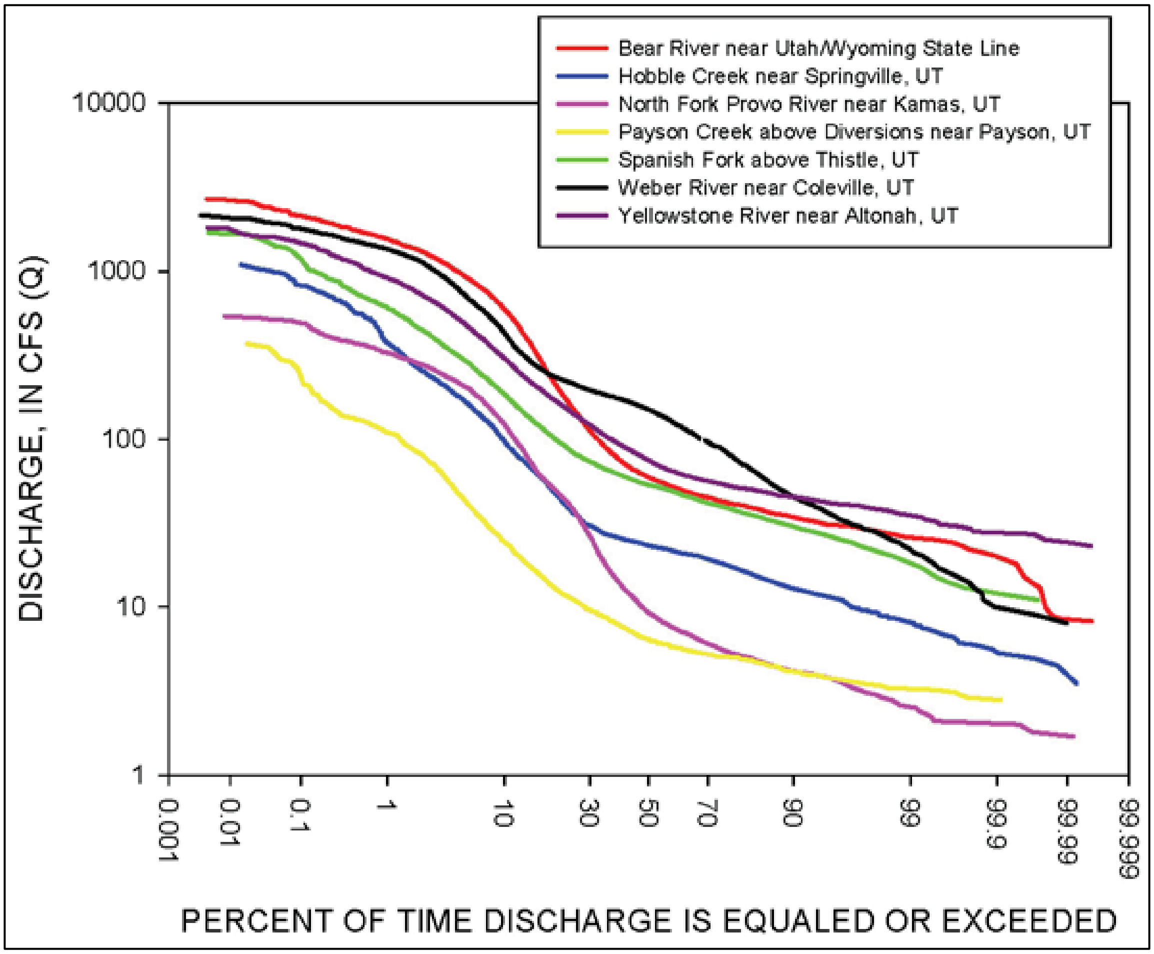

Figure 7.1. **Standard flow-duration relations for seven Utah reference streams.**

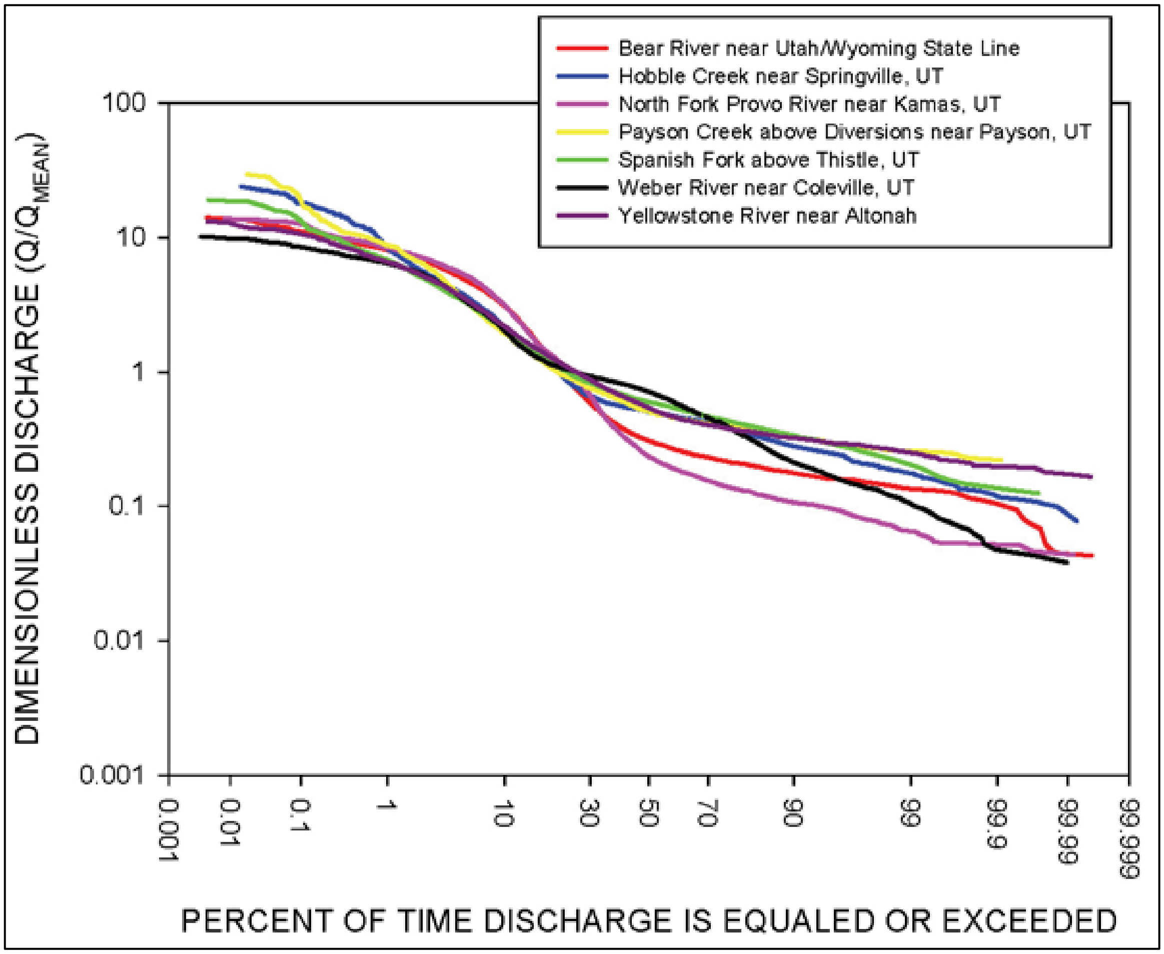

Figure 7.2. **Dimensionless flow-duration relations for seven Utah streams.**

Because this technique is new to most people, a quick example may provide some helpful insight. In a way, the dimensionless discharge units can be thought of in terms of multiples of the mean flow. For example, on the Provo River, which has a mean flow of approx. 200 cfs, the flow on a given spring day may be 50 cfs, which becomes a dimensionless discharge of 0.25 (50 cfs / 200 cfs = 0.25), or 0.25 times the mean flow. Later that spring, during the runoff period, the discharge may be 1,600 cfs, which becomes a dimensionless discharge of 8 (1,600 cfs / 200 cfs = 8), or eight times the mean flow. Once familiar with the concept, dimensionless discharges are actually quite easy to work with.

Streamflow on the lower Provo River has been greatly influenced by damming and diversions, and this influence can be seen clearly in the dimensionless data. Figure 7.3 plots the same data as Figure 7.2 with the addition of the lower Provo River. Notice that the Provo River deviates from the other curves approximately 25% of the time. The Provo River experiences periods of low flow that are substantially lower than the flows that would probably occur under a more natural condition. Also notice that a small portion of the curve for the lower Provo River is higher than the reference streams'. This means that the flows in the Provo River are higher than natural during certain periods.

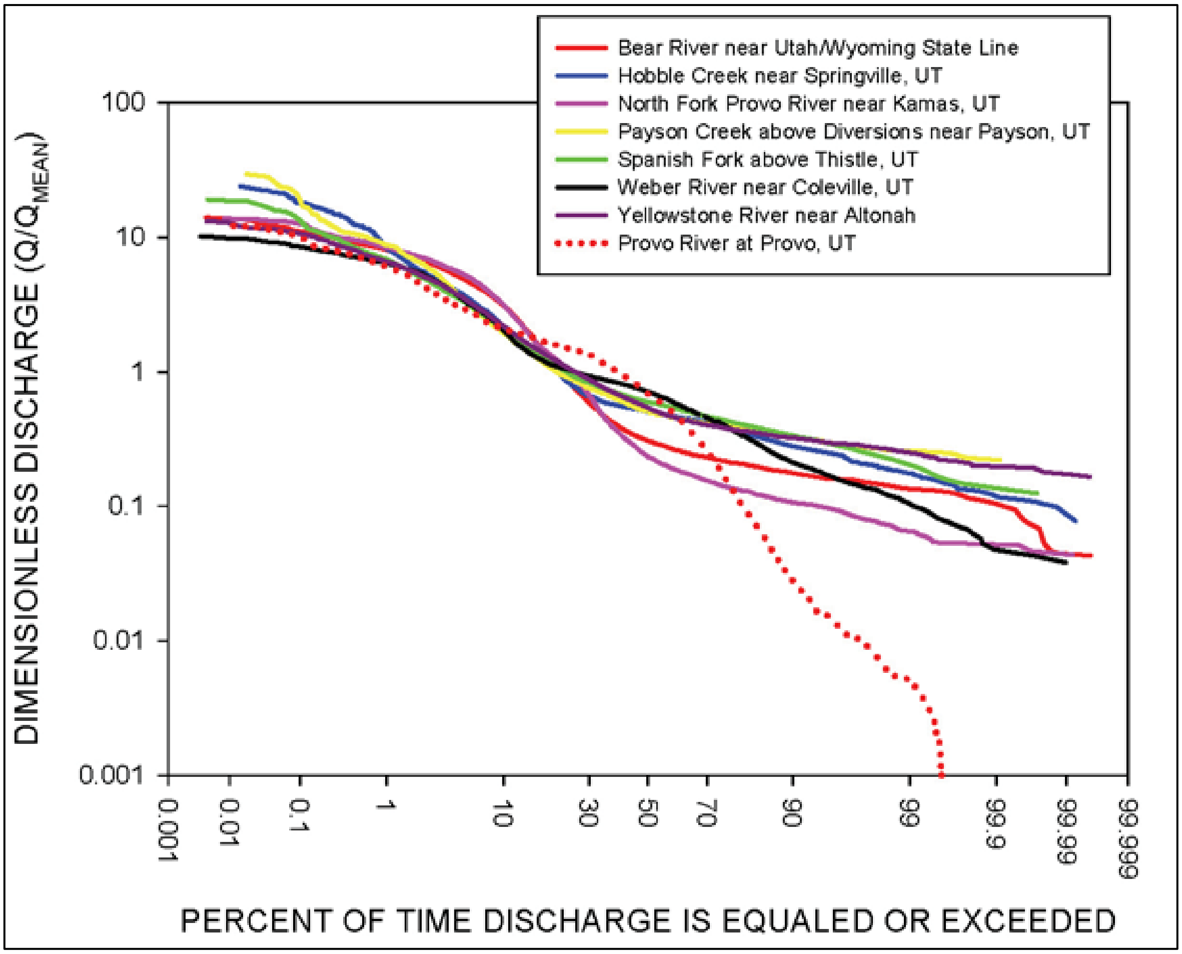

Figure 7.3. Dimensionless flow-duration relations for seven Utah streams and the lower Provo River.

Dimensionless discharges, like those shown in Figures 7.2 and 7.3, can be scaled for any similar stream by multiplying the values by the mean discharge for the new stream. This simple procedure can be applied to any stream with similar characteristics.

In order to determine a more appropriate range of streamflow during different seasons for the lower Provo River, gage data from the reference streams were analyzed to produce dimensionless flow duration curves for each month. Figure 7.4 provides an example of one of these monthly curves (July) for the Utah reference streams and also shows the curve for the same month on the lower Provo River. Notice that the lower Provo River plots well below the reference streams, indicating that flows are substantially lower in July than would be expected in a less-altered system. These low flows occur during the warmest times of the year, when temperatures in the river are hovering at or above lethal levels for many organisms and oxygen levels are extremely low. The biological implications of these low flows are potentially profound.

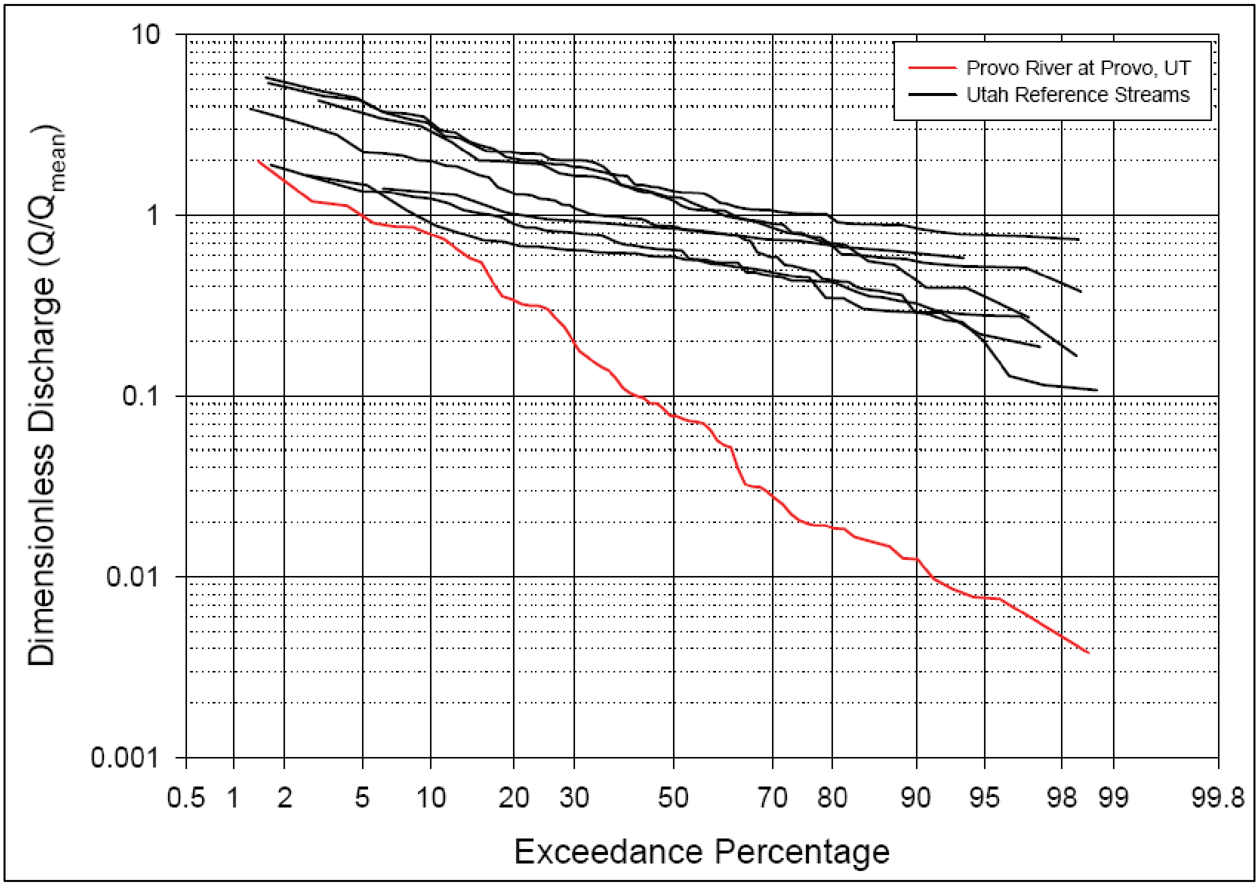

Figure 7.4. Monthly (July) dimensionless flow-duration relations for seven Utah reference streams and the lower Provo River.

Figure 7.5 shows another group of monthly curves (January). In this figure, the lower Provo River plots above the reference streams, indicating that flows exceeded the expected condition during the month of January. These monthly curves were then grouped together and ranked according to water year. The median values from the seven streams were determined for each month of each water year ranking, and those values were used for further analysis. The result is a monthly table of dimensionless values that represent the median values for the seven Utah streams (see Appendix A for further details).

Once created, the monthly table of dimensionless discharges can then be scaled for any similar Utah stream by multiplying by the mean discharge. Such a scaling was completed for the lower Provo River, which resulted in the values shown in Table 7.3. These values were used to help guide low flow recommendations for the lower Provo River, found later in this report. Monthly dimensionless discharge values were computed for water years ranging from a low of the 10th percentile to a high of the 90th percentile; however, scaled recommendations for the Provo River (Table 7.3) are based on the 20th, 50th, and 80th percentile water-years only. The tails of the distribution of dimensionless values are quite variable and are probably not appropriate for use in flow-management scenarios.

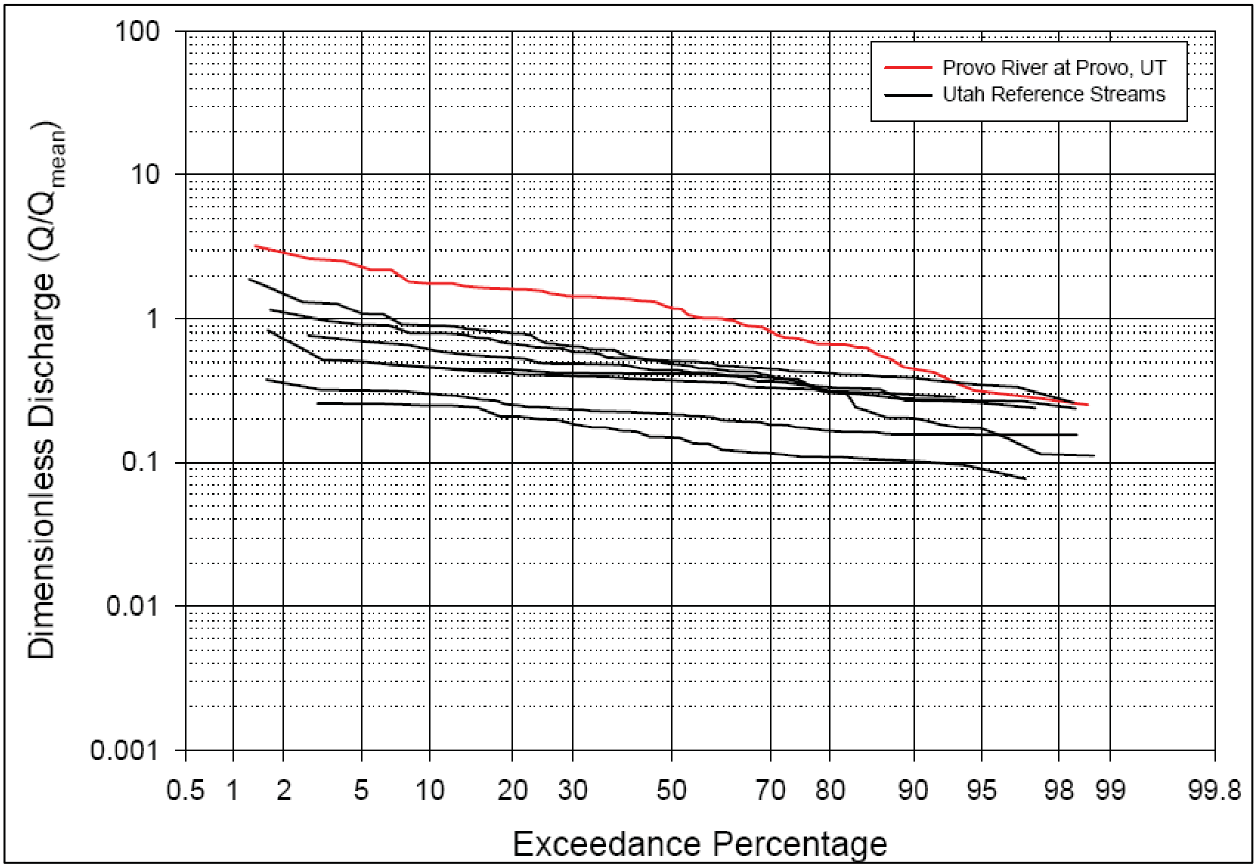

Figure 7.5. **Monthly (January) dimensionless flow-duration relations for seven Utah reference streams and the lower Provo River.**

SECTION 8. LOWER PROVO RIVER INSTREAM FLOW RECOMMENDATIONS

Summary of Existing Instream Flow Requirements and Procedures

Minimum instream flow requirements have been established in Provo Canyon. The year-round minimum instream flow between the confluence of Little Deer Creek (below Deer Creek Dam) and Olmsted Diversion (located approximately 5 miles upstream from the Murdock Diversion) is 100 cfs, and the wintertime minimum instream flow below Olmsted Diversion is 25 cfs. Currently, there are no legally binding summer instream flow requirements for the lower Provo River below Olmsted Diversion. Section 302 of CUPCA authorized funding for acquisition of water rights with the objective of providing a year-round minimum instream flow of 75 cfs. To date, this objective has not been met, although the CUWCD, Mitigation Commission, and U.S. Department of Interior are in the process of acquiring water shares and water rights from willing sellers to help achieve this purpose and have planned and will construct and operate the ULS to provide supplemental instream flows in the lower Provo River. Environmental commitments in the Diamond Fork Final Environmental Impact Statement also acknowledge the need to "acquire and protect a block of water for June sucker." To date, up to 18,000 acre-feet of water have been acquired annually on a temporary or permanent basis for lower Provo River streamflows. These flows have been used to date almost exclusively to benefit June sucker spawning and larval transport.

To coordinate and implement flows for the June sucker spawning, egg incubation, and larval drift period, an interagency June Sucker Flow Workgroup (Workgroup) was established in 1994 to evaluate water availability and cooperatively determine the timing and quantity of flows to be released from the Deer Creek and Jordanelle Reservoirs on the Provo River each spring. Recommendations from the Workgroup represent the consensus view of water managers, biologists, and agency regulatory staff to both provide necessary water to best meet June sucker needs and respond to reservoir and runoff conditions.

Since 1999 the Workgroup has used the flow approach developed by the CUWCD, which provides three target flow regimes for the runoff period for dry , moderate, and wet year scenarios (Keleher 1999). Each of these has target daily flows from April 1 though July 31. The CUWCD's spreadsheet model is used to estimate the quantity of water that would be required to implement any of these scenarios.

The Workgroup, coordinated by Reclamation, typically meets monthly beginning in March to review available reservoir storage and anticipated runoff volumes, based on water supply forecasts from the U.S. Department of Agriculture, Natural Resource Conservation Service snow-pack telemetry (SNOTEL) sites. The appropriate flow regime is discussed by the Workgroup, and any necessary adjustments are made in target flows as the runoff period progresses. Workgroup-guided target runoff releases have been implemented annually since 1999. A comparison of actual flow releases versus the target runoff hydrographs is provided in Appendix I.

After formation of the JSRIP in 2002, the Workgroup has functioned within the auspices of the JSRIP, as a subcommittee of the JSRIP Technical Committee (JSRIP 2002). The Workgroup provides information and recommendations to the Technical Committee. Recommendations will include justification regarding June sucker recovery along with anticipated biological response and will be reviewed and finalized by the Administration Committee.

This report, and others that may follow, are intended to assist the parties involved in operating the lower Provo River when making decisions about streamflows and allocating acquired water for instream flow objectives. These flow recommendations are intended to be adaptive. Studies on the lower Provo River and in Utah Lake are ongoing, and as more is learned about the associations between streamflow and specific ecological functions, with emphasis on June sucker needs, recommendations may be adjusted. Also, if restoration activities that change the physical conditions of the lower Provo River are implemented, flow recommendations may need to be updated.

Base Flow Guidelines

Base flow guidelines to protect the lower Provo River riverine ecosystem were developed for dry, moderate, and wet year conditions (Figure 8.1). Guidelines were developed separately for winter, summer, and autumn base flow seasons. Base flow guidelines were not developed for the spring season (April-June); instead, the recommended spring runoff hydrographs (see below) should be used to guide flow releases during this time period.

Winter Base Flows

Winter base flows apply from January through March and were quantified by averaging the January and February values determined from the dimensionless curve analysis (Table 7.3). The 20th, 50th, and 80th water year percentile values were used to determine guidelines for dry, moderate, and wet years, respectively. March flows were not included in the calculation because they are commonly influenced by early snowmelt runoff inputs and do not reflect a purely "base flow" condition. However, the recommended winter base flow values (Figure 8.1) should be used to guide minimum flow conditions throughout the full January-March period. These winter base flow guidelines mimic natural hydrologic conditions and provide high diversity aquatic habitat during dry years (Table 7.2, Appendix D). The moderate and wet year recommendations of 78 and 83 cfs, respectively, are slightly higher than the ideal range for providing diverse hydraulic habitat, but a good distribution of habitats still remains available at these flows (Appendix D, Figures D2 and D3).

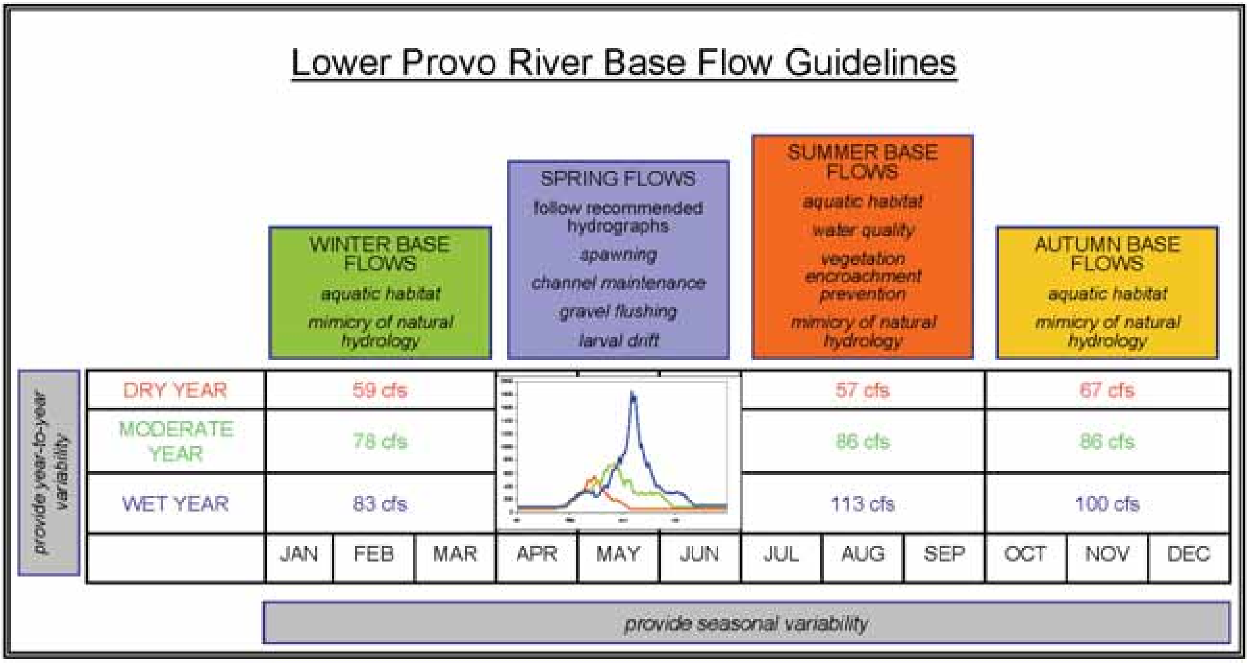

Figure 8.1. **Lower Provo River base flow guidelines.**

Summer Base Flows

Summer base flows apply from July-September (Figure 8.1). The dry and moderate year recommendations of 57 and 86 cfs were calculated by averaging the August and September 20th and 50th percentile values from the dimensionless curve analysis (Table 7.3). The wet year recommendation of 113 cfs matches the September 80th percentile value from the dimensionless duration curve analysis (Table 7.3). The July (dry and moderate year) and July-August (wet year) values were not included in these calculations because they are commonly influenced by the falling limb of the snowmelt runoff period and do not reflect a purely "base flow" condition. These summer recommendations are adequate to protect water temperature and competent to limit riparian vegetation encroachment (Table 7.2). The recommended dry year summer base flow also matches the range of values found to be protective of aquatic habitat diversity (Table 7.2). At flows of 86 cfs, the moderate year recommendation, slow-velocity habitat within the lower Provo River becomes more limited, but a good distribution of habitats still remains available (Appendix D, Figures D2 and D3). At flows of 113 cfs, the wet year recommendation, low-velocity habitats -- especially backwater/edge type habitat – are limited (Appendix D, Figures D2 and D3). However, it is important to keep in mind that the lower Provo River is in a straightened, channelized, and leveed condition with little edge complexity or lateral variability. The "unnatural" geometry of the river limits the availability of low-velocity habitat regardless of flows (Olsen et al. 2003). Therefore, rather than selecting our recommendation based on this "unnatural" river habitat, we instead based our wet year summer base flow recommendation on mimicry of natural hydrology.

Autumn Base Flows

The autumn base flow guidelines apply from October through December (Figure 8.1). The averages of the 20th, 50th, and 80th percentile values for October, November, and December (Table 7.3) were used to calculate recommended values for dry, moderate, and wet year conditions, respectively. The resulting values are quite similar to the summer recommendations. As with the summer values, the recommended autumn moderate and wet year values are somewhat higher than the ideal range for providing diverse hydraulic habitat (Table 7.2, Appendix D). However, the for the reasons discussed above, we opted to base our recommended values on mimicry of natural hydrology rather than making adjustments to accommodate the "unnatural," straightened channel condition of the lower Provo River.

*A Note Regarding Variability

The base flow recommendations presented in Figure 8.1 are intended to serve as flow release guidelines. The intent is not to hold flows perfectly constant (i.e., "flat-lined") at the recommended value throughout each season. Short-term (i.e., 1-3 day) variations within 10-20% of the recommended values are appropriate and would more closely match natural hydrologic patterns than would perfectly constant conditions. However, during the summer season in dry years, dropping flows below 50 cfs (as measured at the CUWCD's Harbor Drive gage) should be avoided due to water temperature concerns (see Appendix G). It is also important to note that the proposed base flow guidelines are not the same as minimum instream-flow requirements in the traditional sense. Under minimum instream-flow requirements, any flows greater than the recommended minimum value (even flows much greater than the recommended minimum) would "meet" the requirement. Under the proposed base flow guidelines (Figure 8.1), releasing flows substantially greater than the recommended values for extended periods of time would not mimic natural hydrology and would not meet the guideline objectives. Base flows that exceed the natural range of values can negatively affect aquatic habitat diversity, riparian vegetation, and sediment-transport processes. These negative effects can occur when base flows are too high relative to the channel size, sediment supply, annual peak flow magnitude, and sediment size of the stream. Releasing excessive base flows also runs counter to the objective of mimicking natural hydrology. Although the current problem on the lower Provo River is that summer base flows are too low and "excessive" releases are unlikely to be an issue, it is nevertheless important to emphasize that the proposed base flow guidelines are not simply minimum requirements.

March and July Considerations

As discussed previously, "natural" average monthly March and July flow values (Table 7.3) are influenced by the rising and receding limb of the snowmelt runoff period and are higher than purely "base flow" conditions. Therefore, in March and July, the base flow guidelines listed in Figure 8.1 should be applied as "minimum" values. Exceeding the recommended winter and summer base flow values during March and July in order to match the snowmelt period is appropriate and encouraged. It is also important to note that the recommended spring runoff hydrographs (see below) extend into July and should take precedence over the July base flow value. However, July was included in the summer base flow recommendations to ensure protection of water temperature conditions.

Spring Runoff Recommendations

The existing June sucker target hydrographs (Keleher 1999) were developed based on an analysis of natural runoff peak magnitude, duration, and timing. As such, the existing targets do a good job of mimicking these aspects of the natural hydrologic pattern. However, the rise and fall rates (day-to-day changes in discharge) included in the existing targets were developed by averaging daily rates of change to provide a smooth recession curve between the peak flow to the base flow at the end of the runoff period duration (Figure 8.2). Because of how they were developed, the target hydrograph rise rate values do not reflect "natural" rates, which tend to be steeper, more variable, and commonly separated by short periods of falling flows (Appendix H). The same is true of the fall rate values. A review of plots of recent, actual lower Provo River flows versus the existing target hydrographs (Appendix I) indicates that, in many years, operational constraints have meant that flow releases have dropped more rapidly than the targets, suggesting that it may not be realistic to consistently follow the target rates. Following the relatively flat target curves also requires substantial amounts of water.

In order to better reflect natural rising and falling limb patterns, we revised the existing targets and developed a new set of spring hydrograph recommendations (Figures 8.2-8.5). We based the new rise and fall rates on the results of our analysis of natural Hailstone gage rates (Appendix B) and also attempted to include variability in the ascending and receding limb patterns. Within the receding limb of the moderate- and wet year hydrographs, we also included a multi-day period of flows in the 300 cfs range. Flows in this range have been found to provide effective transport of larval June sucker from their hatching sites to the mouth of the Provo River (Wilson and Thompson 2001). This "larval drift" hydrograph component was not included in the proposed dry year hydrograph because there is typically not enough water available under dry conditions to hold flows at that high of a level. Strictly from a June sucker recovery standpoint, the emphasis in dry years may be appropriately placed on maintaining base flows for ecological purposes instead of providing spawning and recruitment flows from supplies of stored water because it is likely that spawning and recruitment did not successfully occur every year naturally and is not necessary for June sucker recovery. However, the dry year hydrograph may hold flows within the range found optimal for June sucker spawning (150-200 cfs) for several days (Figure 8.3) if water is available. This type of decision can be made annually, based on desires of the JSRIP and other water interests.

Our proposed wet year hydrograph (Figure 8.5) includes a much higher peak-flow magnitude (1,800 cfs) than the existing target (1,050 cfs). This change was made based on the result of sediment transport calculations that indicate that flows of at least 1,800 cfs are required to mobilize the coarser bed material fractions within the lower Provo River (Appendix C). Powerful flows of this magnitude are able to alter channel morphology and create increased habitat-complexity processes that are important for riparian vegetation and aquatic biota. High flows above 1,800 cfs may pose a flooding risk to residential and commercial development

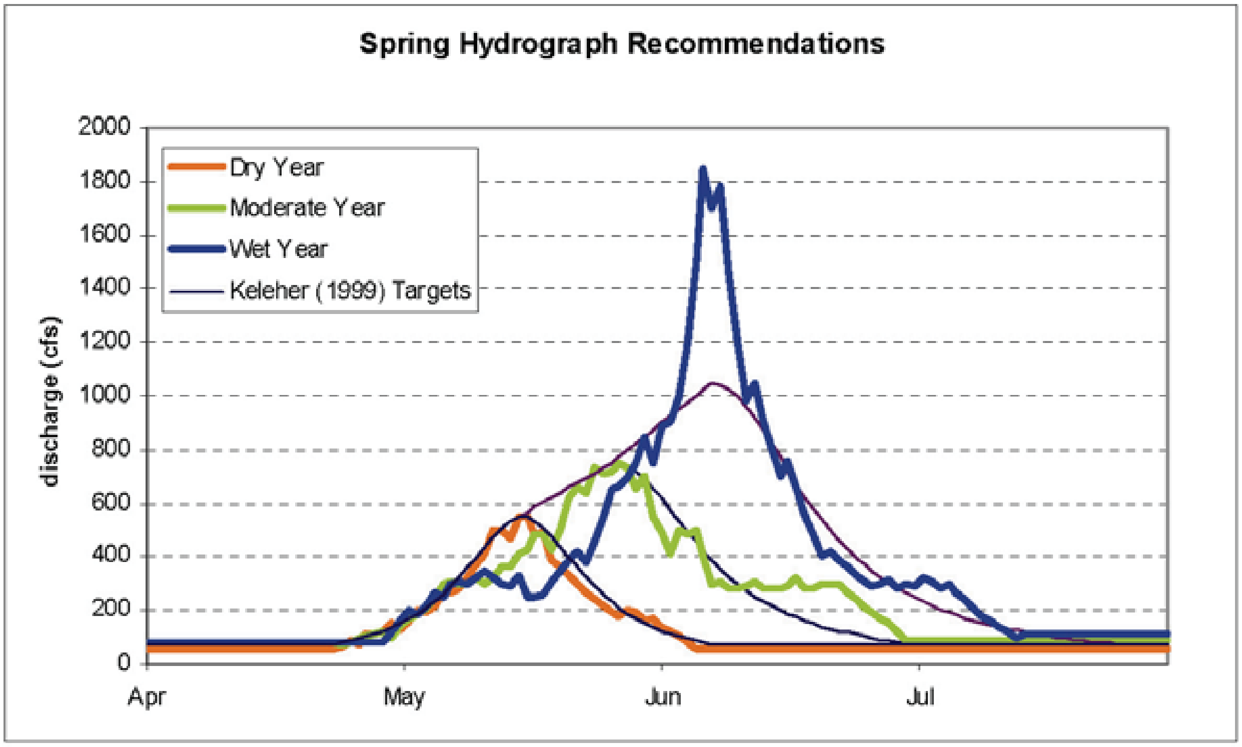

Figure 8.2. **Lower Provo River spring hydrograph recommendations relative to existing June sucker target hydrographs (Keleher 1999).**

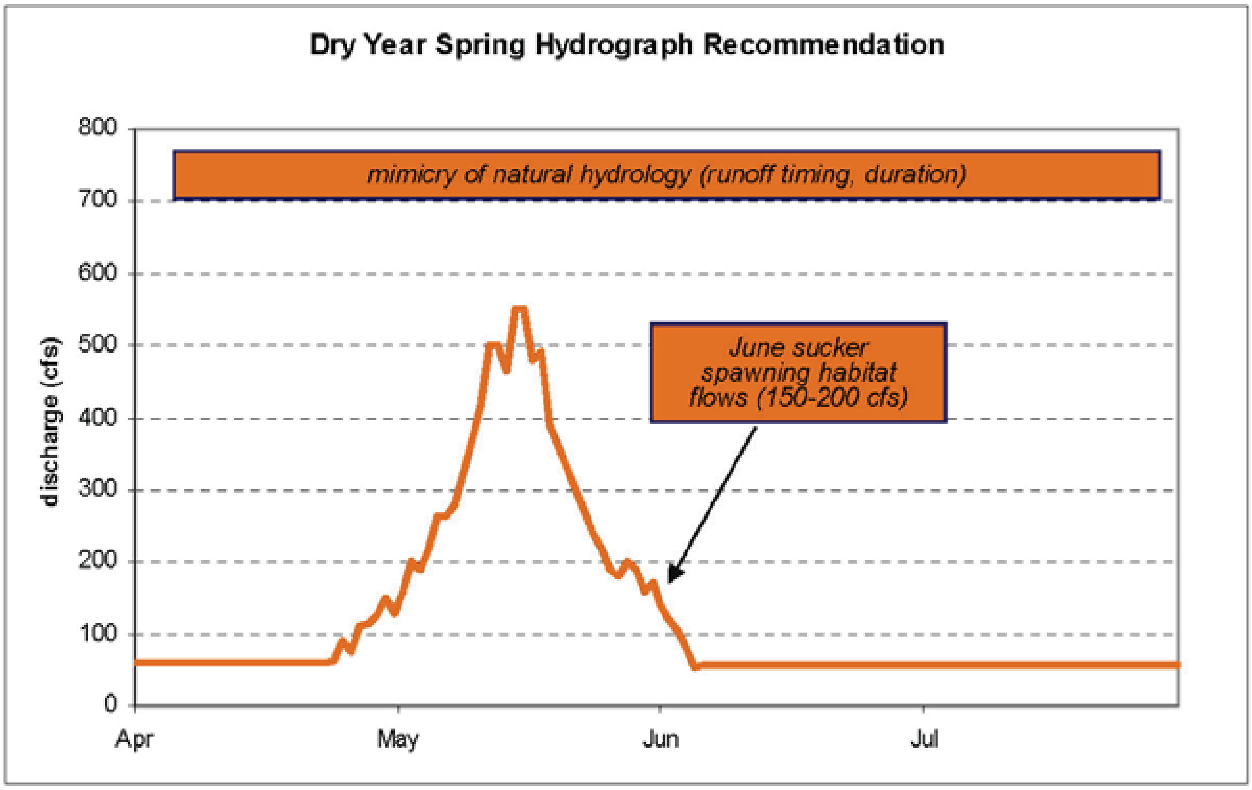

Figure 8.3. **Dry year spring hydrograph recommendation.**

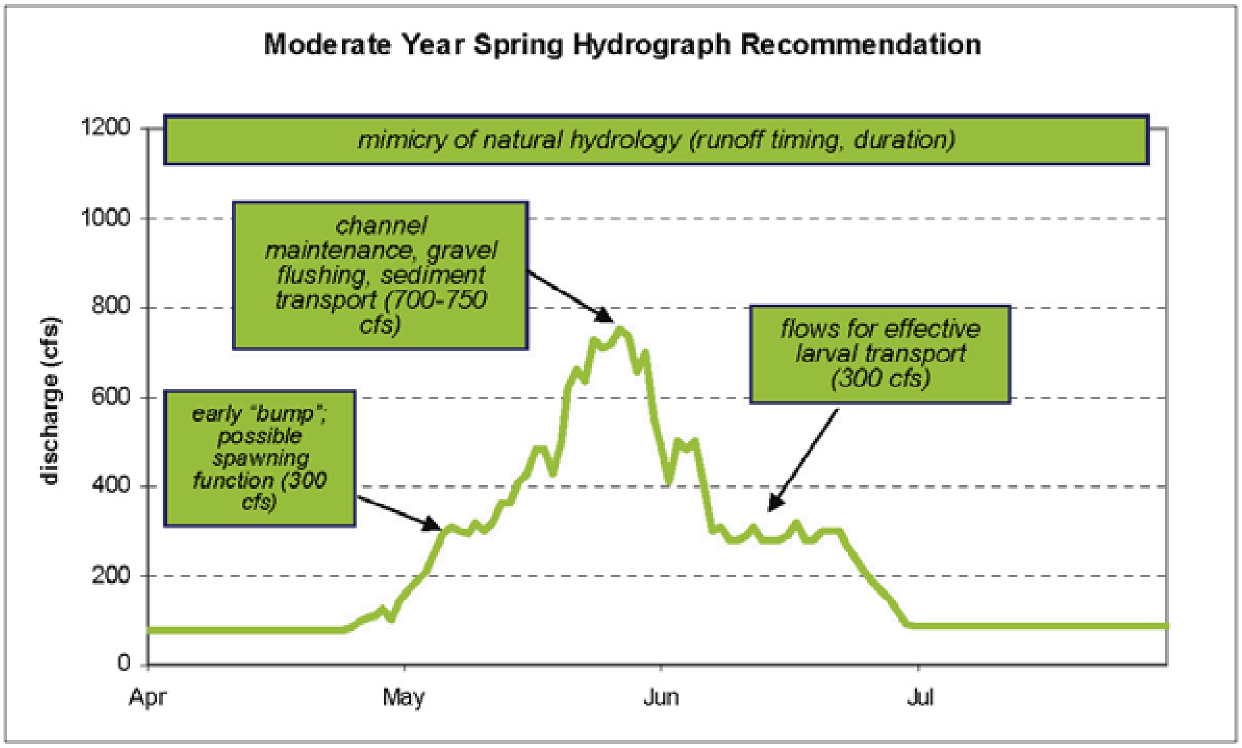

Figure 8.4. Moderate year spring hydrograph recommendation.

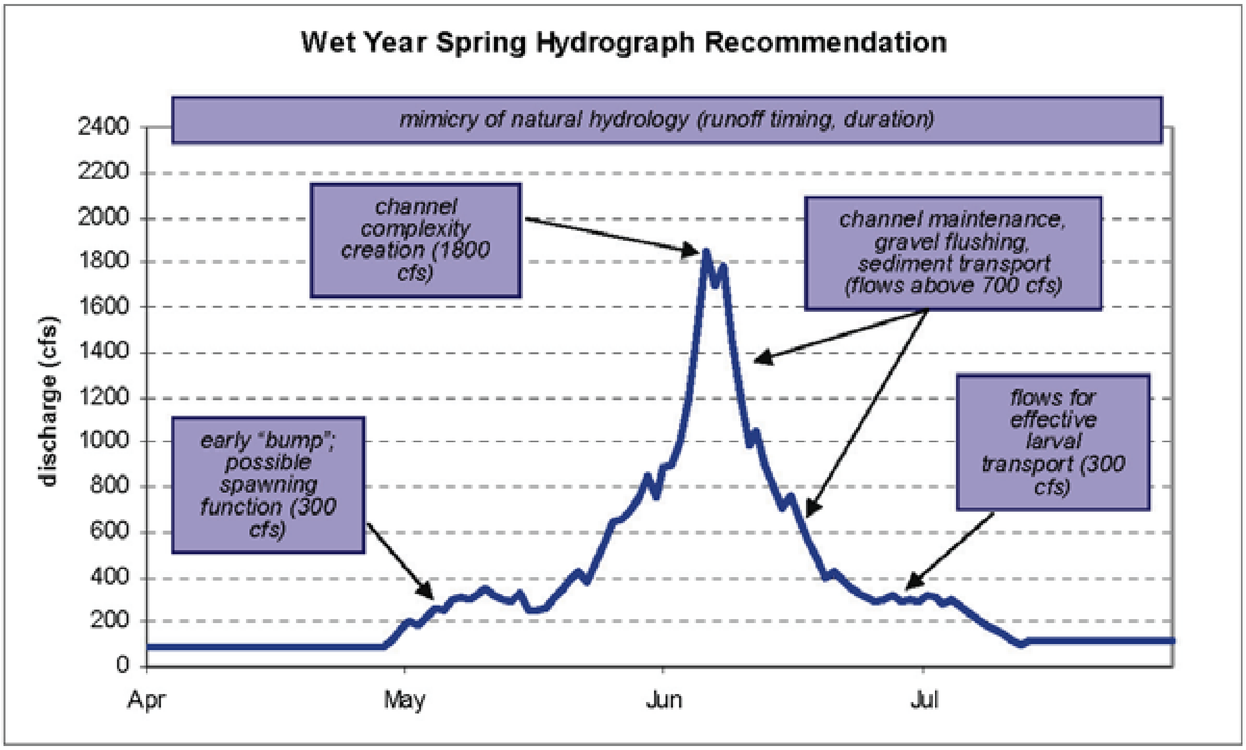

Figure 8.5. Wet year spring hydrograph recommendation.

adjacent to the river corridor. However, Provo City is currently working towards a design capacity goal of 2,300 cfs for the lower river (G. Beckstrom 2008, pers. comm.), so it should become possible to safely pass the recommended wet year spring flows as this flood capacity goal is achieved. In years when the wet year hydrograph is proposed for implementation, the Workgroup should coordinate with Orem and Provo to insure that any specific flooding concerns are addressed prior to the release of the high flows.

On the rising limb of the moderate and wet year hydrographs, we included a multi-day “bump” where flows are held in the 300 cfs range. This feature was included based on the results of analyzing the dual peak characteristics of the naturalized Hailstone hydrographs. In March and April, flows commonly increase to the 300 cfs range and hold at that level for several days prior to the start of the “true” rising limb when flows increase up to their peak magnitude. As discussed in Section 5, the link between spring flow patterns and June sucker spawning success is still unclear. However, it is possible that the early bump in flows and the associated shifts in water temperature and turbidity characteristics may play a role in cuing June sucker to begin staging for their spawning run. We included the early bump in flows in our recommendations for this reason, and because the bump mimics the natural hydrologic conditions observed at Hailstone. The early 300 cfs bump was not included in dry year hydrograph recommendation because there is not typically enough water available under dry conditions to hold flows at that level for a substantial duration.

We also revised the timing of the rising limb in our moderate and wet year recommendations relative to the timing shown in the existing (Keleher 1999) target hydrographs. Keleher’s (1999) analysis of naturalized Hailstone data demonstrated that the ascending limb of springtime runoff naturally begins earliest during dry years, later during moderate years, and latest during wet years. However, in order to make the proposed target hydrographs easier to implement from an operational standpoint, the target rising limbs for moderate and wet conditions were shifted to match the timing of the dry year condition (Keleher 1999). This adjustment was made because in early April it is generally not known with certainty whether the snowpack and climatic conditions will generate a dry, moderate, or wet year scenario. In our revised recommendations (Figure 8.2), we revert to the originally proposed timing for the moderate and wet year curves because this timing is reflective of natural hydrologic variability and may have as-yet unknown ecological importance.

Operational Considerations

The proposed suite of spring runoff hydrographs and base flow guidelines (Figures 8.1-8.5) serves as a comprehensive instream flow prescription that protects the full range of high-priority ecological functions on the lower Provo River. As such, we recommend that the river be managed to match these guidelines to the greatest extent possible. However, following the guidelines precisely may not be possible in all years due to operational constraints, water delivery requirements, and overall water availability. Because of this reality, we provide some guidance as to possible ways to adjust flow releases to save water without sacrificing ecological functions.

In order to identify potential conflicts between the proposed flow recommendations and operational needs, it is helpful to compare actual recent flow release patterns with the proposed guidelines. Toward this end, Table 8.1 provides a summary of comparable flow rates and volumes calculated from USGS gage records (Provo River at Provo gage) for the time period 1992-2007. The gage-based values provided in Table 8.1 were calculated in a way comparable to the techniques used to determine the flow recommendation values. For example, the gage-based winter base flow value is the average of the median January and February flows for 1992-2007. The gage-based spring runoff volumes are the 20th, 50th, and 80th percentile values of the total April 1-July 31 runoff volumes recorded at the gage for 1992-2007. We include Table 8.1 to provide some context for our flow recommendations and to help identify possible conflicts between the recommendations and existing operational practices. We also include the spring runoff volumes associated with the existing June sucker target curves (Keleher 1999) for comparison purposes.

Table 8.1. Comparison of recommendations with existing hydrology and operational practices.

YEAR AND FLOW TYPES	RECOMMENDATION	VALUE BASED ON USGS GAGE RECORDS (1992-2007)	VALUE BASED ON KELEHER (1999) JUNE SUCKER TARGET CURVES
Moderate Year Winter Base Flow (cfs)	78	126	N/A
Moderate Year Summer Base Flow (cfs)	86	34	N/A
Moderate Year Autumn Base Flow (cfs)	86	113	N/A
Dry Year Spring Runoff Volume (acre-feet)	30,409	14,202	34,715
Moderate Year Spring Runoff Volume (acre-feet)	55,668	40,190	55,859
Wet Year Spring Runoff Volume (acre-feet)	86,483	83,764	86,995

Base flows on the lower Provo River are typically higher than the recommended levels during the winter and fall, but substantially lower than the recommended values during the summer. The exact reasons for the relatively high flow releases during the winter and fall are complex and appear to be associated with the need to release water to meet the existing instream flow requirements within Provo Canyon and below Olmsted, ensure adequate reservoir storage will be available to receive spring snowmelt inputs, and deliver water for downstream power plant operations. While the existing winter and autumn flows in the river do not appear to be so high as to be ecologically detrimental or cause excessive sediment transport, they are higher than the natural range of values, especially in the winter months (Appendix A). We recommend that the reasons for the high fall and winter flow releases continue to be investigated to determine whether it might be possible to reduce those releases to levels more in line with the proposed recommendations. The possibility of storing some of the water saved by reducing fall and winter flows for release later in the summer should also be explored in detail.

Current summertime water demand for irrigation and municipal needs makes it difficult to maintain summer instream base flows within a natural hydrologic range (Table 8.1). As discussed above, attempts to secure additional water for instream purposes should improve this situation over time. However, it is unlikely that the recommended summer values of 86 and 113 cfs will consistently be achieved. With this reality in mind, we recommend that the focus be placed on delivering adequate flow to protect water temperature conditions during the critical months of July and August. Based on available data, flows of 50 cfs or greater would be adequate to achieve this function (Appendix G). However, we recommend that in wet years when irrigation demands are relatively low, flows higher than 50 cfs be released to the lower river to provide inter-annual hydrologic variability.

Operational realities in terms of total water volume available may also make it difficult to match the proposed spring hydrograph recommendations in dry and moderate years (Table 8.1). The volume of water associated with the proposed wet year hydrograph is only slightly greater than the volume historically released during wet conditions, and does not appear to pose a significant operational conflict (Table 8.1). As previously alluded, in dry years the emphasis may be appropriately placed on maintaining ecological base flows rather than "spending" water to achieve a low magnitude spring peak that does not accomplish any specific channel maintenance or known biological function. In moderate years, the proposed spring hydrograph could possibly be modified to save water by raising and dropping flows more rapidly around the 700-750 cfs peak -- essentially narrowing the central portion of the peak (Figure 8.4). However, flows should be held at 700 cfs or greater for at least 3 consecutive days in order to achieve effective channel maintenance and ensure that spawning gravels are cleaned (Table 7.2, Appendix C). In addition, even if the central portion of the moderate year hydrograph were narrowed, flows should increase to and be held at a minimum of 200-250 cfs prior to and following the 700-750 cfs central peak in accordance with the recommended timing to preserve the natural duration of the spring runoff period. In addition, holding flows at around 300 cfs on the receding limb to promote effective larval June sucker drift would be an important function to maintain if possible. It may be possible to save some water while still achieving this function through the use of nighttime-only "pulsing" releases (UDWR 2007). Given the uncertainty regarding the biological importance of the early "bump" of 300 cfs on the rising limb, it may be possible to eliminate this component of the proposed spring hydrograph recommendation.

A Note Regarding the Recommendations in this Report

The recommendations presented in this report are based on sound ecological principles and, where available, information, data, and reports specific to the lower Provo River. However, some caution should be exercised when applying these guidelines or recommendations. Since 1994, cooperative efforts among many agencies and partners to manage flows in the lower Provo River have been directed primarily to the June sucker's spawning requirements and, more recently, also the transport requirements for newly hatched June sucker larvae. Attempts have generally not been made to provide year-round flows. The effects of providing year-round flows on non-target non-native fishes that use the lower Provo River have not specifically been evaluated. The potential exists that non-native species would benefit from year-round flows, possibly to the detriment of June sucker, especially larvae, which may be preyed upon or competed with for food resources by the non-natives. The potential also exists that year-round flows could indirectly benefit June sucker by reducing vegetation encroachment and algae growth on substrate material used for spawning. This represents a line of inquiry that might be pursued by the JSRIP prior to implementing year-round instream flows on a permanent basis.

As explained previously in this report, the role of streamflow and the effects of various changes in streamflow regimes are an important component of riverine ecosystems. However, stream flow is not the only factor that influences ecosystem health or function. Other factors can be as important or more important, and may serve as limits or constraints on the ability to achieve naturally functioning and sustaining riverine communities. For example, the lower Provo River ecosystem, especially the lowest several miles that comprise the designated critical habitat for the June sucker, is substantially compromised by the channelized and leveed physical condition of the channel and the influence of the Utah Lake backwater.

Restoring the lower Provo River ecosystem to a high-functioning level will not be achieved by manipulation of streamflow regimes alone. We strongly encourage the continued pursuit of habitat restoration efforts on the lower Provo River and Utah Lake interface. We also recognize that inter-specific interactions among the fish community present in the lower Provo River and Utah Lake interface are complex and may affect especially the efforts to recover June sucker. For example, making changes to the lower Provo River streamflow regime could hypothetically attract increased numbers of June sucker spawners to the river, which could lead to increased spawning activity and increased numbers of larval June sucker produced. There might not be a corresponding increase in recruitment of those larval fish (arguably the main biological objective of the JSRIP) to the juvenile and subsequent life stages because of other factors (e.g., lack of suitable rearing habitat, failure of larvae to reach rearing habitats, predation by other fishes in the lower river and Utah Lake interface). For this reason, the JSRIP is a multi-faceted program that attempts to address all factors that constitute a threat to the species. Similarly, we encourage a multi-faceted approach to restoring functions and improving the lower Provo River ecosystem. Although streamflow regime is a critical component of riverine ecosystems, it is only one of several vital components, and all limiting constraints should continue to be addressed in order to achieve successful ecosystem recovery.

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APPENDIX A: DIMENSIONLESS FLOW-DURATION CURVE ANALYSIS

Appendix A

INSTREAM FLOW: A STATISTICAL APPROACH

Prepared by Tyler Allred - Allred Restoration, Inc.

An Innovative Approach to Developing Improved Instream Flow Recommendations

Many human activities have occurred that alter the temporal patterns and overall quantity of streamflow in rivers and streams of the western United States. These activities have led to degraded conditions in many of the affected waters.

The task of determining how much streamflow is required to sustain the aquatic ecosystems of those waters is difficult at best, and many methods have been suggested to assist resource managers in determining appropriate instream flows. This appendix will summarize the basic steps used to apply a statistical technique for determining instream flows to the lower Provo River in Utah. This technique has been successfully applied on the Truckee River in Nevada (Gourley and Allred, 2000 and Allred and Gourley, 2002), and results from the present study are compared to the Nevada results at the end of this appendix.

The technique outlined in this appendix uses statistical relationships to quantify the range of natural variability that exists in less altered aquatic systems and applies those ranges to degraded systems to improve the streamflow regime. These methods are primarily useful for determining the range of low flow conditions that are found in natural streams and translating those results into meaningful estimates for degraded streams.

First Steps – Locating and Evaluating Reference Streams

USGS personnel from the Salt Lake City, Utah office, provided assistance in selecting a number of gage records from nearby rivers and streams that had limited hydrologic alteration to their flow regime. Each gage record was analyzed using the procedures outlined in steps 1-10 (below). For the Utah study, seven gage records were selected to represent the basic streamflow variability of local streams with minimal hydrologic alteration: they include;

- Bear River near Utah/Wyoming State Line (Station # 10011500),
- Hobble Creek near Springville, UT (Station # 10152500),
- North Fork Provo River near Kamas, UT (Station # 10153800),
- Payson Creek above Diversions near Payson, UT (Station # 10147500),
- Spanish Fork above Thistle, UT (Station # 10148500),
- Weber River near Coleville, UT (Station # 10130500),
- Yellowstone River near Altonah, UT (Station # 9292500).

Although the hydrology of each of these streams has been affected by human activities, their overall timing and distribution of discharge remains largely unchanged. These streams were used as reference streams for the procedures outlined below.

Statistical Procedures and Analyses

The steps outlined below provide a characterization of the temporal variability in streamflow that is found in unaltered systems. These steps were completed for the seven reference streams listed above.

Steps 1-4 (below) are computed using the entire discharge record for each of the seven streams. These steps are used to ensure that the reference streams have similar annual distributions of hydrologic characteristics. If outliers exist after step 4, they may be eliminated from further consideration. After completion of Steps 1-4 to ensure similarity of overall hydrology from gage to gage, those data are set aside and are not used for further analyses.

Step 1 - A list of area streams that met our selection criteria was compiled. Streams had to (1) have minimal human alteration to the upstream watershed and (2) have a USGS streamflow gaging station with a reasonable long period of record.

Step 2 - The measurements of mean daily streamflow were obtained and standard flow duration curves were constructed for each gaged stream (see Figure A1). A standard flow duration curve plots the mean daily streamflow against the percent of time that the streamflow has been equaled or exceeded during the period of record. Notice that streams of different size are distributed vertically along the y-axis (discharge). Although the curves appear to have similar shapes, the vertical distribution makes it impossible to use the data from one stream to guide flow recommendations on another stream, unless they happen to be of exactly the same size. In order to use these data to guide flow recommendations, a way must be found to remove the effect of stream size on the data, which would allow basins of different sizes to plot in the same space.

Step 3 - The flow duration curves, for each gaging station, were non-dimensionalized by dividing the mean daily discharge by the mean discharge for the entire period of record (see Figure A2). The result is a dimensionless variable which we will call "dimensionless discharge". It is dimensionless because the units of discharge cancel out when dividing by the mean discharge. Notice that the plots which were previously distributed along the y-axis, are now grouped much more closely. This procedure causes the large and small streams to collapse onto each other, creating an envelope of streamflow variability that can be compared between streams of all sizes.

Step 4 - The flow duration curves from all stations are plotted together and visually compared to each other to identify similarities and differences. Having established that the overall streamflow variability of the streams was quite similar, these streams were deemed to be useful as "reference streams", and further analyses were completed using those records.

Steps 5-8 are computed using datasets that have been broken down by month, which provides a higher level of temporal resolution for streamflow variability. Separate flow duration relations for each month of the year, January through December, are produced and analyzed.

Step 5 - The mean discharge for each month of each year was computed for the entire gage record of each of the nine streams. For example: the mean daily streamflow was computed for Jan. 1963, Feb. 1963, Mar. 1963, etc.

Step 6 - A duration curve was constructed for each month (Jan-Dec) using the monthly averages computed in step 5. The result is twelve flow duration curves for each gage record (one for each month), that define the range of flow variability that has occurred during that month over the period of record. At this point in the process, the curves are still distributed widely along the discharge axis (y).

Step 7 – In order to remove the effect of stream size on the flow duration curves, the monthly duration curves developed in Step 6 were transformed by dividing the discharge data by the mean discharge for the period of record: the same method that was outlined previously in Step 3. Again, as in Step 3, the result is a similarity collapse that brings the streams of all sizes into a well defined envelope of natural streamflow variability. The data that was spread along the discharge axis are now transformed into the well-grouped dimensionless discharges that are shown in Figures A3 and A4 respectively. Notice that the curves are now grouped together more closely and represent the range of discharge present in the reference stream, but as a dimensionless variable that can be scaled up to any size stream by multiplying by the mean discharge of that stream.

Step 8 - Points were interpolated along each dimensionless flow duration curve, at 10% increments, using a Lagrange interpolation scheme. This allows us to identify important characteristics of the curves (wettest 10%, driest 20%, etc.).

Results from steps 5-8 are used to construct an overall dimensionless instream flow table (Step 9) that can be redimensionalized for other streams (Step 10).

Step 9 - The median values from each of the nine gaging stations, for each 10% increment of each month, were determined and that value was used to establish the overall dimensionless instream flow recommendations table (Table A1, Figure A5).

Step 10 - Dimensionless discharges determined in Step 9 then can be redimensionalized for any river by multiplying the dimensionless discharges by the mean daily discharge for the period of record at whatever gage is appropriate for a given site. The result is a series of monthly mean discharge recommendations for water years ranked by percentile. The results of the rescaling for the lower Provo River will be presented later the following paragraphs.

The Lower Provo River

Data from the USGS gage "Provo River at Provo, Utah" (station # 10163000) were analyzed and an annual dimensionless discharge curve was constructed, as outlined previously in Steps 1-4. This curve was plotted with the seven Utah reference streams to determine the degree of alteration from natural streamflow variability that had occurred in the Lower Provo River (Figure A6). These data suggest that the streamflow of the Lower Provo has been greatly affected by dewatering during periods of low flow, and that those activities cause the streamflow to deviate from the expected natural range nearly 25-30% of the time, or roughly 100 days per year, on average. The lower Provo River experiences periods of low flow that are substantially lower than the flows that would occur under a more natural condition. Also notice that the curve for the lower Provo River is higher than the reference streams, at least for a short section of the plot. This means that the flows in the Provo are higher than natural during certain periods.

Further analyses were completed for the lower Provo River by following Steps 5-8 as outlined above. Monthly dimensionless flow duration plots were constructed and compared to the reference streams. These plots clearly illustrate the time periods when streamflow on the lower Provo is outside the expected range as determined by the reference streams. Figures A7 and A8 present the monthly plots for the reference streams and the lower Provo, for July and January respectively.

In order to determine a more appropriate range of streamflow for the Lower Provo River, the dimensionless flow duration data from the Utah reference streams (see Table A1), were re-dimensionalized for the Lower Provo River by multiplying the dimensionless discharge by the mean discharge for the Provo River at Provo, Utah gage (approx. 196.45 cfs). This produced a table of flow recommendations that would better mimic the range of natural streamflow variability that likely would have occurred in the river without human intervention (Table A2 and Figure A9). These recommendations were used to guide suggested overall streamflow recommendations found in the body of this report.

Previous Work – A Brief Review of the Truckee River Study

When the present study began, we considered the possibility of using the curves from the Nevada streams to help set instream flow values for the lower Provo River. The Nevada streams have a snowmelt-dominated hydrology, similar to the Provo River, and are geographically similar in many ways. However, the Nevada streams were later deemed to have substantial temporal differences from the Utah streams, and the determination was made to construct all new reference data for Utah streams. Since the Nevada streams were considered to use in earlier drafts of this report, a brief summary of the Nevada study is included in this appendix for purposes of complete reporting of methods.

The Nevada Reference Streams

For the Truckee River study, USGS personnel from the Carson City, Nevada office, provided assistance in selecting a number of gage records from nearby rivers and streams, which had little hydrologic alteration to their flow regime. Each gage record was analyzed using the procedures outlined previously in Steps 1 through 10. Eventually, nine area gage records were selected to represent the basic streamflow variability of local streams with minimal hydrologic alteration: they included;

- West Fork Carson River at Woodfords, CA (Station #10310000),
- West Walker River near Coleville, CA (Station #10296500),
- West Walker River below Little Walker River near Coleville, CA (Station #10296000),
- Trout Creek near Tahoe Valley, CA (Station #10336780),
- Sagehen Creek near Truckee, CA (Station # 10343500),
- Little Walker River near Bridgeport, CA (Station #10295500),
- East Fork Carson River near Gardnerville, NV (Station #10309000),
- East Fork Carson River below Markleeville Creek near Markleeville, CA (Station #10308200),
- Buckeye Creek near Bridgeport, CA (Station #10291500).

Comparisons between Nevada and Utah Streams

We were initially encouraged that new curves may not need to be established because the annual plots from Utah and Nevada appeared to be very similar (Figure A10). The range of flow variability in the unaltered Utah streams is remarkably similar to the Nevada streams, although some of the Utah streams appear to have a slightly elevated baseflow. Interestingly, the bottom of the envelope of Utah curves is very similar to the Nevada streams, which suggests that the dimensionless discharge data from the Nevada streams might be useful for a surrogate to determine flow recommendations for the Utah streams.

Closer examination found that although the annual curves were similar, monthly patterns were not the same (see Figure A11). As such, the decision was made to create the all new set of Utah reference curves presented earlier in this appendix. If budget constraints had limited the time and effort that could be given to the lower Provo Study, the Nevada reference streams would have been a reasonable tool for determining approximate streamflow values. However, the development of the seven Utah reference streams added a level of confidence to the estimates that would have been lacking with lesser data.

Table A.1 Dimensionless Discharges - Medians from Seven Utah Reference Streams

	Percentile Rank Water Year								
Month	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Jan	0.269	0.306	0.339	0.398	0.408	0.415	0.416	0.419	0.449
Feb	0.264	0.298	0.348	0.355	0.389	0.389	0.403	0.424	0.445
Mar	0.288	0.321	0.385	0.408	0.424	0.435	0.459	0.460	0.468
Apr	0.332	0.449	0.556	0.767	0.923	1.163	1.615	1.947	2.419
May	0.927	1.564	1.931	2.455	2.894	3.225	3.488	4.037	5.131
Jun	0.690	0.870	1.092	1.733	2.585	2.837	3.197	4.007	5.017
Jul	0.408	0.606	0.705	0.777	0.843	0.956	1.060	1.299	1.882
Aug	0.244	0.309	0.358	0.422	0.457	0.537	0.637	0.832	0.878
Sep	0.233	0.271	0.345	0.390	0.422	0.470	0.546	0.576	0.690
Oct	0.252	0.325	0.370	0.415	0.442	0.489	0.494	0.513	0.575
Nov	0.275	0.342	0.382	0.425	0.464	0.495	0.527	0.542	0.563
Dec	0.277	0.349	0.376	0.395	0.410	0.448	0.458	0.468	0.501

Table A.2 Discharges (in cfs) - Medians from Seven Utah Reference Streams, Scaled for the Lower Provo River

Month	Percentile Rank Water Year								
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
Jan	53	60	67	78	80	81	82	82	88
Feb	52	59	68	70	76	76	79	83	87
Mar	57	63	76	80	83	85	90	90	92
Apr	65	88	109	151	181	229	317	382	475
May	182	307	379	482	569	633	685	793	1008
Jun	136	171	214	340	508	557	628	787	986
Jul	80	119	138	153	166	188	208	255	370
Aug	48	61	70	83	90	106	125	163	173
Sep	46	53	68	77	83	92	107	113	135
Oct	50	64	73	81	87	96	97	101	113
Nov	54	67	75	84	91	97	104	107	111
Dec	54	69	74	78	81	88	90	92	98

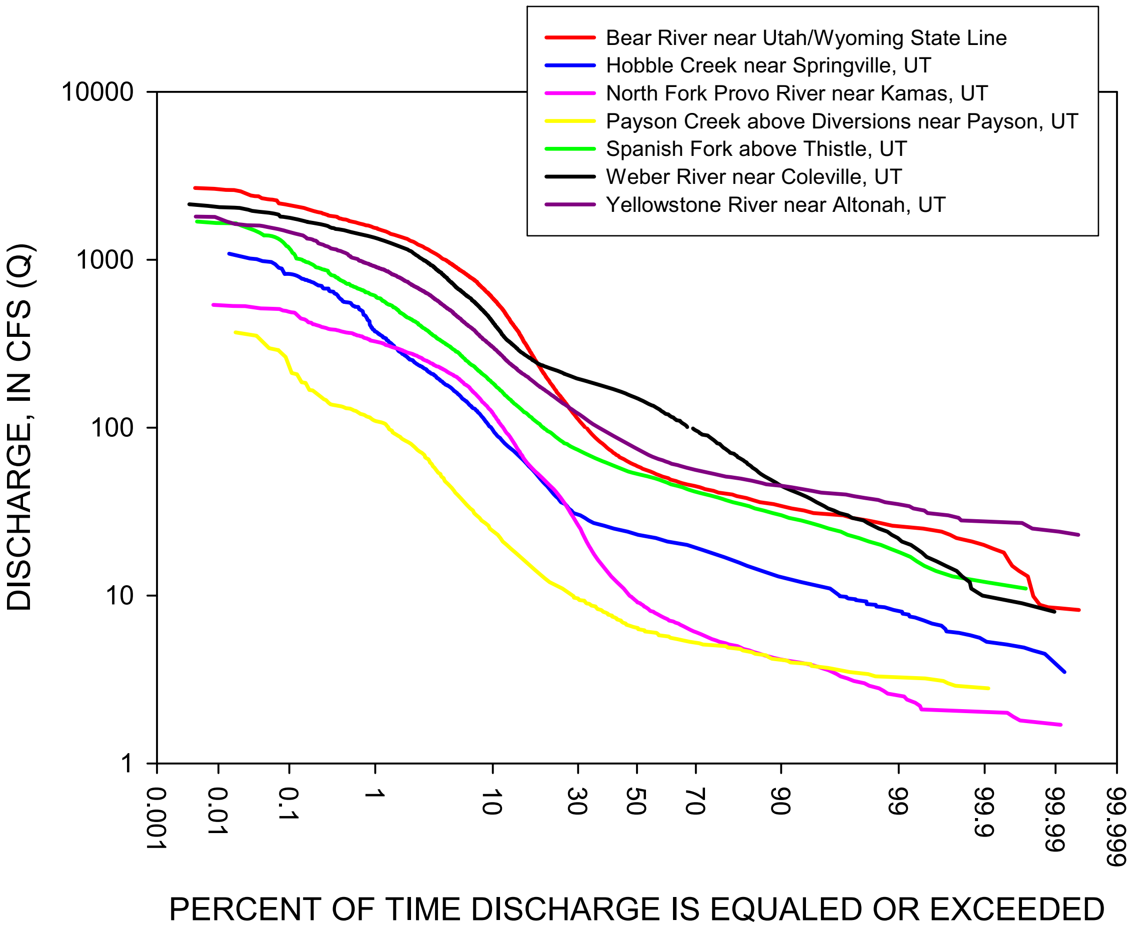


Figure A.1. Standard flow duration relations for seven Utah reference streams.

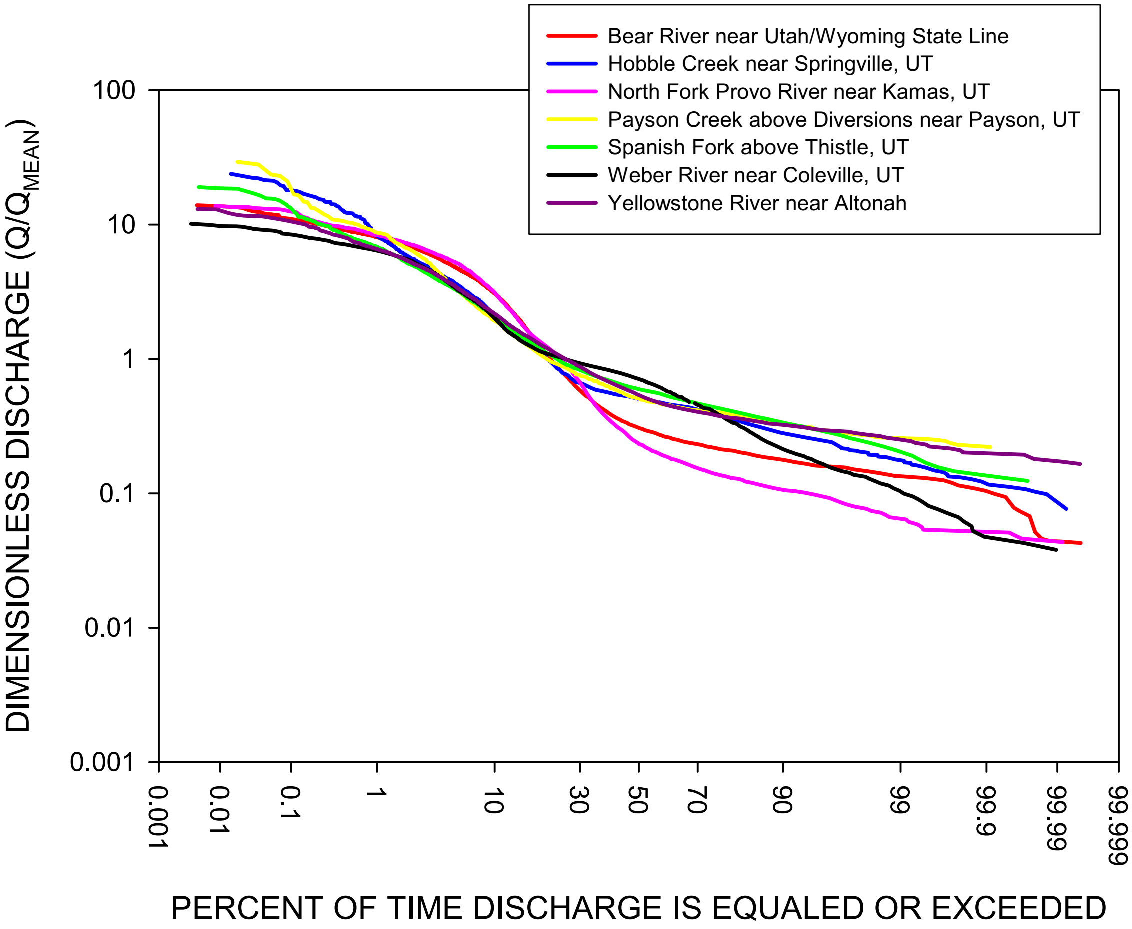


Figure A.2. Dimensionless flow duration relations for seven Utah reference streams.

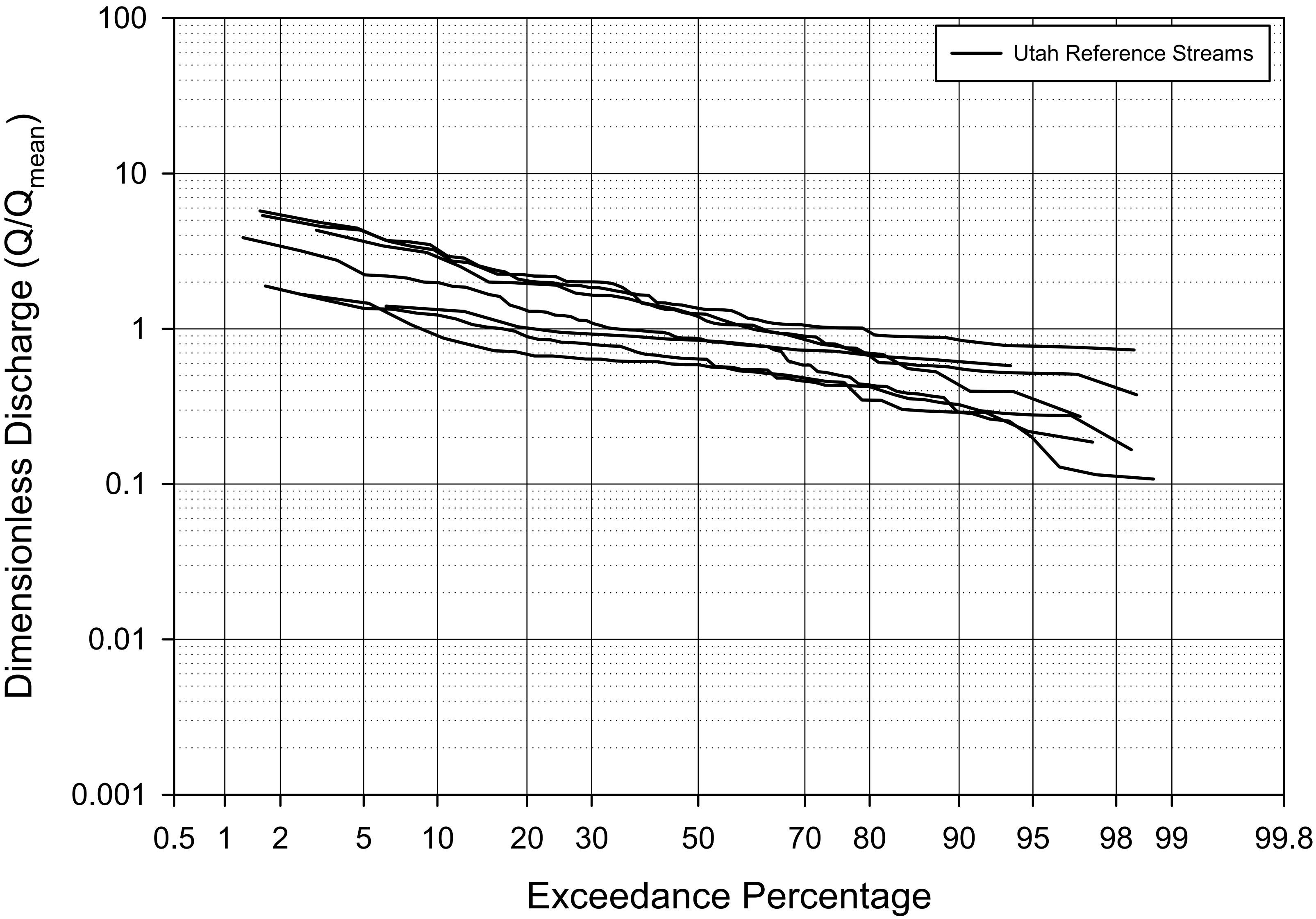


Figure A.3. Monthly (July) dimensionless flow duration relations for seven Utah reference streams.

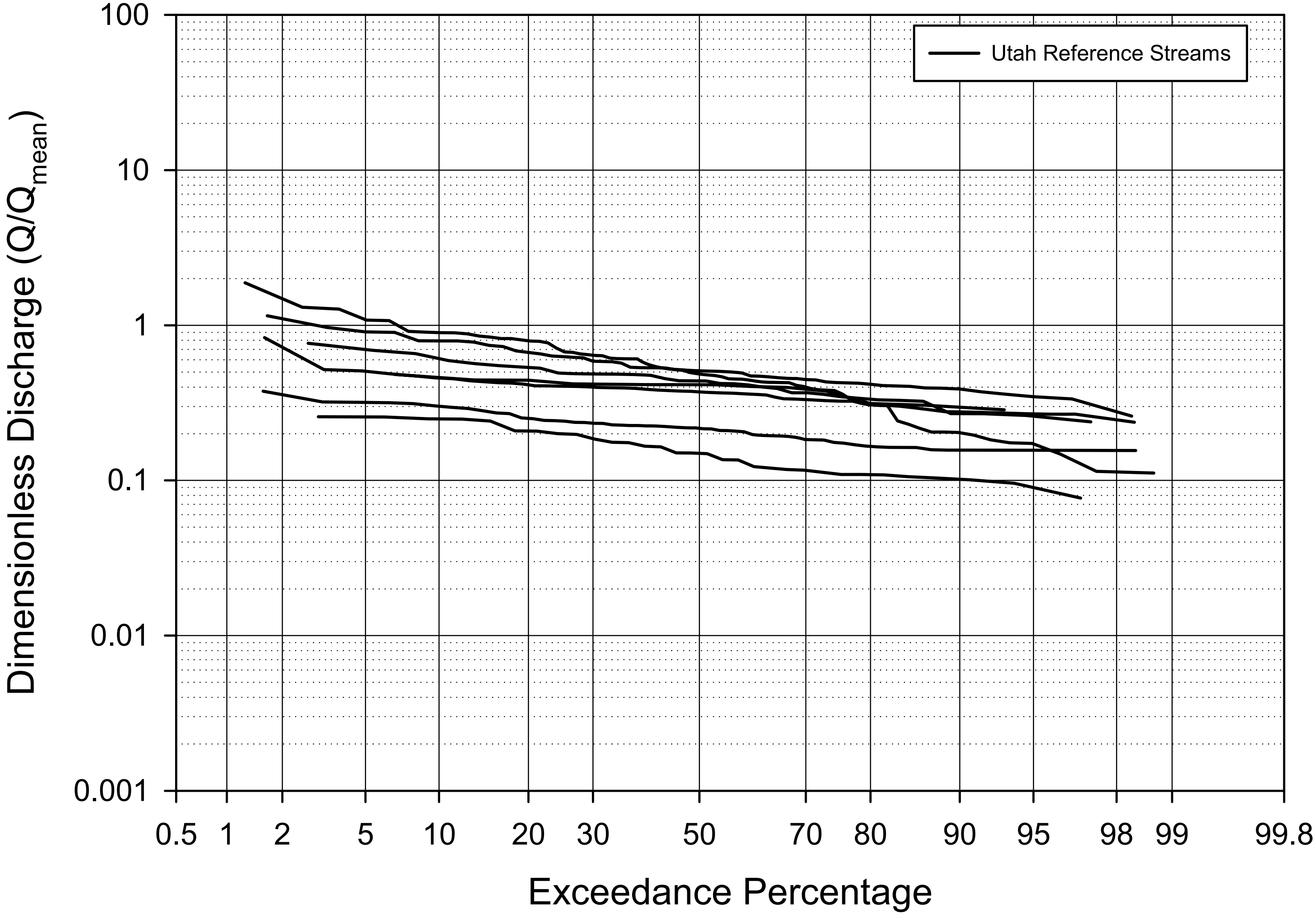


Figure A.4. Monthly (January) dimensionless flow duration relations for seven Utah reference streams.

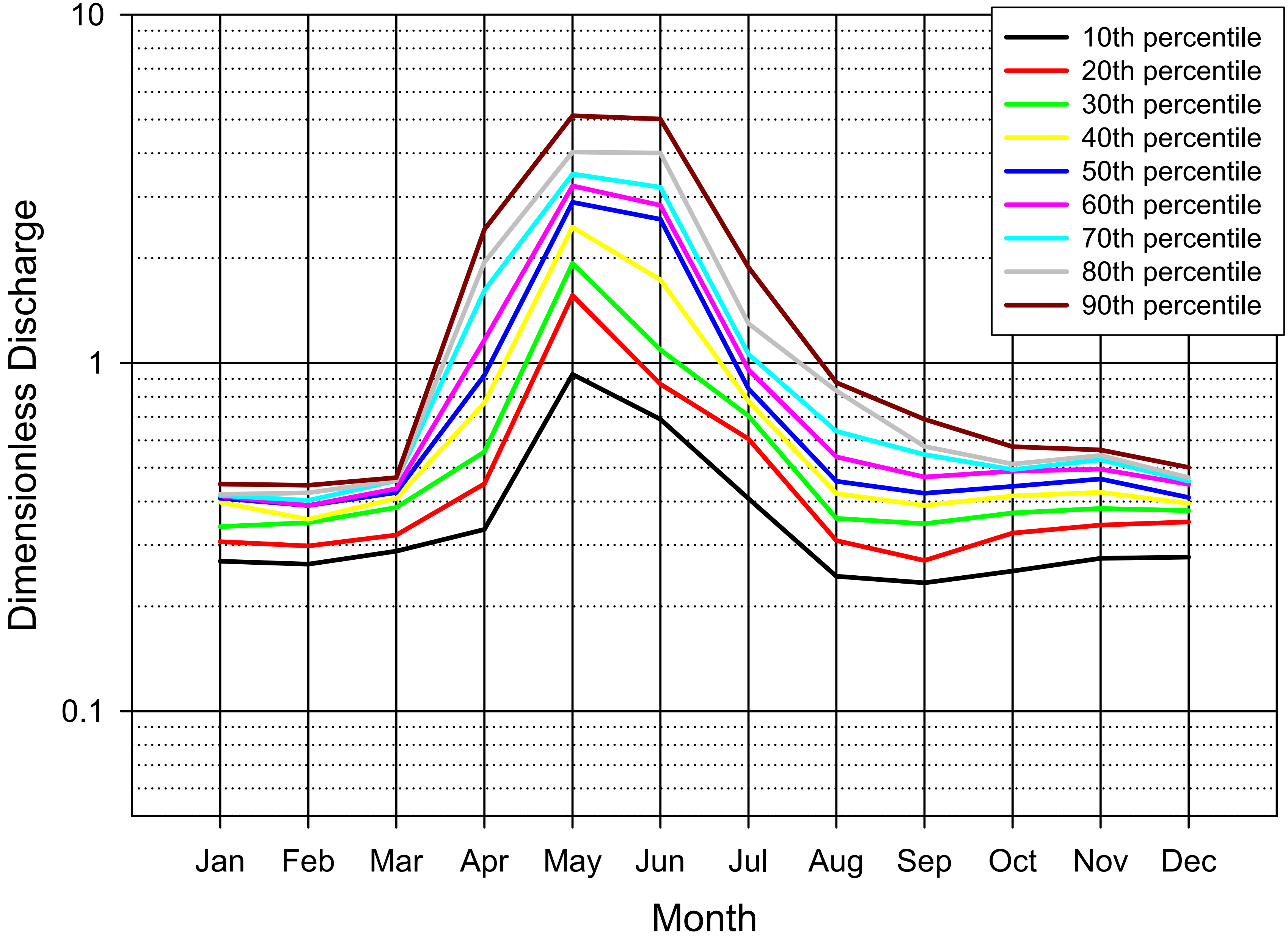


Figure A5. Dimensionless discharge recommendations for ranked water years - from seven Utah reference streams.

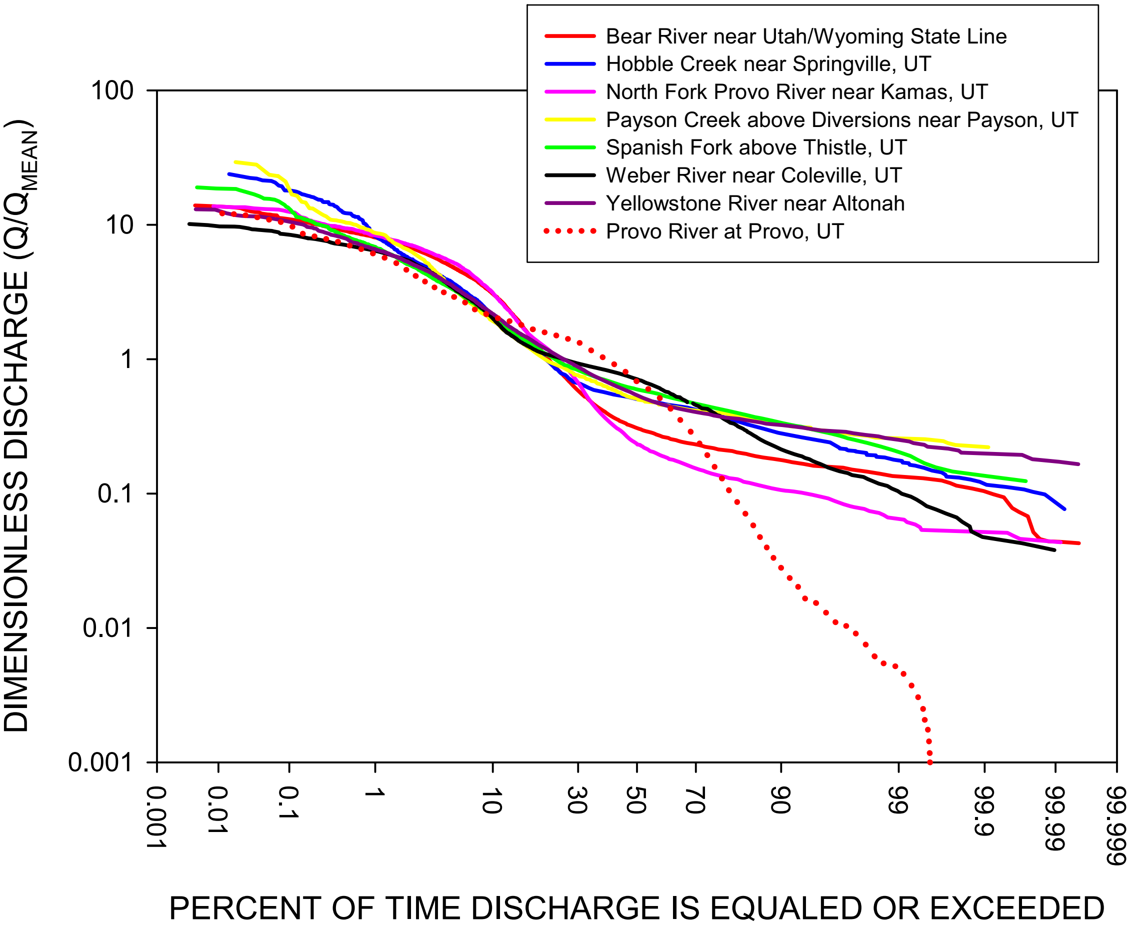


Figure A.6. Dimensionless flow duration relations for seven Utah reference streams and the lower Provo River.

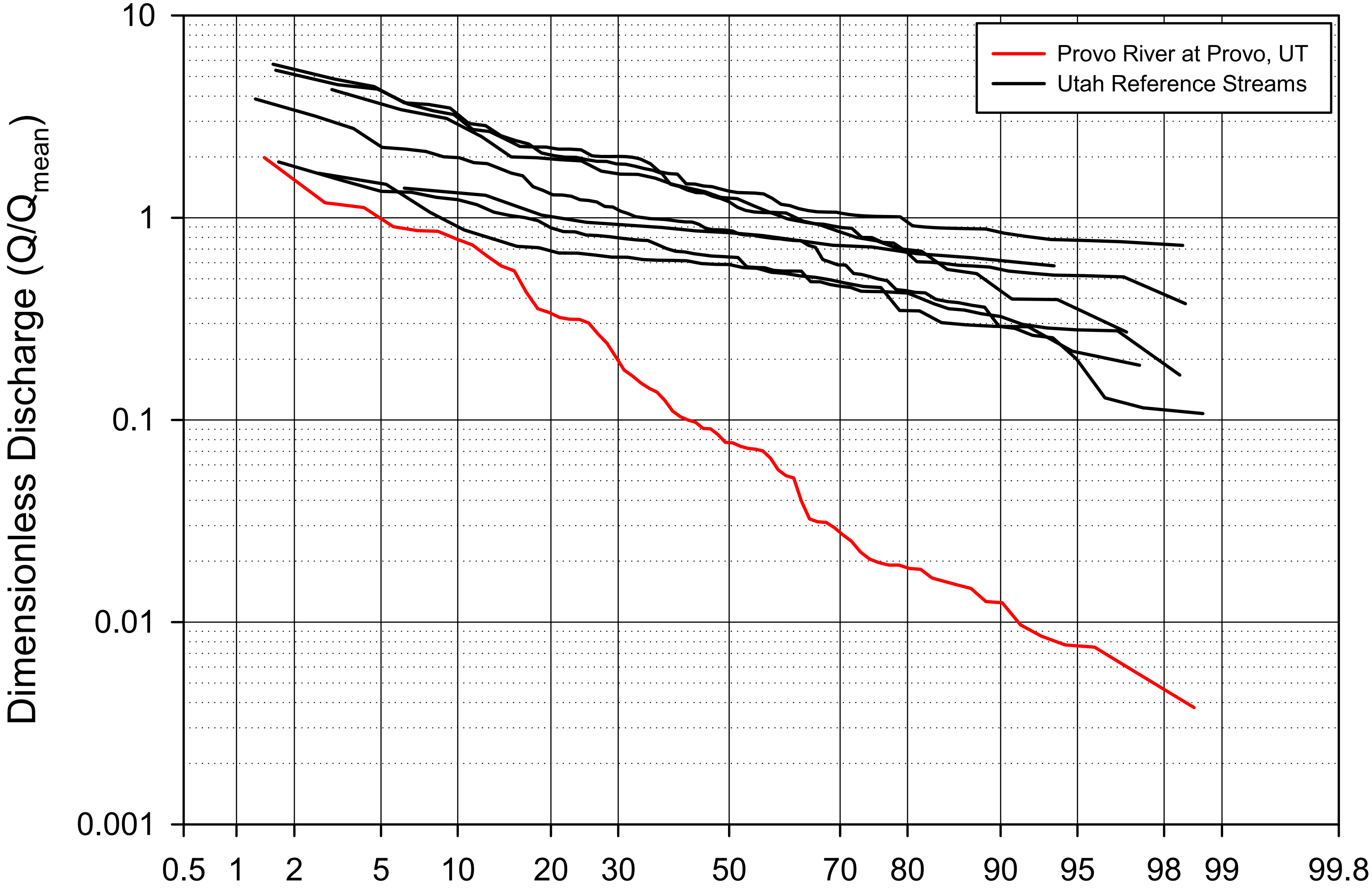


Figure A.7. Monthly (July) dimensionless flow duration relations for seven Utah reference streams and the lower Provo River.

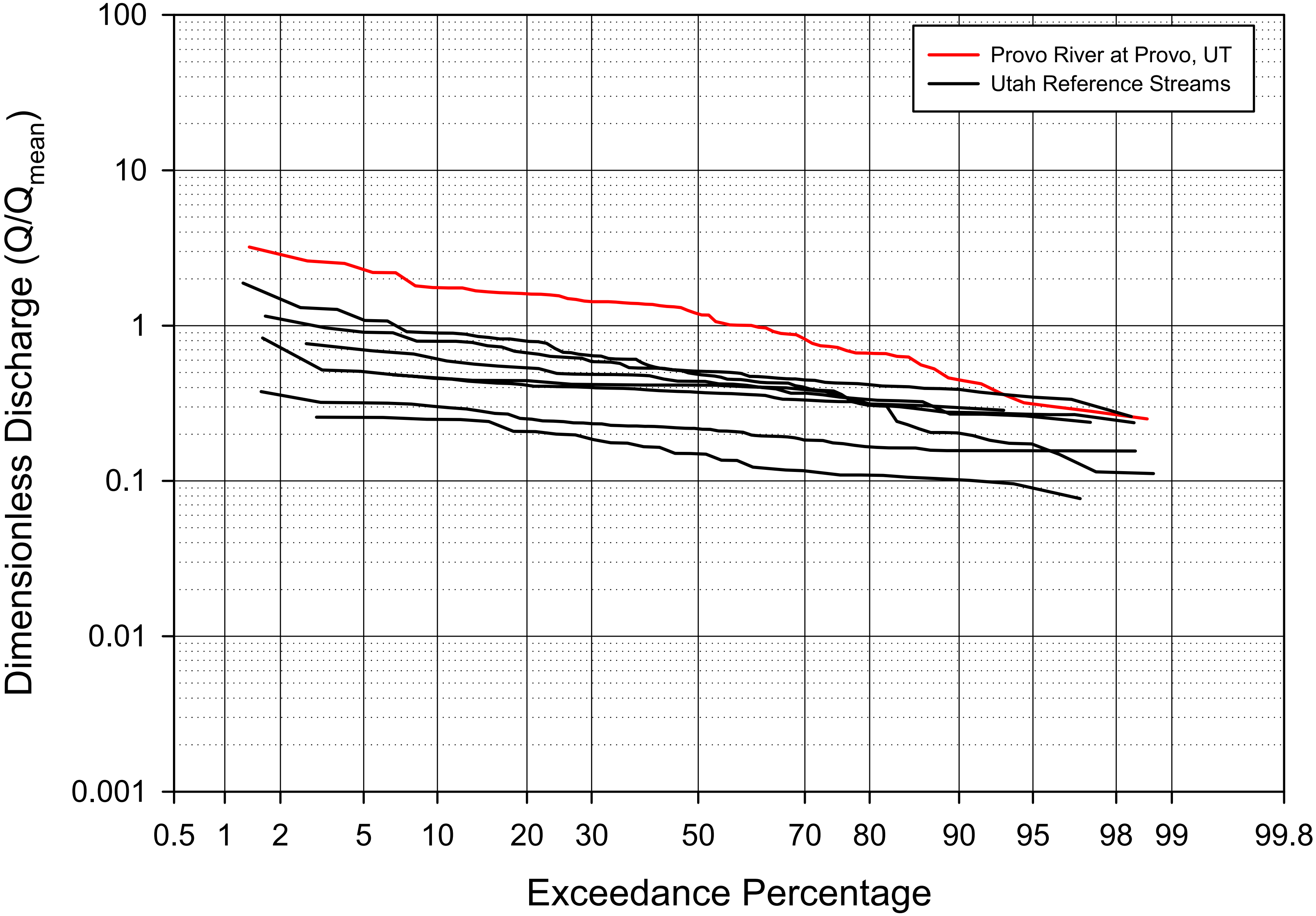


Figure A.8. Monthly (January) dimensionless flow duration relations for seven Utah reference streams and the lower Provo River.

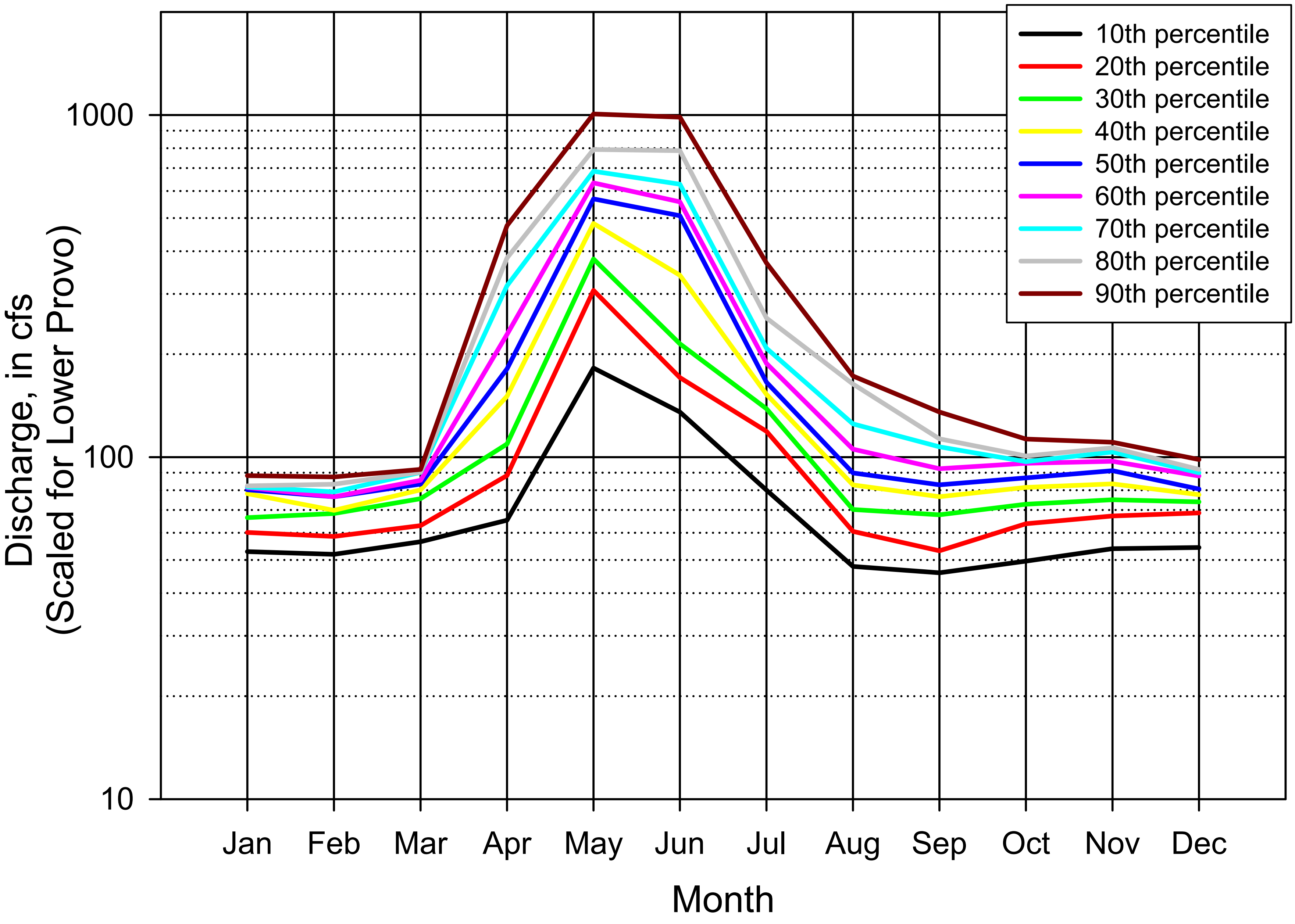


Figure A9. Dimensionless discharge recommendations for ranked water years: scaled for the Lower Provo River

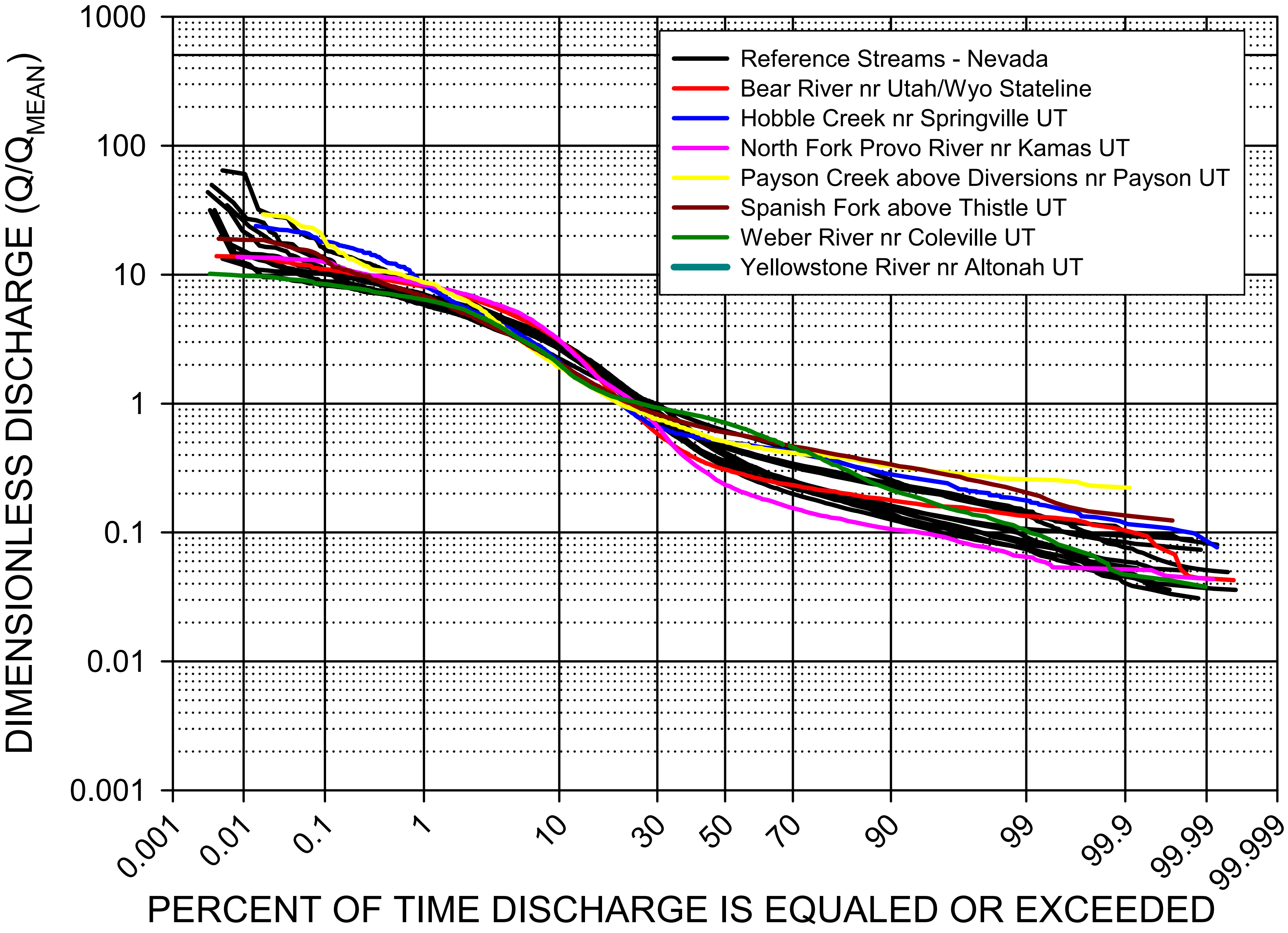


Figure A10. Plot of dimensionless discharge for reference streams in Nevada with Utah streams added.

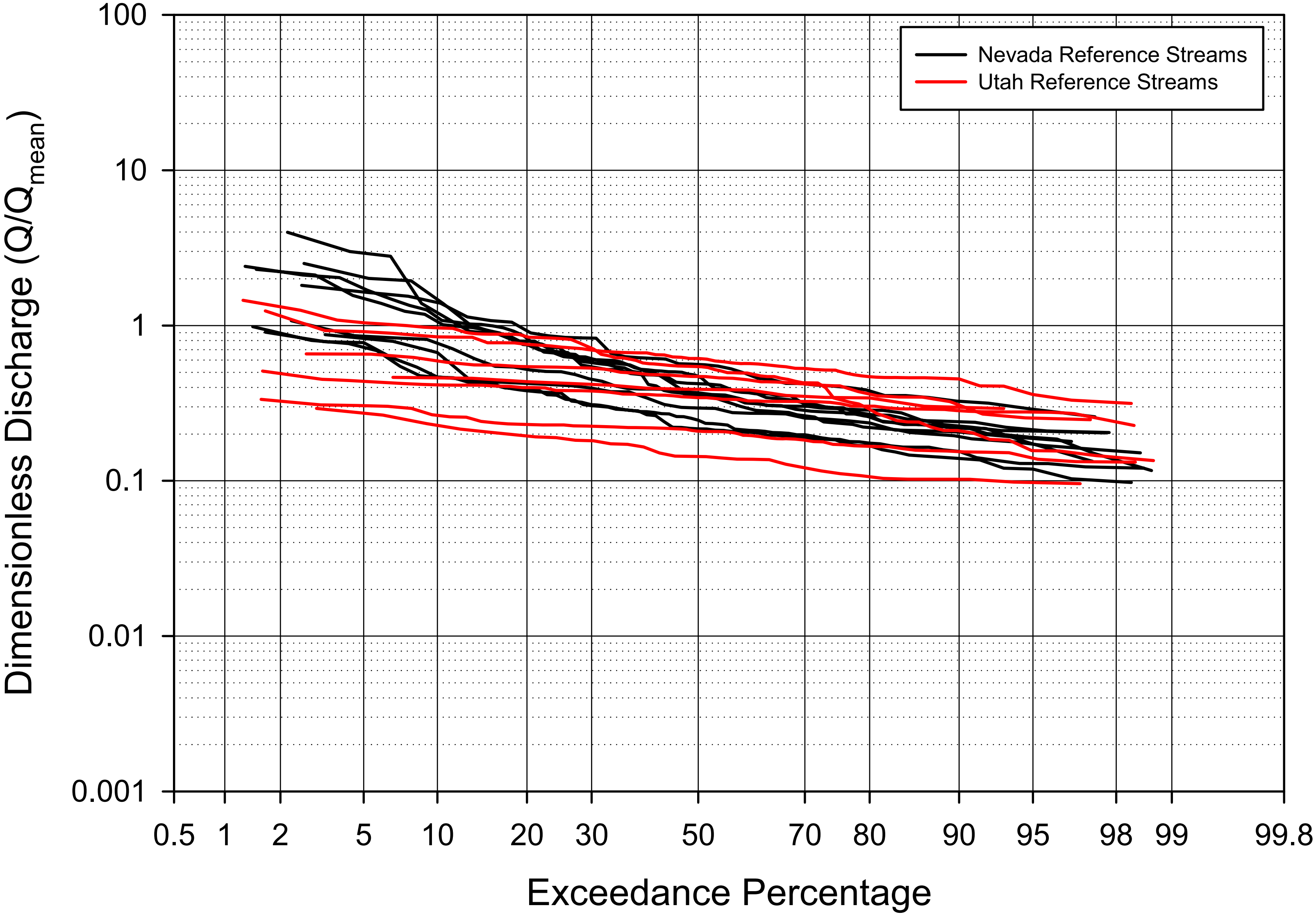


Figure A11. Plot of dimensionless discharge, for the month of February, for reference streams in Nevada (black) and Utah (red).

APPENDIX B: ANALYSIS OF NATURAL SPRING HYDROGRAPH CHARACTERISTICS

APPENDIX B: ANALYSIS OF NATURAL SPRING HYDROGRAPH CHARACTERISTICS

Receding Limb Analysis

Previously-developed guidelines for springtime flow releases (Keleher 1999) provide recommendations for the timing, duration, and magnitude of peak-flow releases under dry, moderate, and wet year conditions. However, the fall rates (day-to-day drop in discharge) included in these "target hydrographs" (Keleher 1999) were developed by averaging daily rates of change to provide a smooth recession curve between the peak flow down to the base flow at the end of the runoff period duration (Figure B1). Because of how they were developed, the target hydrograph fall rate values do not reflect"natural" fall rates, which tend to be steeper, more variable, and commonly separated by short periods of rising flows. In order to more accurately describe "natural" fall rates, we performed the recession rate analysis described below.

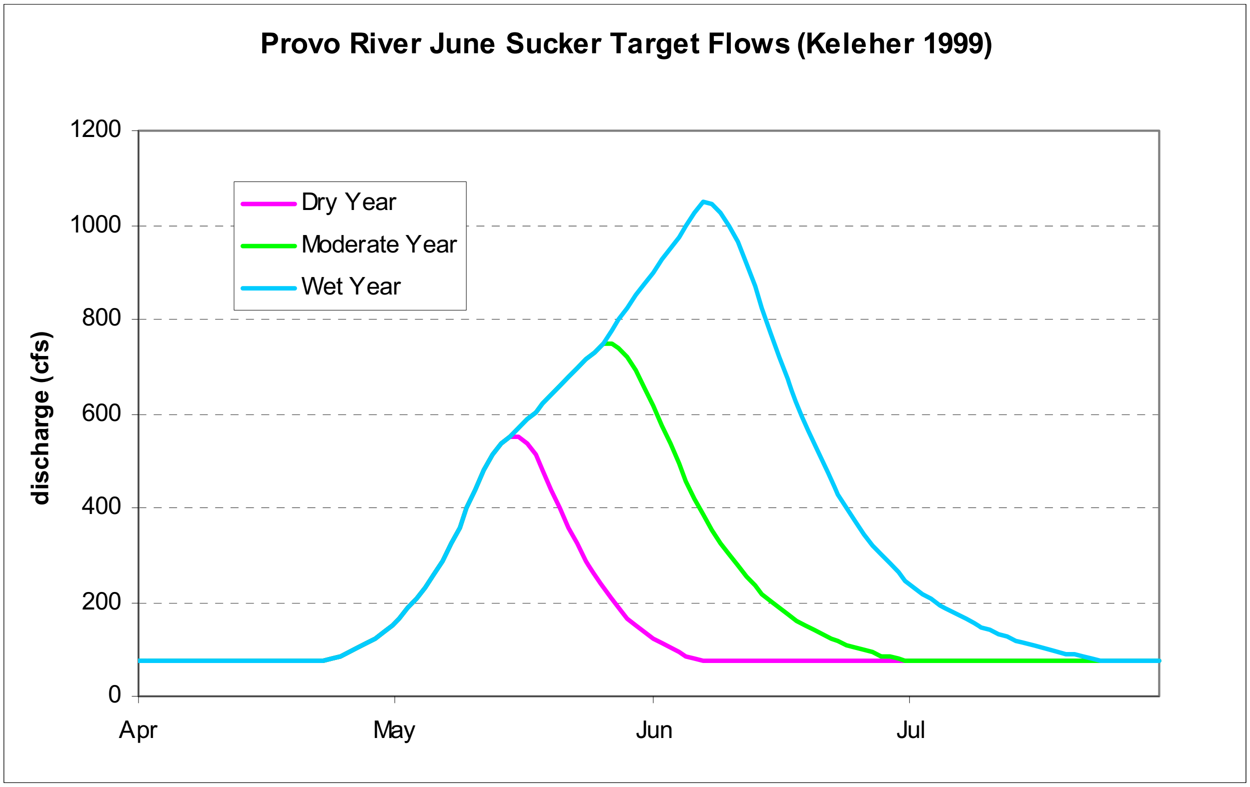


Figure B1. Existing Provo River target hydrographs (Keleher 1999).

The hydrologic data set used for recession rate analysis was originally developed by Keleher (1999). This data consists of daily flows at the Provo River at Hailstone USGS gage (Figure 5.1) that have been "naturalized" by subtracting imported water. The data set includes flows from April 1-July 31 of each year for the years 1950-1994, excluding 1988 and 1989. Data for 1988 and 1989 were not included in the analysis because of problems with negative flow values resulting from the subtraction of water imports from gaged flows.

The final data set was input into the Indicators of Hydrologic Alteration (IHA) software program (TNC 2006) in order to identify low flow periods included within the data set and help isolate the high flow (i.e., snowmelt runoff-affected) component of the data. Within IHA, a non-parametric analysis was completed using IHA default values to define hydrologic parameters and environmental flow components. Version 7 of IHA categorizes each daily flow value into an Environmental Flow Component (EFC). EFC categories include both low ("extreme low flow" or "low flow") and high flows. Rising flows between the 50th-75th percentile flow values as well as any flows above the 75th percentile flow are considered high flows (using the default non-parametric thresholds/definitions). The EFC algorithms classify "high flows" into three categories: high flow pulses, small floods (high flows with return intervals between 2 and 10 years), and large floods (high flows with return intervals of 10 years and greater; see TNC 2006 for more details regarding these parameter definitions). Figure B2 provides a graphical example of how the IHA program separates daily flows into the EFC categories.

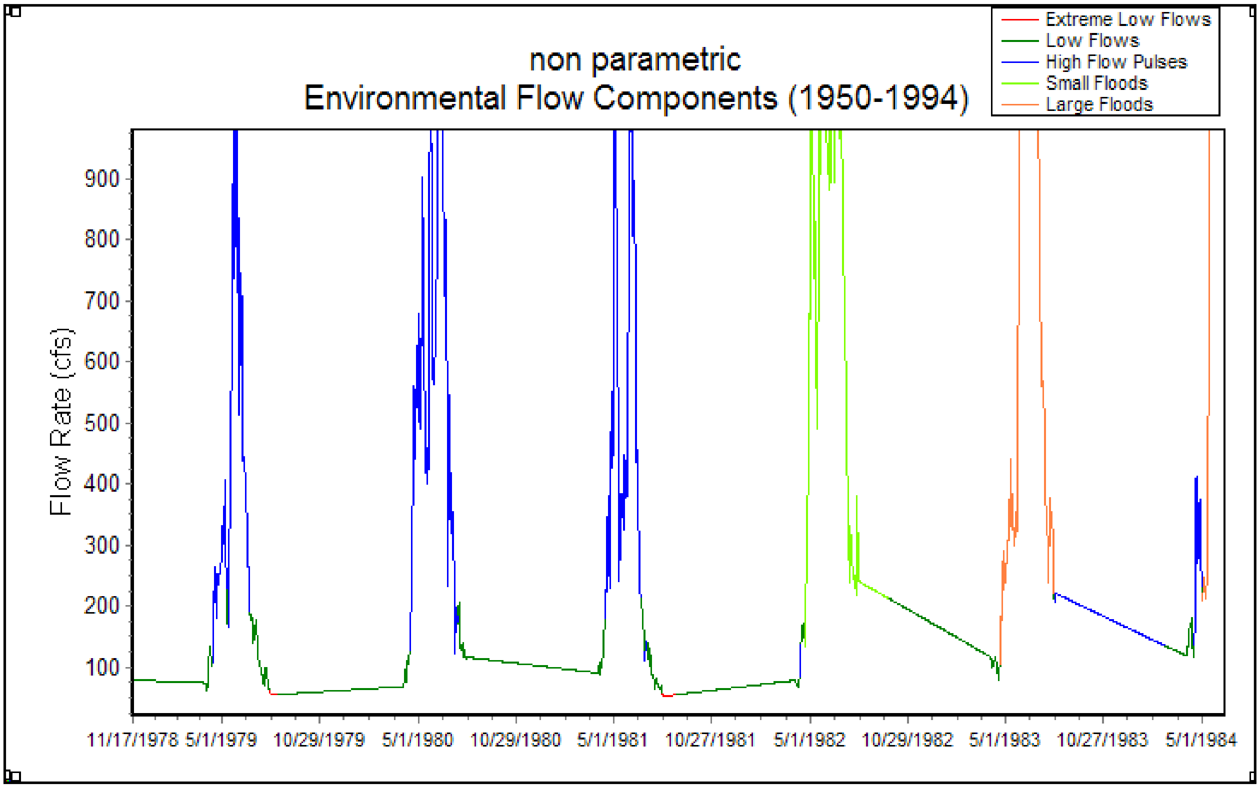


Figure B2. Sample plot of IHA environmental flow components.

Day-to-day fall rates (today's flow value minus yesterday's flow value) were calculated in a spreadsheet. Days identified by the EFC analysis as "low flow" or "extreme low flow" were excluded from further analysis. Average, median, and 75th/25th percentile values of high flow fall rates were then determined. The relationship between fall rate and flow magnitude was also examined (Figure B3).

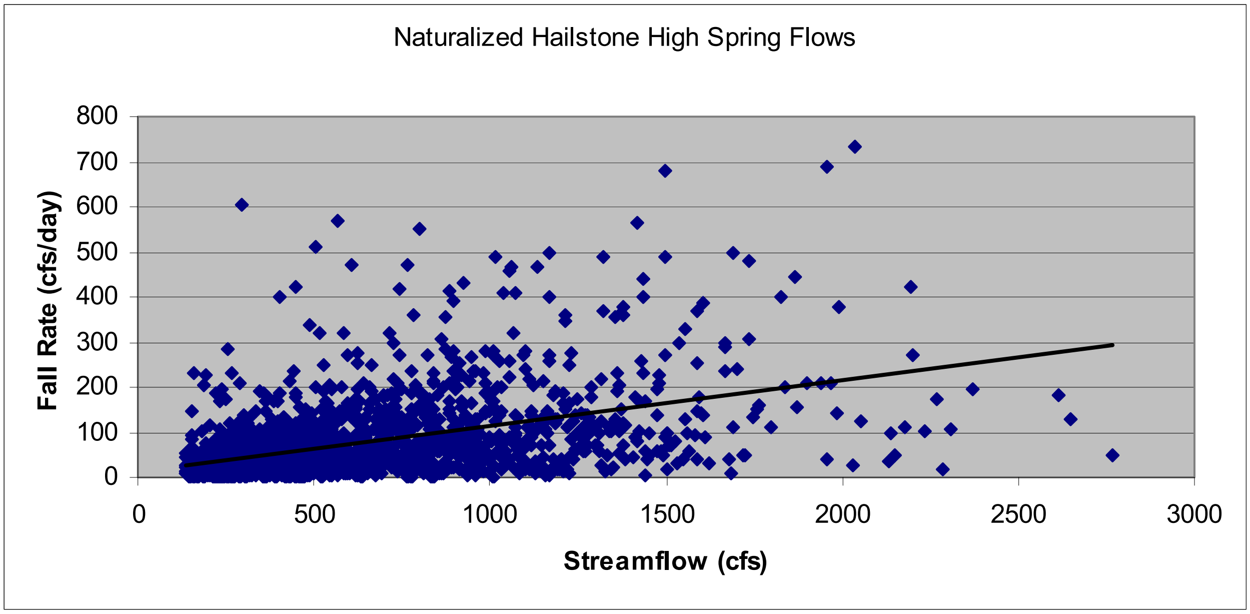


Figure B3. **Plot of streamflow magnitude versus daily recession rate for naturalized Hailstone spring flows identified by IHA as high flows (high flow pulse, small flood, or large flood).**

A separate analysis of recession rates was completed using CUWCD-supplied "natural" Hailstone flows for the years 1996-2006. Hydrograph plots of daily springtime flows and matching plots of the daily rate of change in flow were prepared and visually examined.

Results are summarized in Table B1 and Figures B3 and B4. In general, recession rates are greater when flows are greater. However, there is considerable scatter in the data (Figure B3). The values summarized in Table B1 indicate that fall rates of 60-100 cfs/day are appropriate for flows above 400 cfs, and fall rates of 20-30 cfs are appropriate for flows less than 400 cfs. Values in these ranges are commonly seen in the "naturalized" Hailstone hydrographs (Figure B4). Recession rates of as much as 200-400 cfs/day also occasionally occur for short periods, especially during wet years (Figure B4).

Table B1. Summary of recession rate analysis results.

ending flow	fall rate relative to preceding day (cfs/day)			
	average	25th %	median	75th %
<500 cfs	40	14	28	48
>500 cfs	113	43	84	147
all high flow data	74	20	43	94
<400 cfs	35	14	26	42
400-800 cfs	79	30	60	108
>800 cfs	134	54	100	179

Rising Limb Analysis

The "naturalized" Hailstone gage data were used to examine the rate of change in flow for the rising limb of the hydrograph. These data offer the best guidance for rise rates for the lower Provo River, despite being located many miles upstream, because they eliminate the effects of the two large dams: Deer Creek and Jordanelle. These naturalized data are available only for recent years (1996-2006), so a limited time period is represented in the data, however, a very wide range of hydrologic conditions occurred during the period of record, so the data should capture the range of conditions reasonably well.

The gage data were compiled and changes in discharge were computed. The discharge from a given day was paired with the change in discharge on the following day. The primary point of interest for this analysis is changes that occur during runoff periods, thus the data were filtered to remove all days with streamflow below 200 cfs. The remaining data are shown in Figure B.5.

In order to characterize the data further, they were broken into discharge categories and ranked into percentile groups. This was completed for two discharge breakdowns: the first was for flows between 200 and 500 cfs, and flows over 500 cfs; and the second was for flows between 200 and 400 cfs, flows between 400 and 800 cfs, and flows over 800 cfs. Percentile rankings for these analyses are shown in Table B.2.

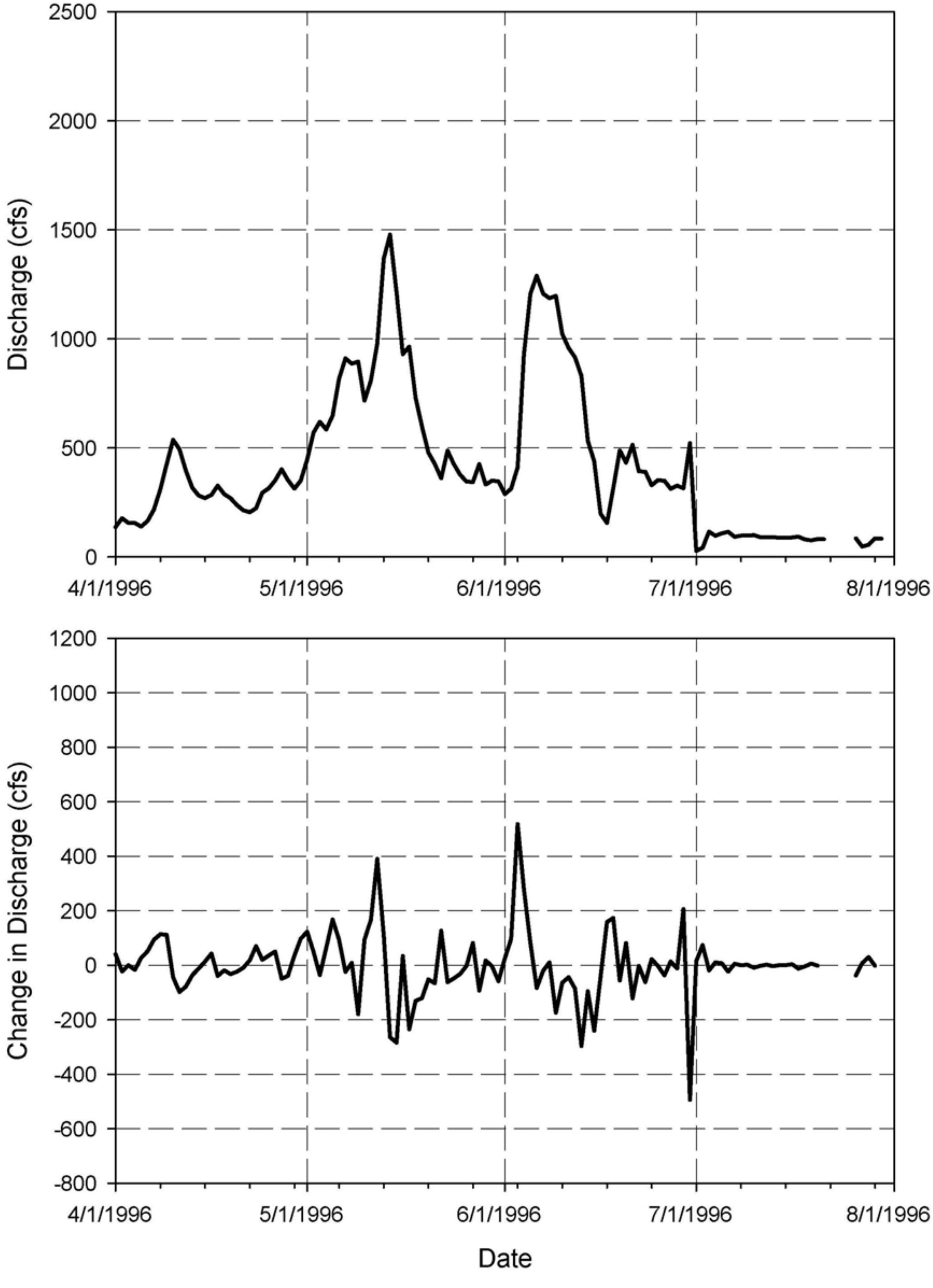


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change.**

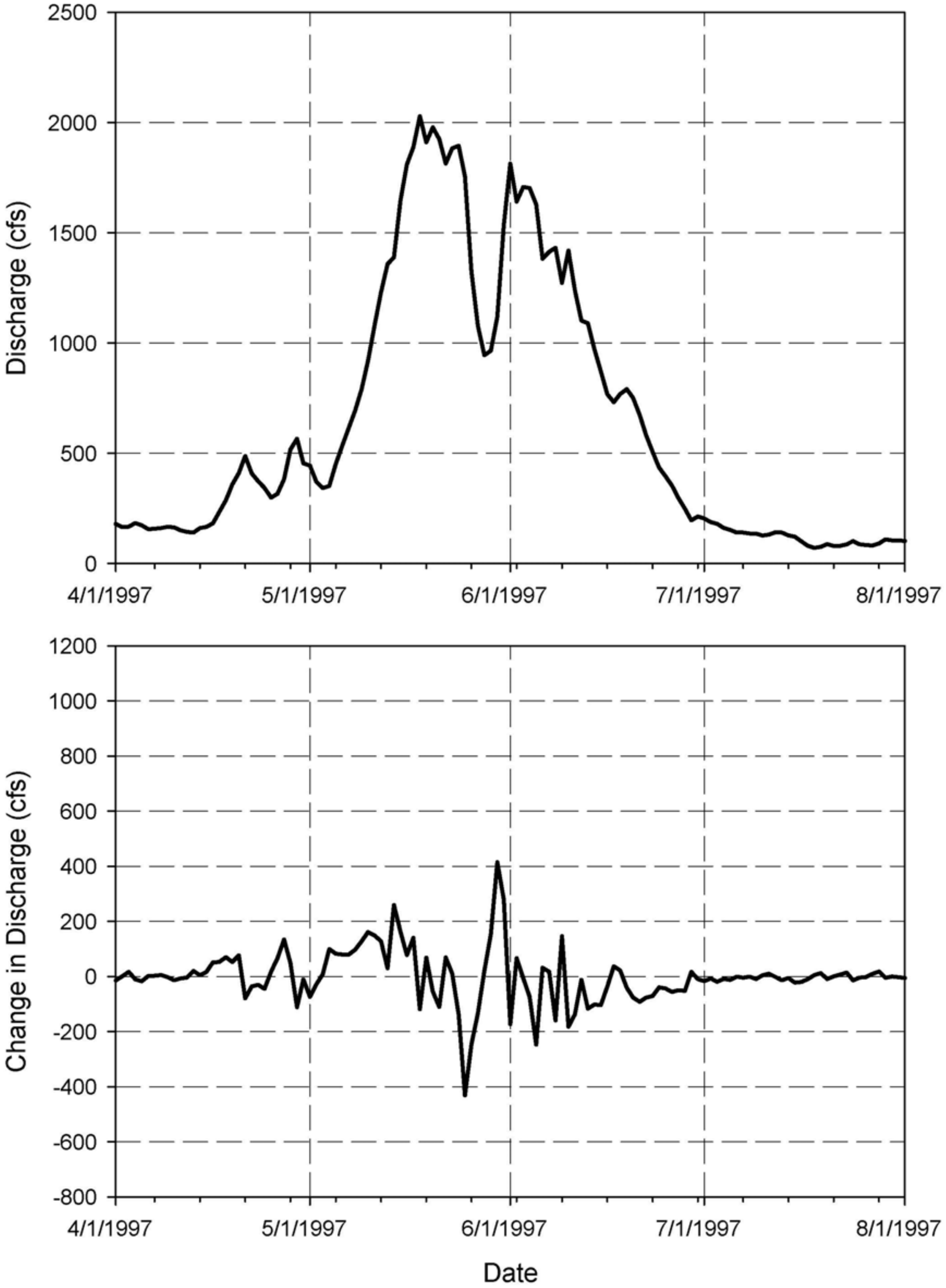


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

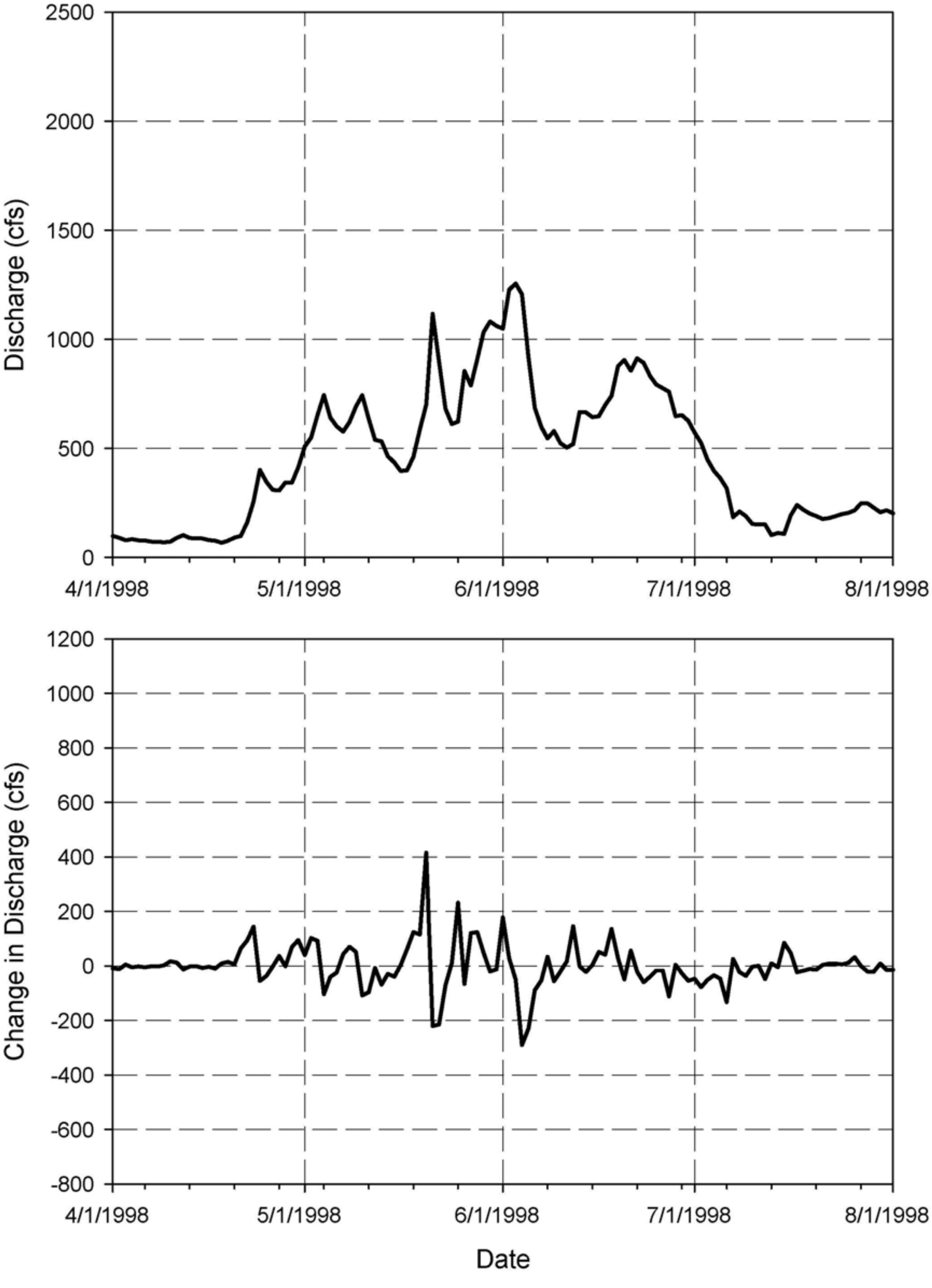


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

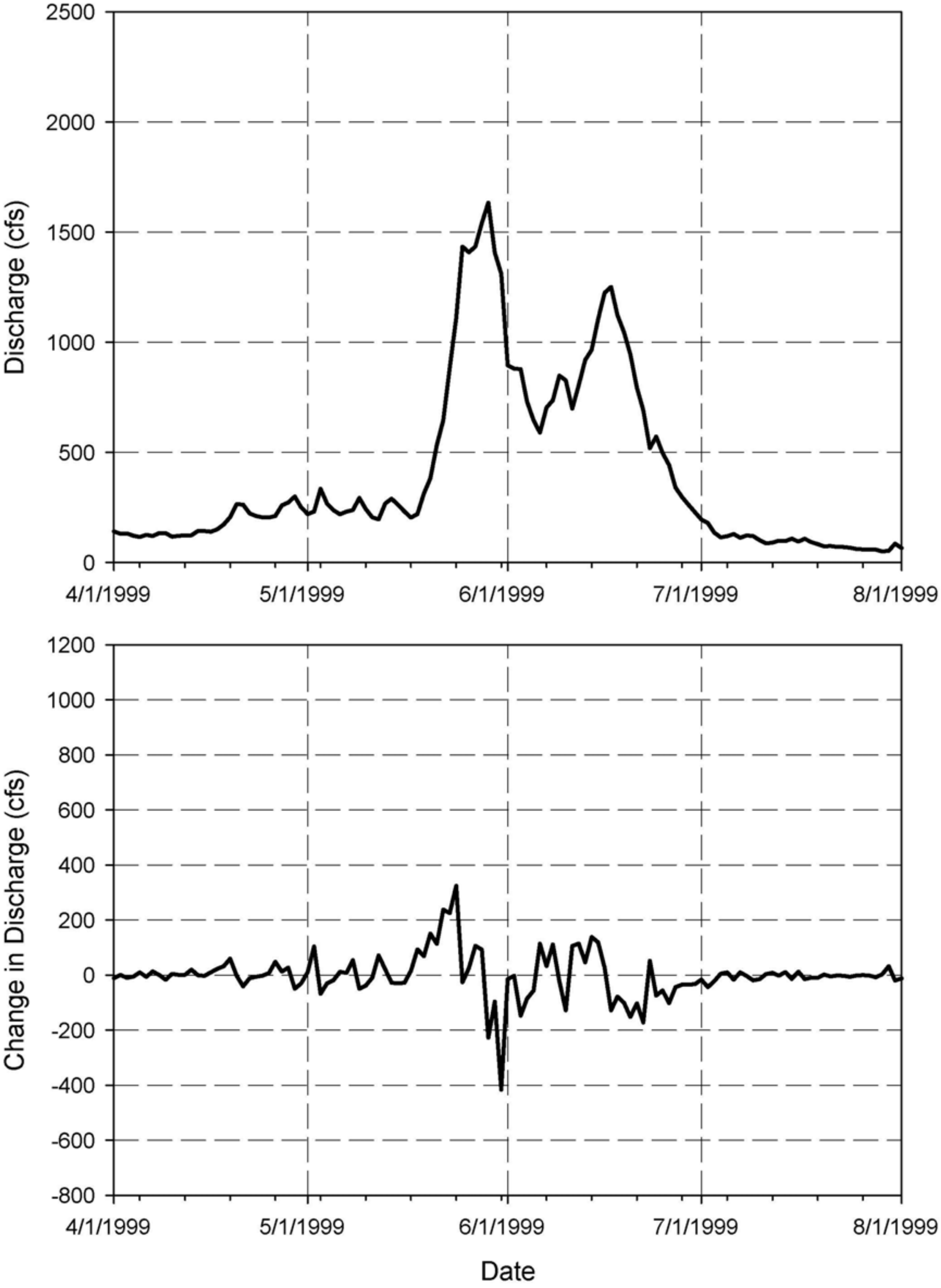


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

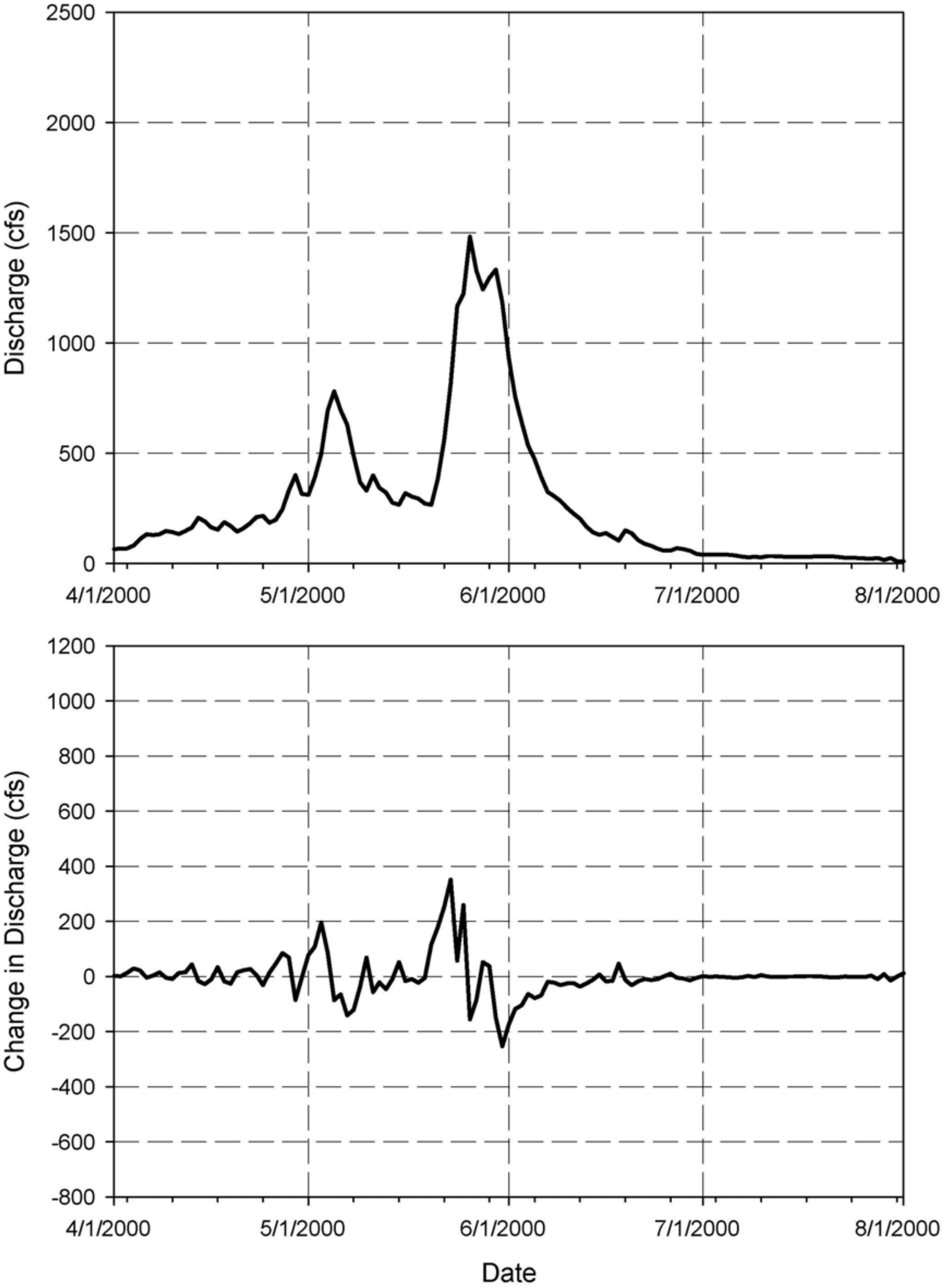


Figure B4. Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).

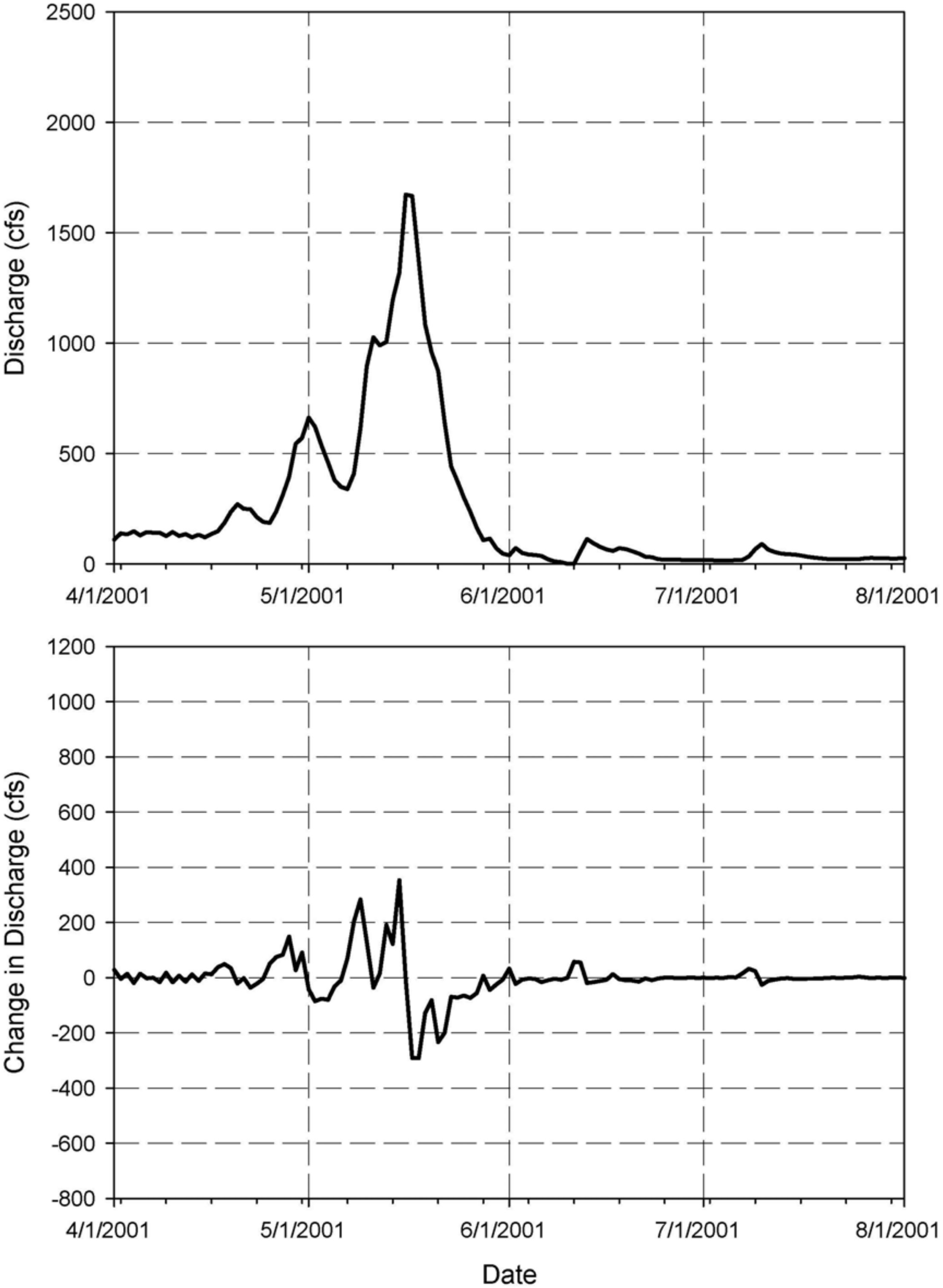


Figure B4. Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).

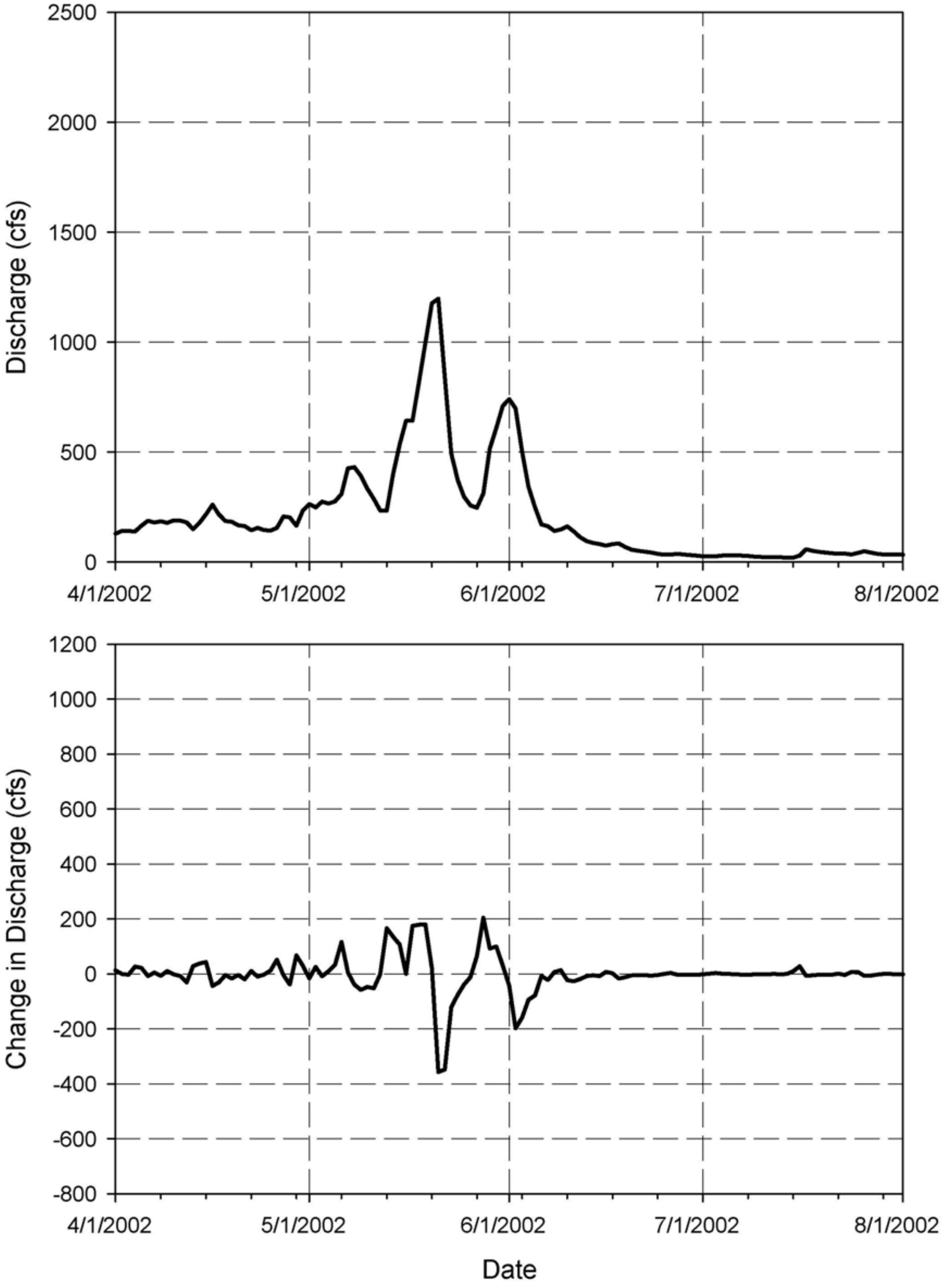


Figure B4. Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).

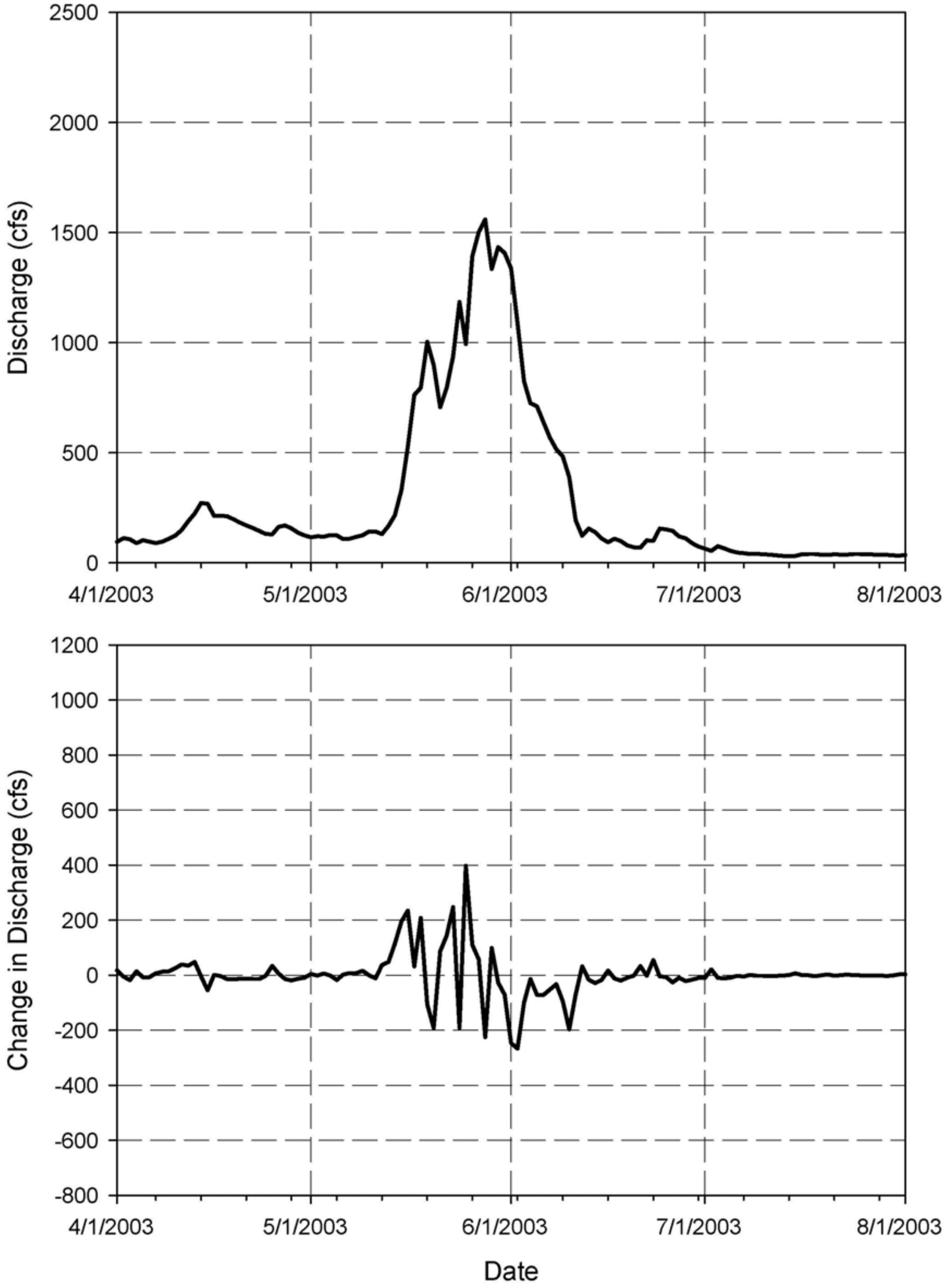


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

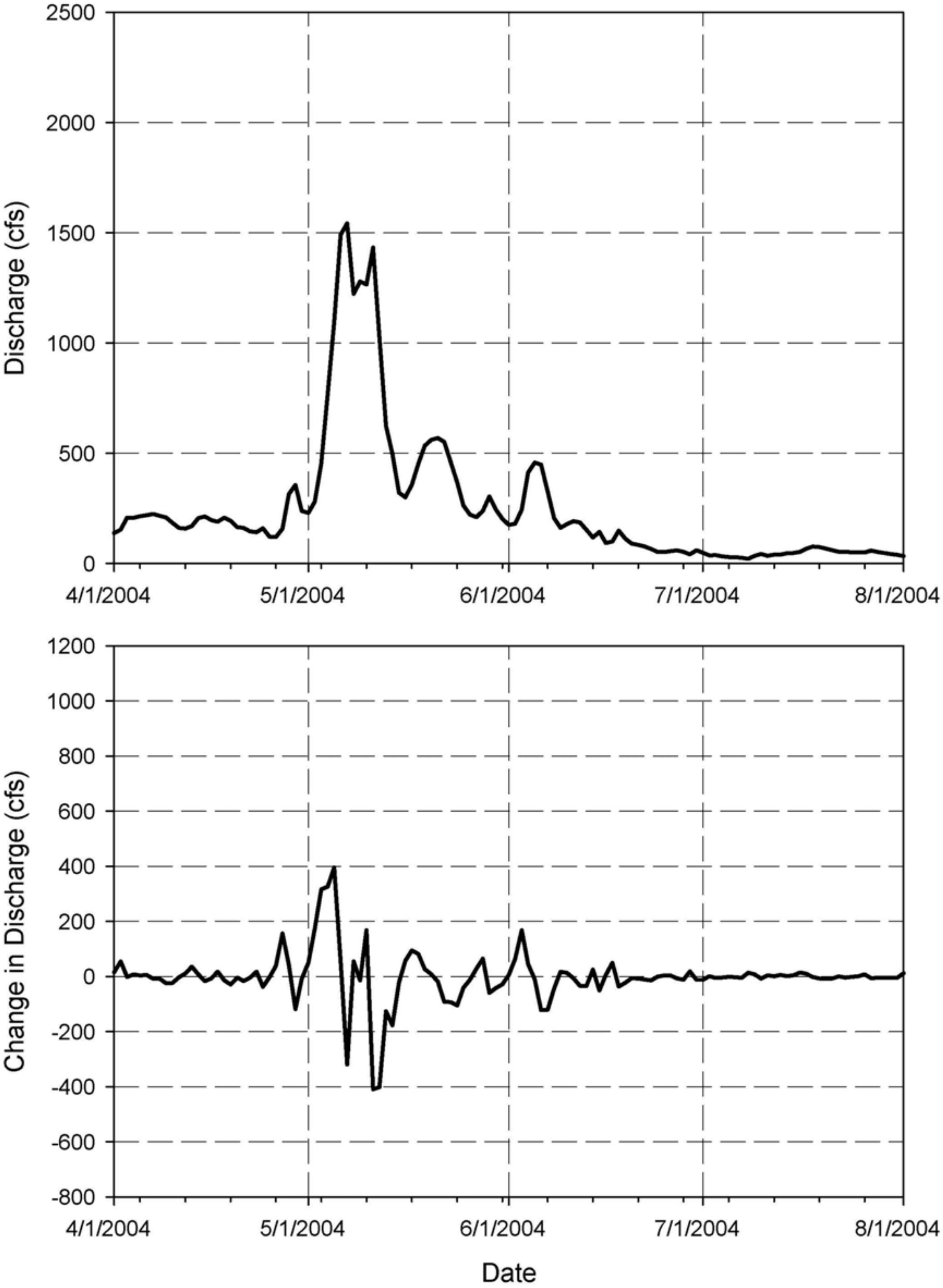


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

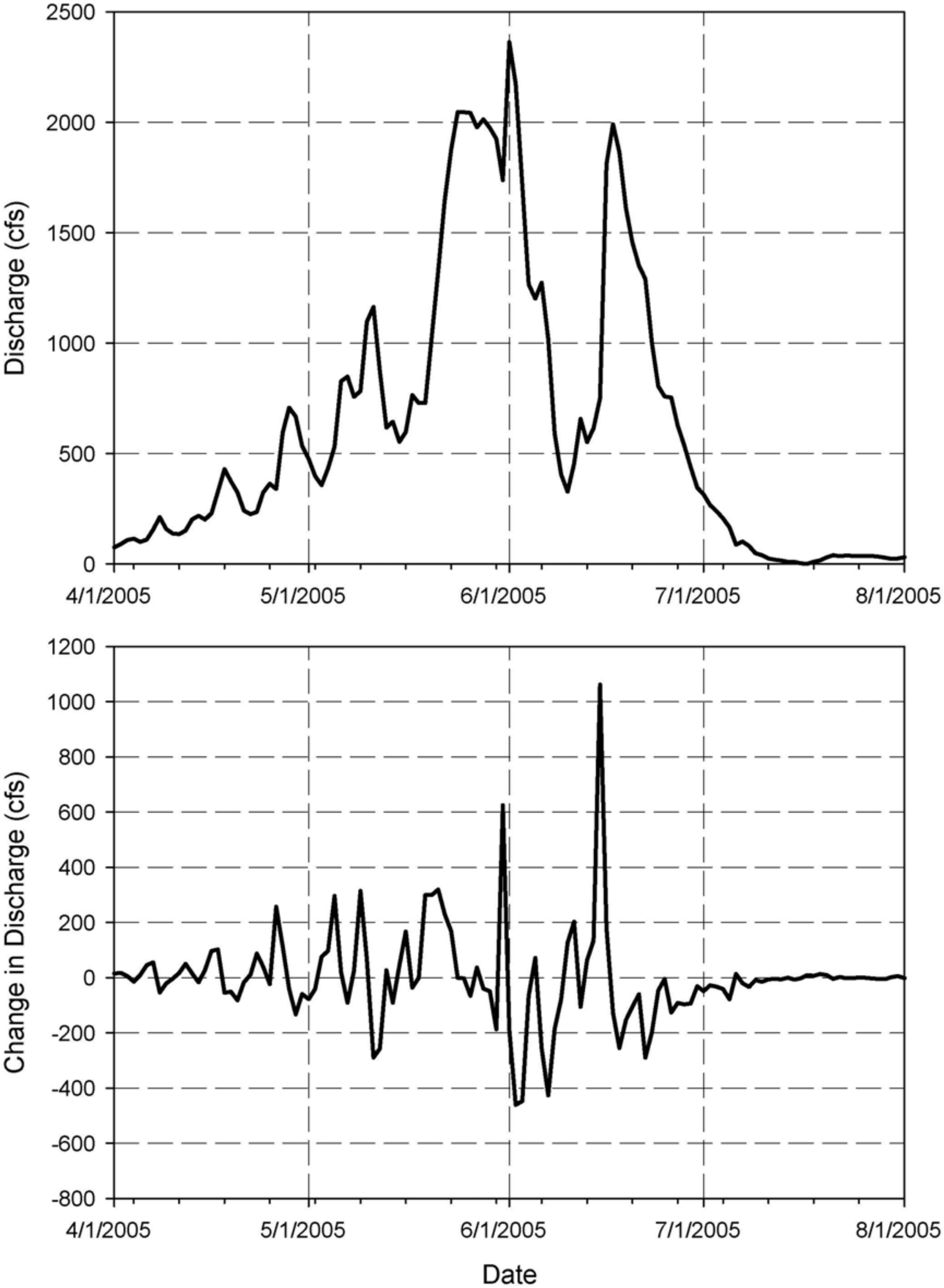


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

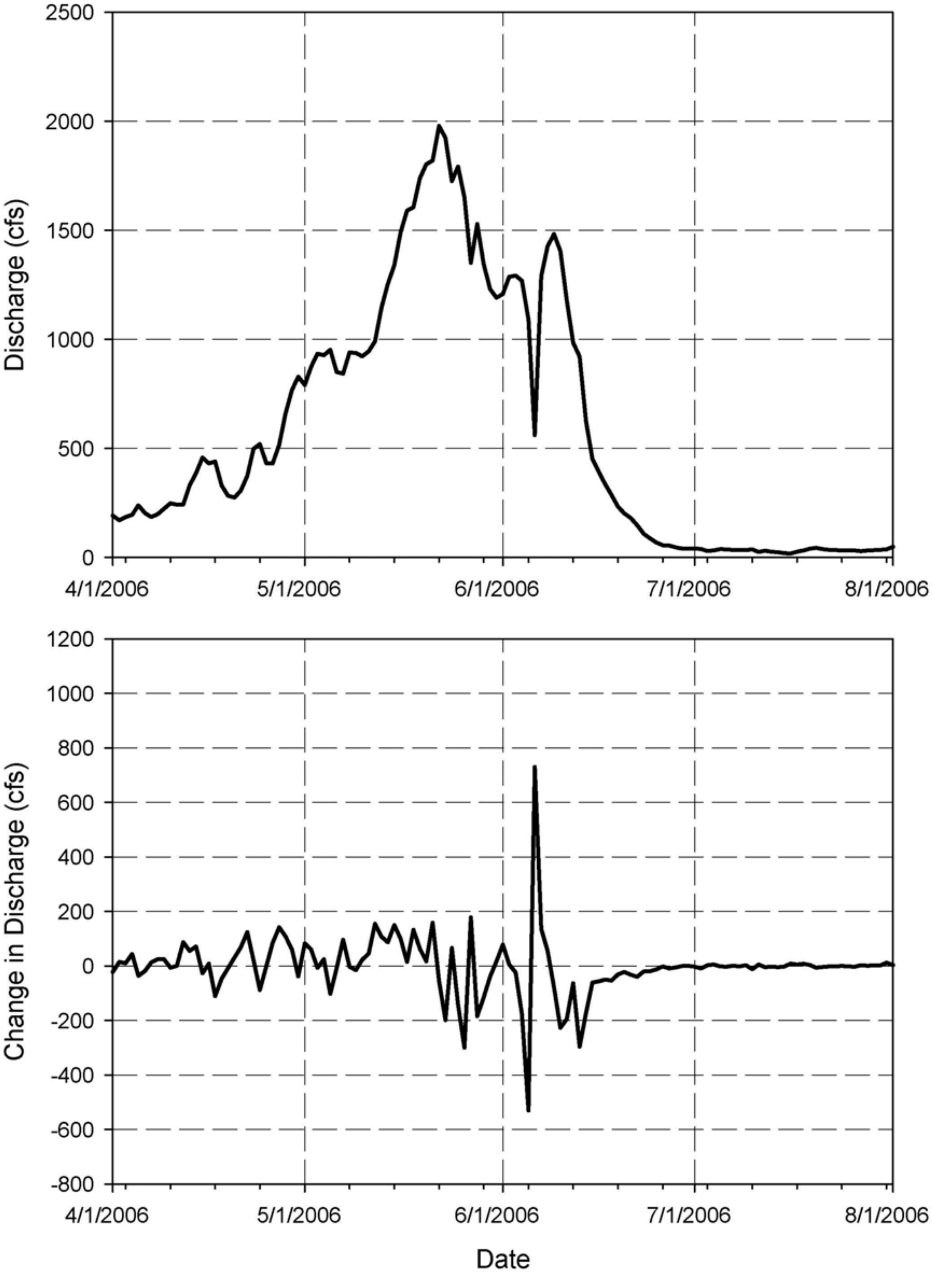


Figure B4. **Naturalized Provo River at Hailstone Spring hydrographs and plots of daily rates of change (cont.).**

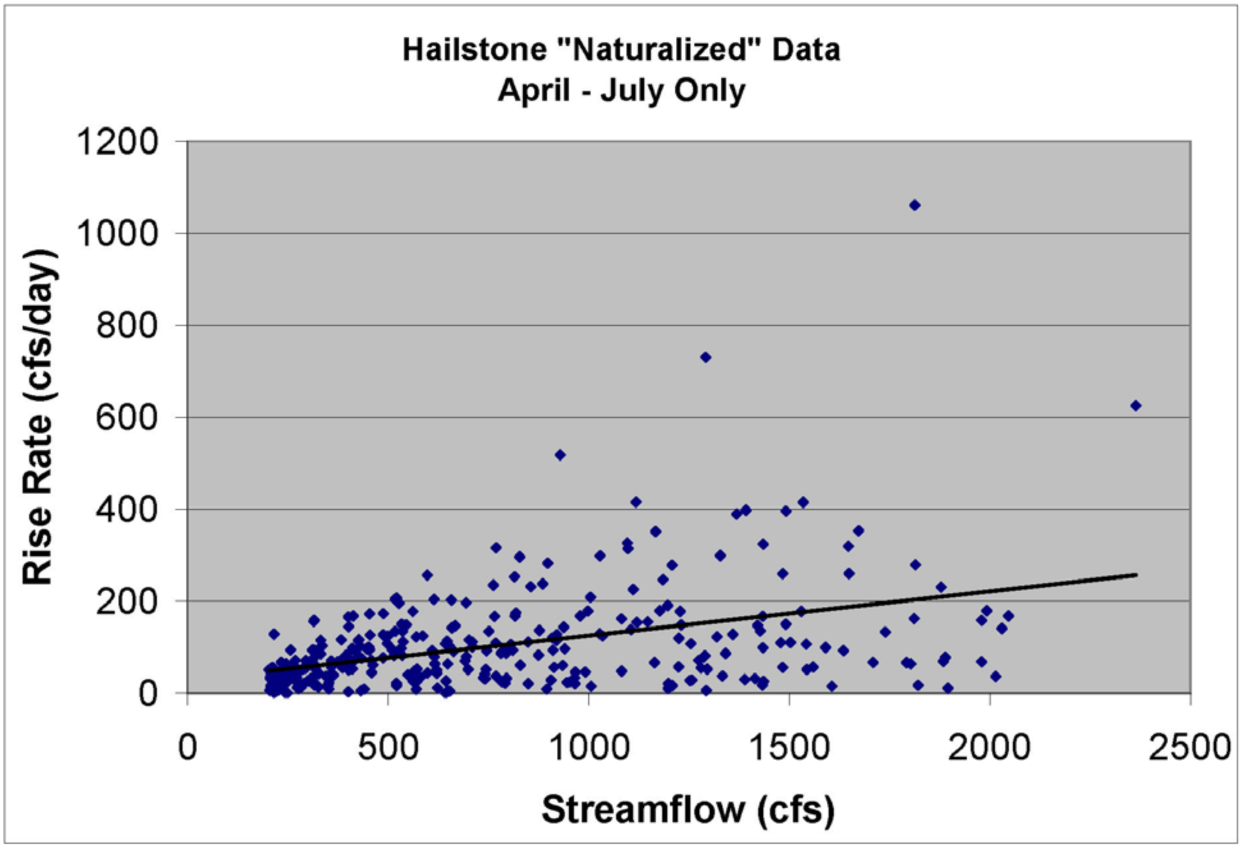


Figure B.5. Plot of streamflow versus rise rate for the Hailstone "naturalized" data for discharges over 200 cfs.

Table B.2. Rising limb change rates and percentile rankings.

	Rise Rate Percentile Groups (cfs/day)			
Discharge (cfs)	Mean	25th	Median	75th
x > 500 cfs	133	50.4	102	168
200cfs > x < 500cfs	55	22	49	75
x > 800cfs	156	56	120	191
400cfs > x < 800cfs	94	50	87	125
200cfs > x < 400cfs	44	18	37	60

Table B.2 clearly demonstrates that rates of increase often occur which are considerably greater than the maximum rate of change that was incorporated in the existing target curves, which was a change of 51 cfs. Although rapid rise and fall rates may not necessarily be desirable, they certainly occur under a natural hydrologic regime and can be incorporated into flow recommendations. Several examples of spring hydrographs at the Hailstone gage are shown in Figure B.4. Note that the positive rates of change in discharge often approach or exceed 400 cfs/day.

The Provo River at Provo, UT gage operated for only a short time before the closure of Deer Creek Dam, however, those data are useful for comparison of rising streamflow rates to the naturalized Hailstone gage data. Figures B.6 and B.7 plot spring hydrographs for the gage at Provo, Utah, along with the rates of change in discharge. Although these data cover a time frame of just two years, the plots clearly show that the rates of change which occurred in the longer record at Hailstone were also present on the lower Provo River before the large dams were constructed.

Table B.2 was used as a guide for instream flow recommendations, but exact values for rates of change were not taken directly from this table because some attenuation of the change rates probably would have occurred historically between the Hailstone gage and the lower Provo River. These data simply demonstrated that higher rates of change were a frequent part of the natural flow condition on the lower Provo River.

Dual Peak Analysis

Data presented in Figure B.4 and other sections of this report have demonstrated that the Provo River often experiences more than one peak in discharge. Examination of the Hailstone gage data shows that these peaks are often separated by several weeks and both peaks can reach high discharge levels. The decision was made to attempt to explore the nature of these peaks and to see if a way could be found to characterize them.

Initial plotting of the Hailstone naturalized hydrographs was completed and proved to be difficult to describe. Several questions existed as to what would constitute a "peak” and what would simply be considered a fluctuating hydrograph. When daily data were used, the fluctuations were so irregular that it was difficult to find any real trends. In order to smooth out the daily bumps and to separate them from the actual peaks, the daily data were averaged for a period of seven days and plotted onto new smoothed hydrographs (example in Figure B.8). Although these plots tended to smooth out some of the daily peaks, characterization of the peaks was still problematic. Table B.3 shows the analyses of the 11-year record for the Hailstone "naturalized" gage. Notice that, in seven of the eleven years, there was a dual peak. These peaks were defined as an initial runoff period with a decline in the seven day average of at least 200 cfs and then another increase. This definition is somewhat arbitrary, but it does allow some characterization to occur. In some years the first peak was the largest, and in other years it was not. The time between peaks averaged almost 20 days or nearly 3 weeks.

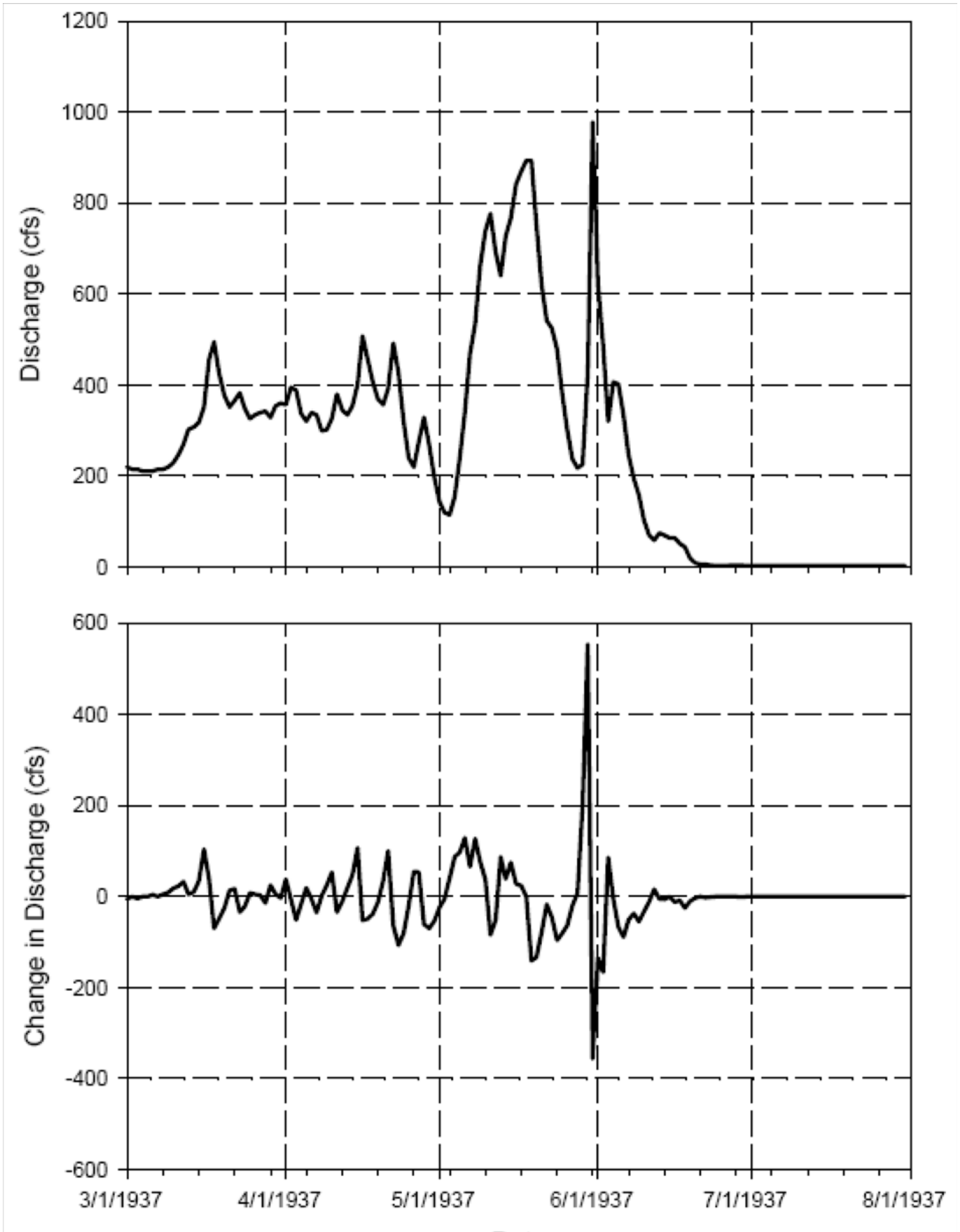


Figure B.6. **Plot of the 1937 spring runoff at the "Provo River at Provo, UT" gage, with rates of change.**

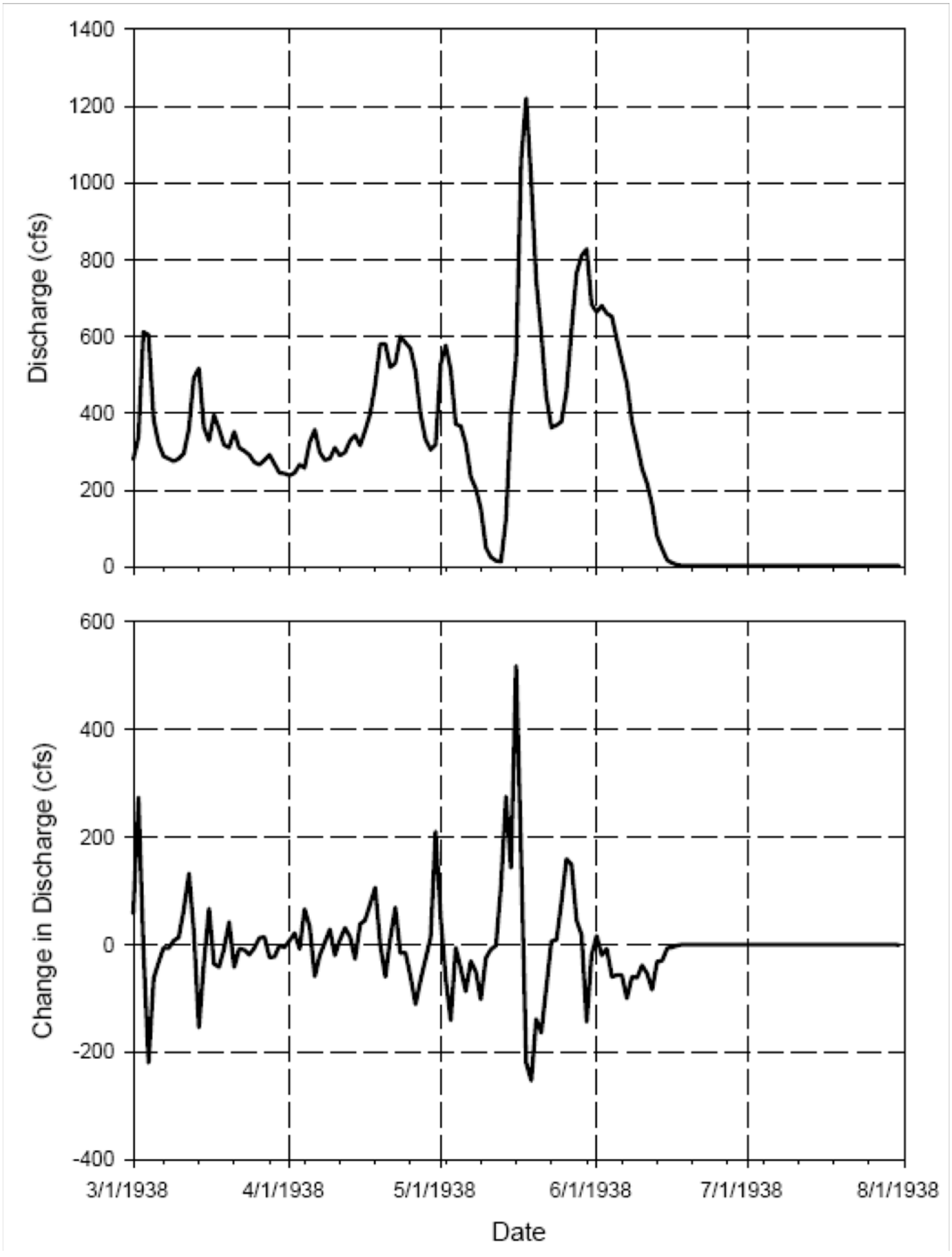


Figure B.7. **Plot of the 1938 spring runoff at the "Provo River at Provo, UT" gage, with rates of change.**

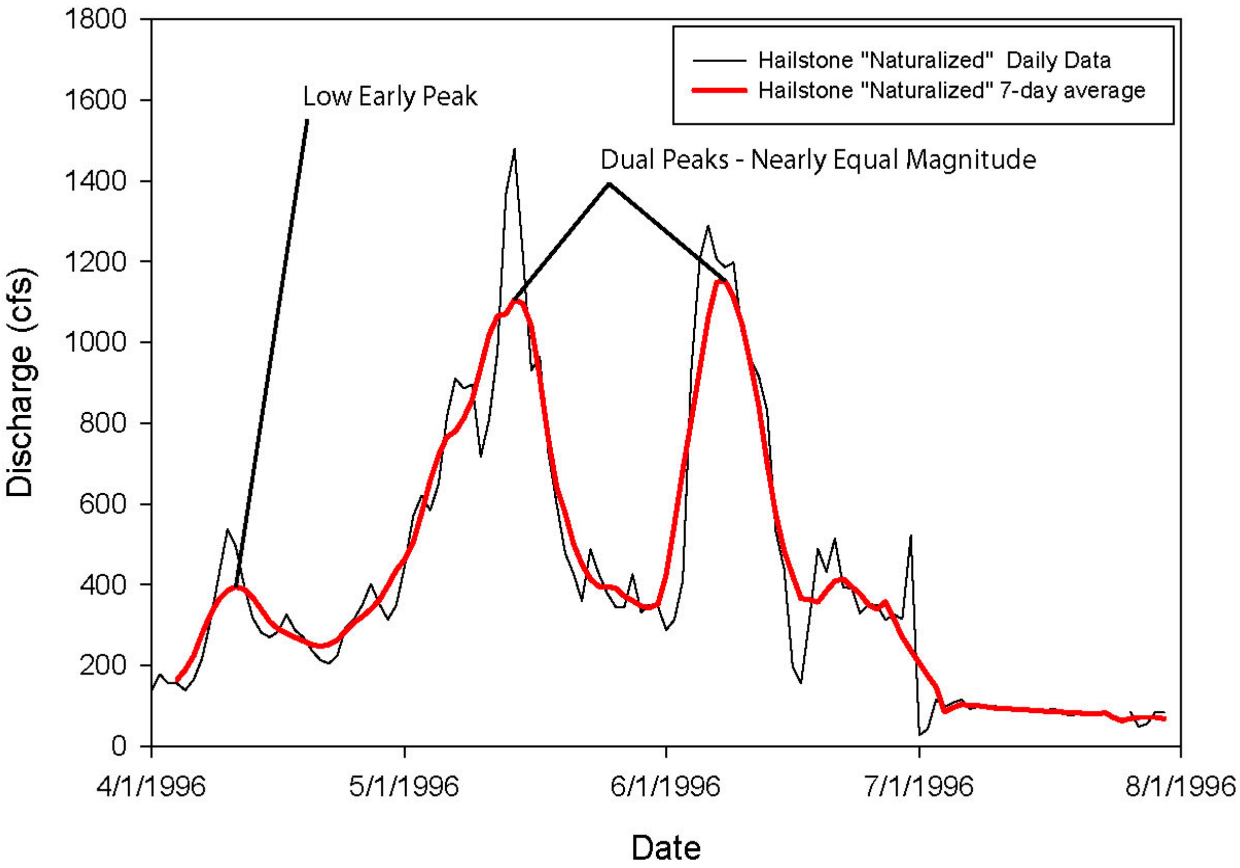


Figure B.8. **Plot of the 1996 spring hydrograph for the naturalized Hailstone data.**

Table B.3. **Analysis of dual peaks - Hailstone naturalized data.**

Year	Peak1 Date	Peak1 Avg (7day)	Peak2 Date	Peak2 Avg (7day)	Days Between
1996	5/14/1996	1106.5	6/8/1996	1152.8	25
1997	5/21/1997	1919.6	6/3/1997	1630.6	13
1998	5/7/1998	660.3	6/1/1998	1131.1	25
1999	5/28/1999	1453.5	6/17/1999	1094.8	20
2000	5/5/2000	596.9	5/28/2000	1298.6	23
2001	5/16/2001	1331.8			
2002	5/19/2002	902.6	6/1/2002	588.8	13
2003	5/29/2003	1423.9			
2004	5/8/2004	1333.5			
2005	5/30/2005	2024.0	6/19/2005	1625.5	20
2006	5/22/2006	1826.2			
				Average ---->	**19.9**

Because the naturalized gage record at Hailstone is very short, additional data was used to help further characterize the peaks. The entire flow record at Hailstone (not naturalized) was examined to see if any additional information could be gleaned. Again, this approach provided little in the way of quantitative information, although some characteristics were identified.

Several major points were identified in this dual peak analysis, some of which are illustrated in Figure B.8: they are;

1. Two or more peaks appear to occur on the Provo River on average during about two-thirds of the years in the period of record,

2. The peaks are often separated by two to three weeks,

3. Any of the peaks can be the largest (no consistent pattern)

4. Many years show an early peak of low magnitude that occurs in April or May.

The biological importance of the multiple peaks on the Provo River is unclear, but organisms that evolved on the river would certainly have needed to adapt to the presence of those peaks, which were almost certainly a regular occurrence.

REFERENCE

[TNC] The Nature Conservancy. 2006. Indicators of Hydrologic Alteration Version 7 User's Manual. 74 p.

APPENDIX C: FLUSHING FLOW, EFFECTIVE DISCHARGE, AND CHANNEL-CHANGING FLOWS IN THE LOWER PROVO RIVER

APPENDIX C: FLUSHING FLOW, EFFECTIVE DISCHARGE, AND CHANNEL CHANGING FLOWS IN THE LOWER PROVO RIVER

Periodic high discharge events (peak flows) are important in natural rivers for many purposes. First, peak flows of a certain magnitude and duration flush accumulated fine sediments from the streambed and “clean” potential spawning substrates. Fine sediments such as sand and silt accumulate on the streambed during the summer and winter low flow months, and then are washed downstream when peak flows exceed transport thresholds. Second, peak flows are also important to maintain channel capacity and to prevent encroachment of riparian vegetation within the established bankfull dimensions and geometry. Channel dimensions are largely controlled by fairly regular peak flow events, that if added up over a long period of time, transport more sediment than higher magnitude yet less frequent events. Third, occasional higher peak flows that overtop streambanks and are powerful enough to break up the armored surface layer of the streambed are important to maintain channel dynamics (i.e., meander migration and floodplain development) and maintain the lateral connectivity between the channel and floodplain components of the ecosystem. Channel dynamics are important for riparian vegetation recruitment and creation of substrate patches and vegetation mosaics on bar and floodplain features. Channel dynamics are also important for the creation of micro-topographic features adjacent to the main river channel such as side channels and oxbows which support many types of aquatic and terrestrial wildlife.

Flushing Flows

In 1995 and 1996 BIO-WEST developed “flushing flow” recommendations for the lower Provo River (Olsen et al, 1996) to determine the magnitude and duration of peak flows that would effectively clean spawning gravels in early spring in preparation for the June sucker spawn. The studies included bedload transport measurements, substrate monitoring, and evaluations of algae and periphyton growth rates. The results of this study show that flows that exceed 700 cfs are high enough to move gravel and some cobble, and effectively flush sand and silt from known June sucker spawning substrate in the lower Provo River. The flushing flow study recommends flows greater than 700 cfs occur for a duration more than three consecutive days. The recommendations conclude that peak flows of 700 cfs should occur fairly often with a return interval of two out of every three years on average to maintain spawning substrate without becoming overly embedded.

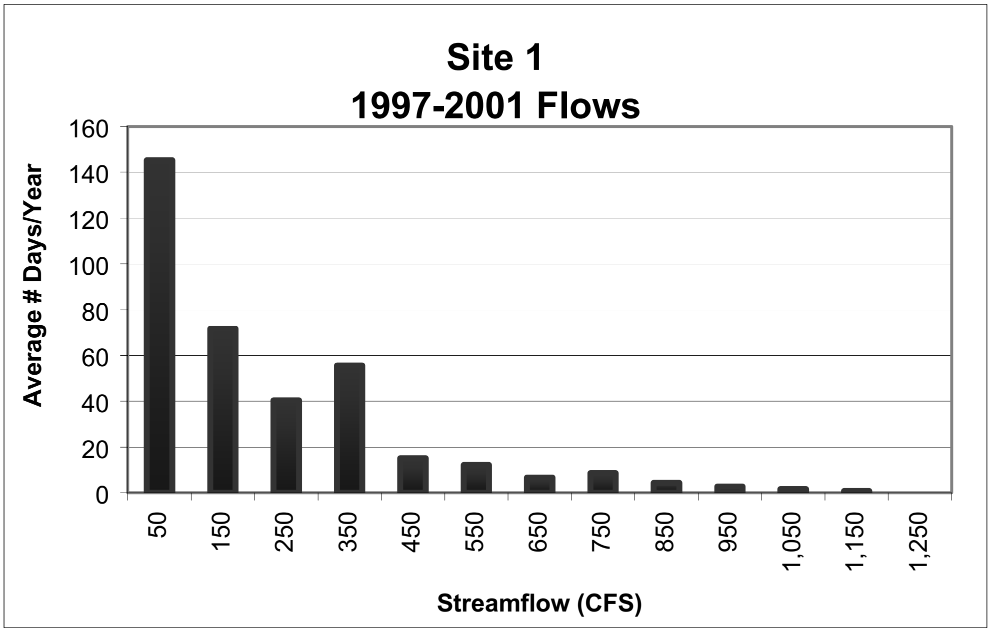
Effective Discharge

In 2002 BIO-WEST performed additional sediment sampling and analysis in the lower Provo River for the purpose of evaluating the geomorphic effects of alternative flow regimes (Olsen et al. 2003). Flow duration information was categorized into 100 cfs increments (0-100, 100-200, etc.) and bedload transport was calculated at the mid-point of each flow increment (50, 150, etc.) using modeled bedload rating curves (Olsen et al, 2003). The number of days per year each flow increment occurred was multiplied by the corresponding bedload transport rate to determine the average annual sediment load for each 100 cfs increment. Sediment loads were then graphed to determine the increment of discharge that transports the most bedload sediment over the period of record and identify the effective discharge.

Effective discharge calculations show a single peak (flow increment transporting the greatest sediment loads over the past five years) between 700-800 cfs at Site 1 (Figure C1). The majority of the year (90% of the time) is dominated by flows less than 500 cfs with no bedload transport. Flows between 700-800 cfs only occur approximately 9 days per year (2% of the time) but have transported the most bedload sediment over the past 5 years. Flows greater than 800 cfs occur less frequently at Site 1 (see Figure 5.2 for Site 1 location) and even though they have a higher daily transport rate, are less and less effective as their occurrences decline.

Channel-Changing Flows

Channel-changing flows were evaluated for this report using study sites and available information from the Flushing Flow and Provo River Flow Studies (Olsen et al, 1996 and 2003). Substrate particle size distributions, channel geometry, and hydraulic conditions during a range of flows (500 to 2,000 cfs) were determined for this study at Sites 1 and 2 (Figure 5.2). Shear stress calculations (tau = pgRS) were made based on the available information at these two study sites, where tau is measured in Newtons per square meter, p is the density of the flow, g is acceleration due to gravity, R is the hydraulic radius, and S is the water surface slope. Shear stress represents the frictional force, per unit area, causing flow resistance along the streambed. This evaluation calculated mean cross sectional shear stress over the streambed at 100 cfs increments from 500 to 2,000 cfs.



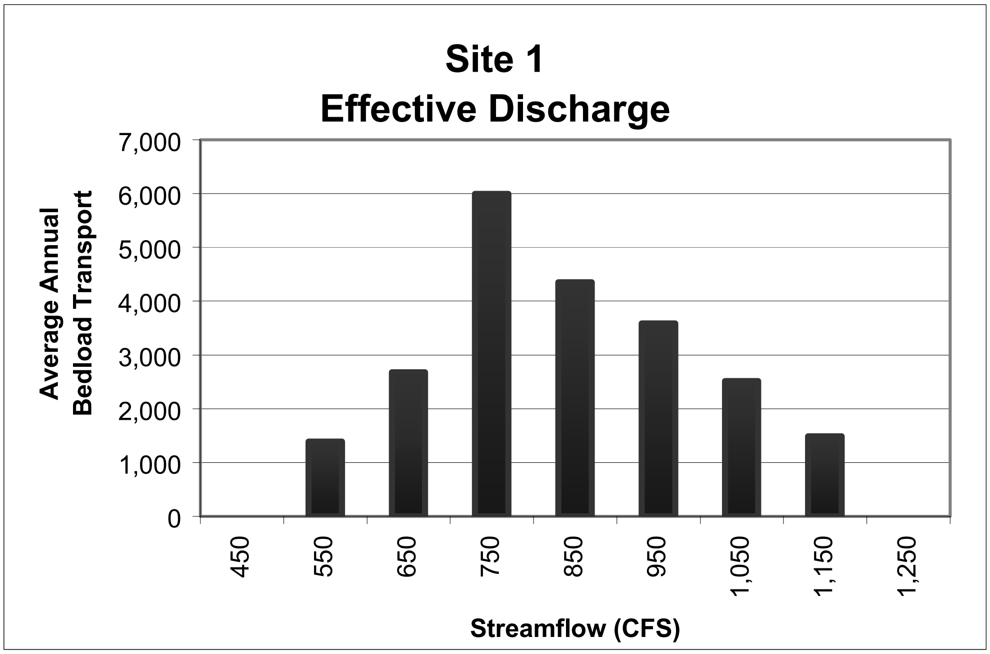


Figure C1. **Effective Discharge Results for Site 1. The upper graph shows the average number of days per year streamflow has been within each 100 cfs increment (0-100, 200-300, etc.). The lower graph applies the modeled bedload transport rate multiplied by the number of occurrences to determine the streamflow that transports the most bedload sediment over the period analyzed.**

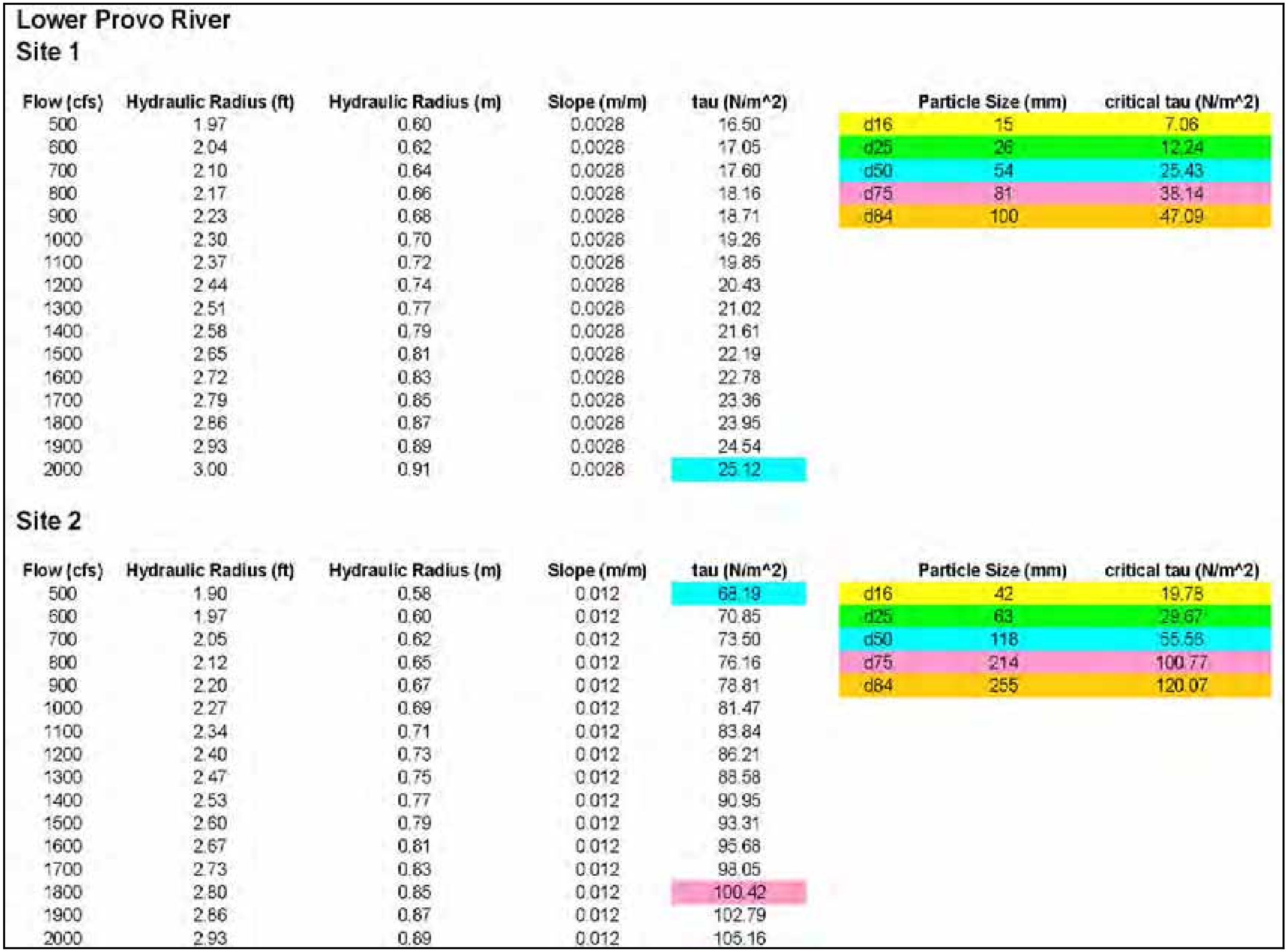
The next step in this evaluation was to determine the threshold at which forces acting on the streambed (tau) will begin to transport bed material of different sizes (i.e., D_{16}, D_{50}, and D_{84}). The selected incipient motion equation used in this evaluation relates critical shear stress (tau_{ci}) to the size of the largest particle that can be put into motion at a given discharge. The Shields criterion (Shields 1936) is the classic means of predicting thresholds of bedload initiation:

$tau_{ci} = tau_{ci}^{*} (p_s\text{-}p)gD_i$

where tau_{ci} and tau_{ci}^{*} represent the critical dimensional and dimensionless streambed shear stress, respectively, to entrain a particle of diameter D_i. The p_s and p represent densities of sediment and water, respectively, and g is acceleration due to gravity. Work in gravel bed streams has shown that the value of tau_{ci}^{*} , the critical dimensionless shear stress, varies as a function of both absolute particle size, and the relative size compared with larger and smaller particles also present on the streambed. The dependence of critical dimensionless shear stress on relative particle size is explained in terms of particle hiding and exposure. Particles larger than the median size are relatively more exposed due to their greater protrusion from the streambed, and hence are more easily entrained than would be the case in uniform sized sediments. The converse is true for particles smaller than the median size, which remain relatively hidden in the streambed matrix. The critical dimensionless shear stress value used for this evaluation was set at 0.03 for all calculations. The standard critical dimensionless shear stress value of 0.045 for homogeneous sediments was not used for this evaluation as it does not take into consideration the protrusion of mixed sized particles. Channel change is not expected unless particles larger than the D50 are predicted to become mobilized.

The results of this evaluation (Table C1) show that motion of the D50 occurs at different flows between Sites 1 and 2. At Site 2, the channel is much steeper and more confined and the D50 moves at flows less than 500 cfs. You could expect that the channel would be susceptible to change at flows exceeding 500 cfs at Site 2 if the banks were not hardened and leveed. The D75 is predicted to move when flows exceed 1,800 cfs. Movement of the larger bed fractions such as the D75 would likely result in some channel changes even in this highly controlled reach. At Site 1, channel changing flows are not predicted to occur until flows exceed 2,000 cfs.

Table C1. Shear stress and critical shear stress calculations for Sites 1 and 2 of the lower Provo River.



Lower Provo River

Site 1

Flow (cfs)	Hydraulic Radius (ft)	Hydraulic Radius (m)	Slope (m/m)	tau (N/m^2)
500	1.97	0.60	0.0028	16.50
600	2.04	0.62	0.0028	17.05
700	2.10	0.64	0.0028	17.60
800	2.17	0.66	0.0028	18.16
900	2.23	0.68	0.0028	18.71
1000	2.30	0.70	0.0028	19.26
1100	2.37	0.72	0.0028	19.85
1200	2.44	0.74	0.0028	20.43
1300	2.51	0.77	0.0028	21.02
1400	2.58	0.79	0.0028	21.61
1500	2.65	0.81	0.0028	22.19
1600	2.72	0.83	0.0028	22.78
1700	2.79	0.85	0.0028	23.36
1800	2.86	0.87	0.0028	23.95
1900	2.93	0.89	0.0028	24.54
2000	3.00	0.91	0.0028	25.12

	Particle Size (mm)	critical tau (N/m^2)
d16	15	7.06
d25	26	12.24
d50	54	25.43
d75	81	38.14
d84	100	47.09

Site 2

Flow (cfs)	Hydraulic Radius (ft)	Hydraulic Radius (m)	Slope (m/m)	tau (N/m^2)
500	1.90	0.58	0.012	68.19
600	1.97	0.60	0.012	70.85
700	2.05	0.62	0.012	73.50
800	2.12	0.65	0.012	76.16
900	2.20	0.67	0.012	78.81
1000	2.27	0.69	0.012	81.47
1100	2.34	0.71	0.012	83.84
1200	2.40	0.73	0.012	86.21
1300	2.47	0.75	0.012	88.58
1400	2.53	0.77	0.012	90.95
1500	2.60	0.79	0.012	93.31
1600	2.67	0.81	0.012	95.68
1700	2.73	0.83	0.012	98.05
1800	2.80	0.85	0.012	100.42
1900	2.86	0.87	0.012	102.79
2000	2.93	0.89	0.012	105.16

	Particle Size (mm)	critical tau (N/m^2)
d16	42	19.78
d25	63	29.67
d50	118	55.58
d75	214	100.77
d84	255	120.07

APPENDIX D: SUMMARY OF HYDRAULIC HABITAT NICHE RESULTS

SUMMARY OF HYDRAULIC HABITAT NICHE RESULTS

BIO-WEST conducted an evaluation of the relationships among streamflow and various ecological processes and conditions of the Provo River from Jordanelle Dam to Utah Lake in 2002 (Olsen et al. 2003). This effort resulted in modeling tools that can be used to evaluate the ecological effects of various streamflow regimes. With the resulting models, the effects of different flow regimes can be determined on the individual ecological components of the Provo River system. This includes aquatic habitat (for fish), channel processes, sediment transport, riparian vegetation, water quality, and recreational usability.

From the aquatic habitat perspective, different discharge values within a given river reach can be used to determine the anticipated amount of suitable habitat to many fish species individually as well as various life stages of certain species. Although data availability at the time of the model development was sufficient for some species to permit development of individual habitat suitability criteria, many species did not have the requisite data. As such, a niche approach was used where species were grouped into a habitat classification (e.g., moderate/shallow habitat) using the best available information to determine habitat use. A cluster analysis by Belk and Elsworth (2000) assisted in niche classification for species with limited habitat use data. Eight habitat niches were selected with individual species and life stages placed into categories with high suitability (Table D1) (see Olsen et al. 2003 for more detail on niche characteristics and placement of species within niches).

The results from Study Site 1 (approximately 2 miles upstream of Utah Lake) are most critical for spawning June sucker. The availability of June sucker spawning habitat is maximized at approximately 200 cfs (Figure D1), but this observation is limited by inability to sample/observe spawning adults in the river at higher flow conditions. The Utah Division of Wildlife Resources samples spawning adults and larvae using a variety of methods (trap-nets, spotlighting, snorkeling, and light-trapping) but cannot determine spawning success in years when flow is high (UDWR 2005). Thus, suitable habitat for spawning may be in higher abundance at higher flows than is predicted by this model, but the current sampling methods for the spawning run are not conducive to such modifications in the suitability curve.

The availability of the various habitat niches in Site 1 over a discharge range of 0-100 cfs is presented in Figure D2. Niches 4 and 6-8 (higher flow conditions and deeper habitats) do not occur within this range of flow conditions. Niches 6 and 7 are primarily occupied by adult mountain sucker, adult mountain whitefish, and adult Utah sucker. Niche 4 is used primarily by mountain sucker adults and mottled sculpin. Niche 8 is not within the high suitability range for any species. Niches 1 and 2 (important to early life stages of most species and adults of some native fish species) peak at a very low discharge value since these are low velocity, backwater habitats that occur in this channelized area only when flows are very low. Niches 3 and 5 (moderate/shallow and moderate/mid-depth, respectively) include habitat that is suitable for a large proportion of the species in the Provo River including spawning habitat for June sucker

Table D1. Habitat niches and the species and life stages associated with each as determined during model development of the Provo Flow Study. Some species, those with more general habitat requirements, were placed in multiple niches as indicated with "partial" and the list of niches occupied in the "use" column.

Niche	Species	Lifestage	Use
(1) Backwater / Edge	mountain whitefish	fry	Partial (1,5)
	mountain sucker	YOY	Full
	Utah sucker	YOY	Full
	speckled dace	YOY	Full
	longnose dace	YOY	Full
	leatherside chub	adult, juvenile, YOY	Full
	redside shiner	adult, juvenile, YOY	Full
(2) Slow / Shallow	brown trout	spawning	Partial (2,3,5)
	all trout	juvenile, fry, spawning	Partial (2,3,5)
	mountain sucker	adult	Partial (2,3,4,5,6)
	mottled sculpin	adult, juvenile	Partial (2,3,4)
	mottled sculpin	YOY	Full
	speckled dace	adult	Partial (2,3)
	speckled dace	juvenile	Full
	longnose dace	adult	Partial (2,3,5)
	longnose dace	juvenile	Full
(3) Moderate / Shallow	brown trout	spawning	Partial (2,3,5)
	all trout	juvenile, fry, spawning	Partial (2,3,5)
	mountain sucker	adult	Partial (2,3,4,5,6)
	mottled sculpin	adult, juvenile	Partial (2,3,4)
	speckled dace	adult	Partial (2,3)
	longnose dace	adult	Partial (2,3,5)
(4) Fast / Shallow	mountain sucker	adult	Partial (2,3,4,5,6)
	mottled sculpin	adult, juvenile	Partial (2,3,4)
(5) Moderate / Mid-depth	brown trout	adult, juvenile, fry	Full
	brown trout	spawning	Partial (2,3,5)
	all trout	adult	Full
	all trout	juvenile, fry, spawning	Partial (2,3,5)
	June sucker	spawning	Full
	mountain whitefish	adult	Partial (5,7)
	mountain whitefish	juvenile, spawning	Full
	mountain whitefish	fry	Partial (1,5)
	mountain sucker	adult	Partial (2,3,4,5,6)
	Utah sucker adult - partial	adult	Partial (5,7)
	Utah sucker	juvenile	Full
	longnose dace	adult	Partial (2,3,5)
(6) Fast / Mid-Depth	mountain sucker	adult	Partial (2,3,4,5,6)
(7) Moderate / Deep	mountain whitefish	adult	Partial (5,7)
	Utah sucker	adult	Partial (5,7)
(8) Fast / Deep	None		

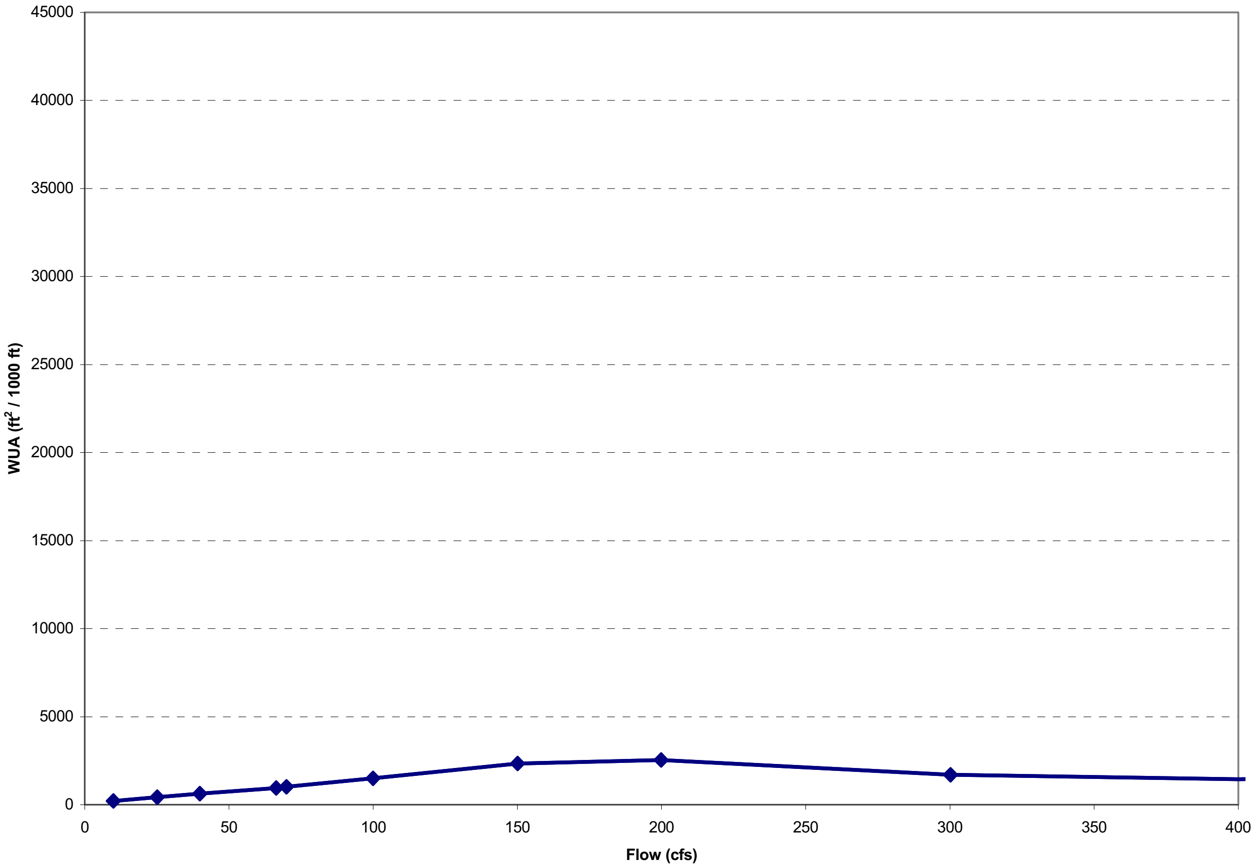


Figure D1. Weighted usable area for June sucker spawning habitat in Site 1 as predicted using modeling tools developed during the Provo Flow Study.

(Table D1). Both niche 3 and niche 5 habitat increases with discharge between 0-100 cfs. Based on these data, a discharge value in the range of approximately 40-70 cfs would preserve good diversity of habitat availability by maintaining a moderate amount of niche 2 habitat (which would decrease further at higher flows) as well as moderate niche 3 and 5 habitat (reduced at lower flows). At the lower end of this range, niche 2 habitat would be more abundant and the upper end would favor niche 3 and 5 habitats. This range of flows would provide little niche 1 habitat (early life stages for many native fish) but native fishes are not generally able to reproduce successfully in this area due to the large number of predators. It would not be possible to have significant amounts of niche 1 habitat without very low flows, which would reduce the total amount of habitat as well as minimizing the total area of most habitat niches.

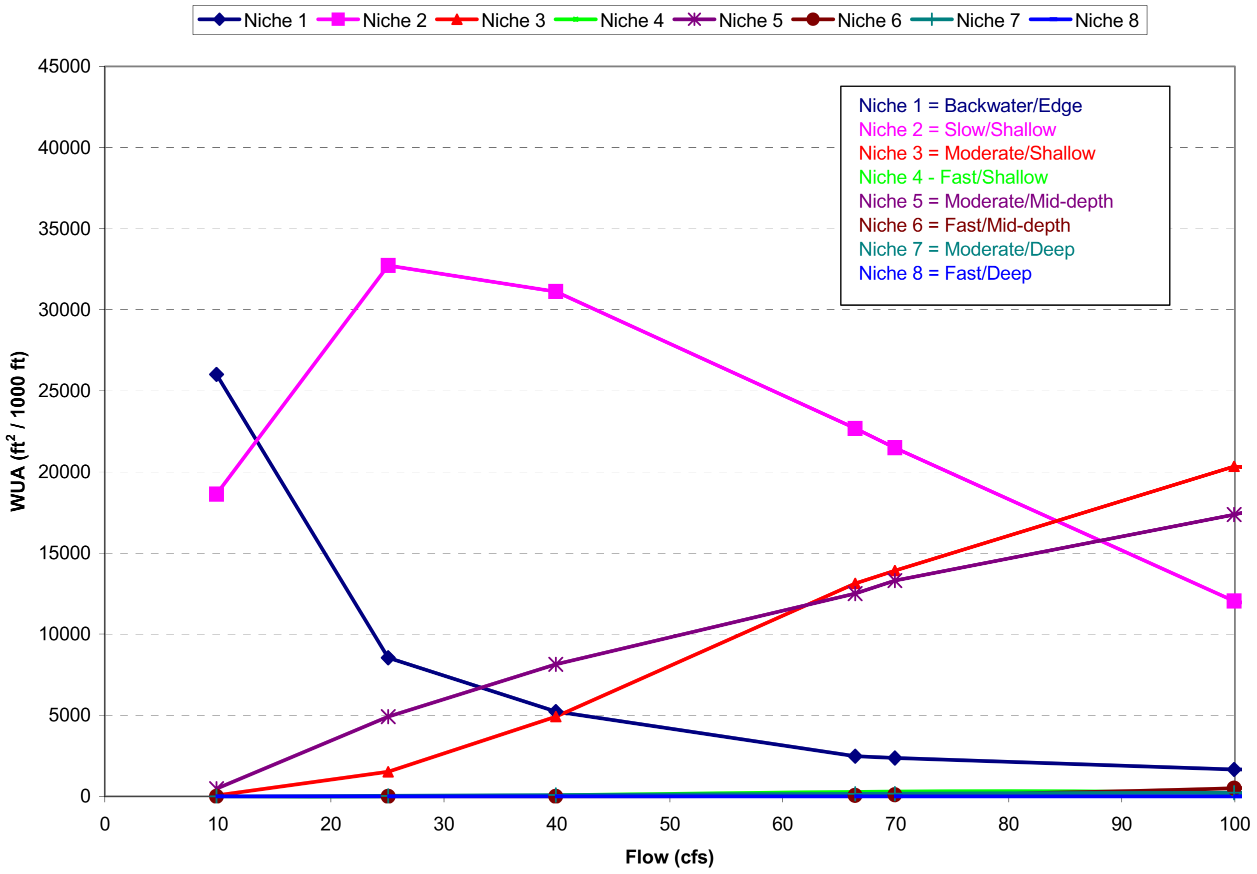


Figure D2. Weighted usable area for habitat niches in Site 1 as predicted using modeling tools developed during the Provo Flow Study.

The habitat availability among niches over a discharge range of 0-100 cfs in Study Site 2 is presented in Figure D3. This site is located within the reach between Lower City Dam and Murdock Diversion (Figure 5.2). Niches 4 and 6-8 occur in a very small proportion of the surface area of Site 2 within this range of flows. Niche 1 is highest at only 10 cfs discharge and declines in area rapidly with higher flows. Niche 2 also peaks at a low discharge (~28 cfs) but approximately 70% of the peak in suitable area remains at 70 cfs. Similar to Site 1 results, Niches 3 and 5 increase at a fairly consistent rate between 0-100 cfs with no distinct inflection point. As in Site 1, a discharge value of approximately 70 cfs would maximize habitat among niches. Niche 1 habitat area would remain low, but it is impossible to have much niche 1 habitat in this area without excluding all other niches.

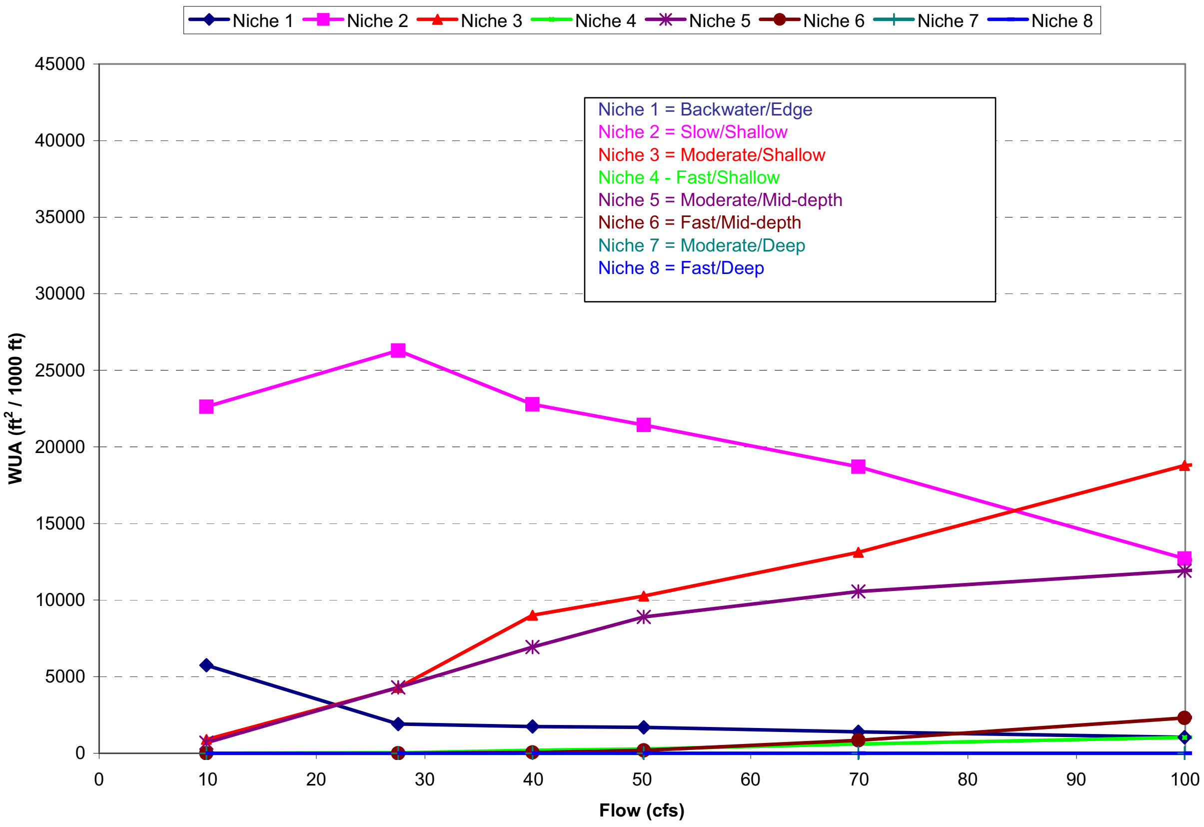


Figure D3. **Weighted usable area for habitat niches in Site 2 as predicted using modeling tools developed during the Provo Flow Study.**

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APPENDIX E: SUMMARY OF JUNE SUCKER SPAWNING AND LARVAL-DRIFT MONITORING RESULTS

SUMMARY OF JUNE SUCKER SPAWNING AND LARVAL DRIFT MONITORING RESULTS

The Utah Division of Wildlife Resources (UDWR) conducts annual sampling during the June sucker spawning period as part of the June Sucker Recovery Implementation Program (UDWR 2002, UDWR 2003, UDWR 2004a, UDWR 2004b, UDWR 2005, UDWR 2006). Results of this monitoring are summarized in Table E1.

Table E1. Summary of springtime June sucker monitoring data.

YEAR	ADULT MONITORING	LARVAL MONITORING
1999	Spot lighting 17 May-8 July no suckers caught, high flows	Larval drift net 17 May-9 July peak not reported, suckers caught 8 June -8 July, total 48
2000; high flows	Spot lighting 8 May -1 June 47 suckers caught, no peak reported	Larval drift net 8 May-22 June, total 103 no peak reported
2001	Trap net only	Larval drift net 23 April-14 June 14 May-11 June suckers observed Peak 31 May Total 308 suckers
2002	Snorkel surveys added 15 Apr-17 June Peaked 24 May and 7 June High flows 2-22 May	Larval drift net 29 April – 27 June 23 May-26 June, suckers observed Peak 16 June Total 565 suckers
2003	Snorkel surveys 14 Apr-20 June Peak 26 May 2003	Larval drift net 21 April-23 June 14 May – 25 June, suckers observed Peak 11 June Total 115 suckers
2004	Snorkel surveys 12 April 28 May Peak 13 May	Larval drift net 14 April – 24 June 6 May – 17 June, suckers observed Peak 7 June Total 41 suckers
2005	Snorkel surveys 15 April-5 May and 13 June-15 July High flows May and early June 3 suckers seen 7 July	Larval drift net 14 April-1 August 12 May-10 July, in side channel-high river flows 17 May-14 June no sampling-high river flows 20 June – 20 July Peak 23 July High flow Total 823 suckers
2006	Spot lighting 1 April-23 June 17 May-13 June no sampling- high river flows 16 total suckers/8 June sucker caught Peak 23 June (6 total suckers/3 June sucker)	Larval drift net 10 April-15 July 10 June-15 July, suckers observed Peak 23 June Total 486 suckers

Interpretation of these results is hindered by the limited years of comparable data, However, the date of observed peak larval drift is reported in 6 of the 8 years of monitoring data. The date of peak drift is summarized along with peak flow conditions in Table E2, and is also plotted on the annual spring runoff hydrographs (Figure E1).

Table E2. Timing of peak larval drift relative to springtime flow patterns.

YEAR	PEAK FLOW MAGNITUDE/DATE	APPROXIMATE DATE OF END OF SNOWMELT RUNOFF PERIOD	DATE OF REPORTED PEAK LARVAL DRIFT	DAYS FROM PEAK FLOW TO PEAK DRIFT	DAYS FROM END OF SNOWMELT RUNOFF TO PEAK DRIFT
1999	---	---	Not reported	---	---
2000	---	---	Not reported	---	---
2001	313 cfs/ May 8	May 17	May 31	23	14
2002	694 cfs/ May 11	May 17	June 16	36	30
2003	185 cfs/ May 3	n/a	June 11	39	n/a
2004	148 cfs[a]/ May 4	n/a	June 7	34	n/a
2005	1,610 cfs/ May 24	July 17	July 23	60	6
2006	672 cfs/ April 15 657 cfs/ May 28	July 1	June 23	69 (first peak) 26 (second peak)	-8

[a] Annual peak of 186 cfs occurred March 26.

During 2001-2004, peak larval drift occurred between May 31 and June 16. These four years span a drought period with low spring peak flow magnitudes and short snowmelt runoff durations (Table E2, Figure E1). In these years, peak larval drift was observed 23-39 days after the peak flow date (Table E2). In 2005, which was a wet year, flow peaked later in the year and peak larval drift did not occur until July 23 (60 days after peak flow). Because the high flows in 2005 limited mid-river drift sampling, the 2005 results may not be fully comparable to the previous years' data. In 2006, flows came up very early, and were already 370 cfs at the beginning of April. The 2006 high flows were prolonged, with two peaks of similar magnitudes occurring in April and late May (Table E2, Figure E1). Peak larval drift was observed 26 days after the second peak and 69 days after the first peak.

The largest number of larval suckers (823) were sampled in 2005, followed by 2002 (565 suckers), 2006 (486 suckers) and 2001 (308 suckers). These were the years with the highest peak flow magnitudes (Table E2), suggesting a positive correlation between flow magnitude and larval drift density. However, this correlation may simply be due to the fact that more total flow volume is collected in drift nets per unit time when flows are higher (i.e., sampling efficiency is greater).

In general, it is difficult to draw strong conclusions from the available monitoring data about the relationship between flow conditions and spawning success/larval transport effectiveness. Until additional data and/or new high-flow monitoring techniques become available, the results from the Wilson and Thompson (2001) bead study provide the primary guidance regarding flows for larval drift. Their recommendation of 300 cfs should be evaluated and modified if needed as additional monitoring data are collected. Remote monitoring of adult fish using a stationary antenna set in the lower river is planned for 2008; this new data set should provide valuable information about the timing of spawning and how it relates to flows because continuous data will be collected, even during periods when flows are too high to safely enter the river.

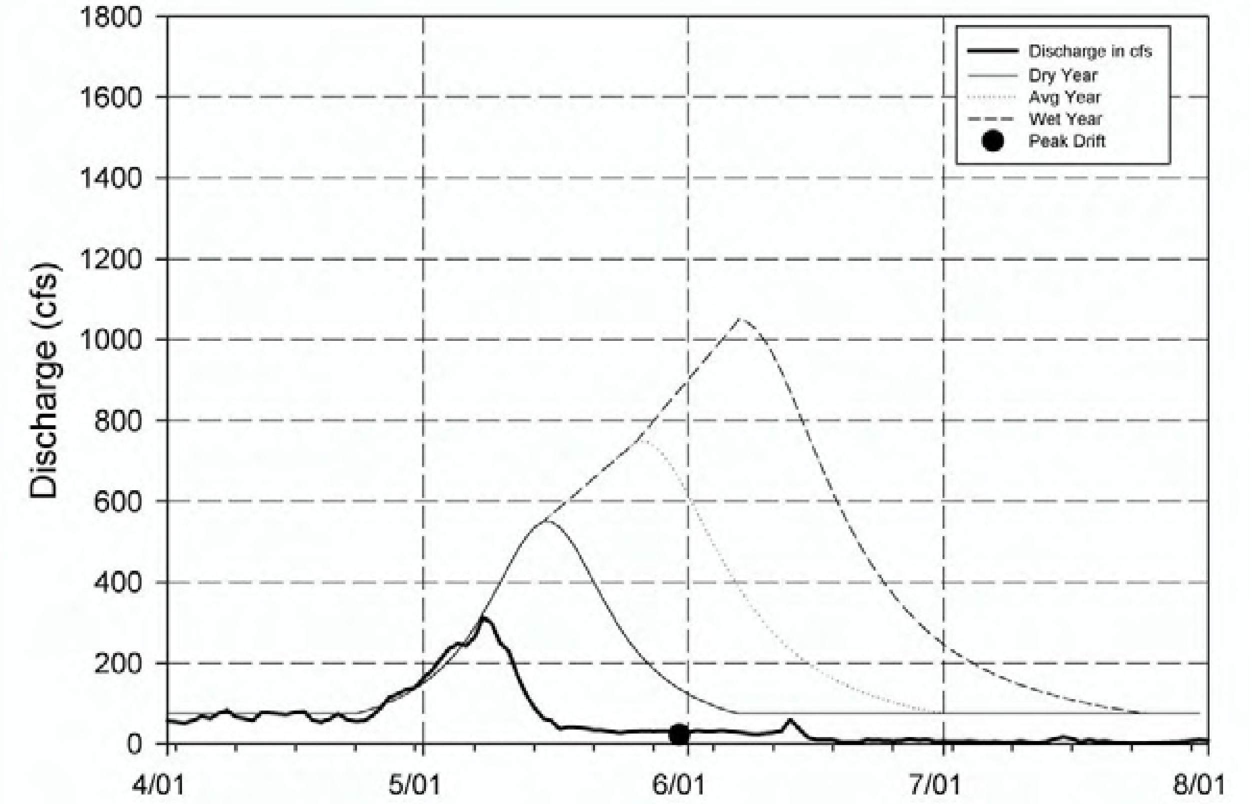

Figure E1. Plots of recent lower Provo River spring hydrographs and dates of peak larval drift.

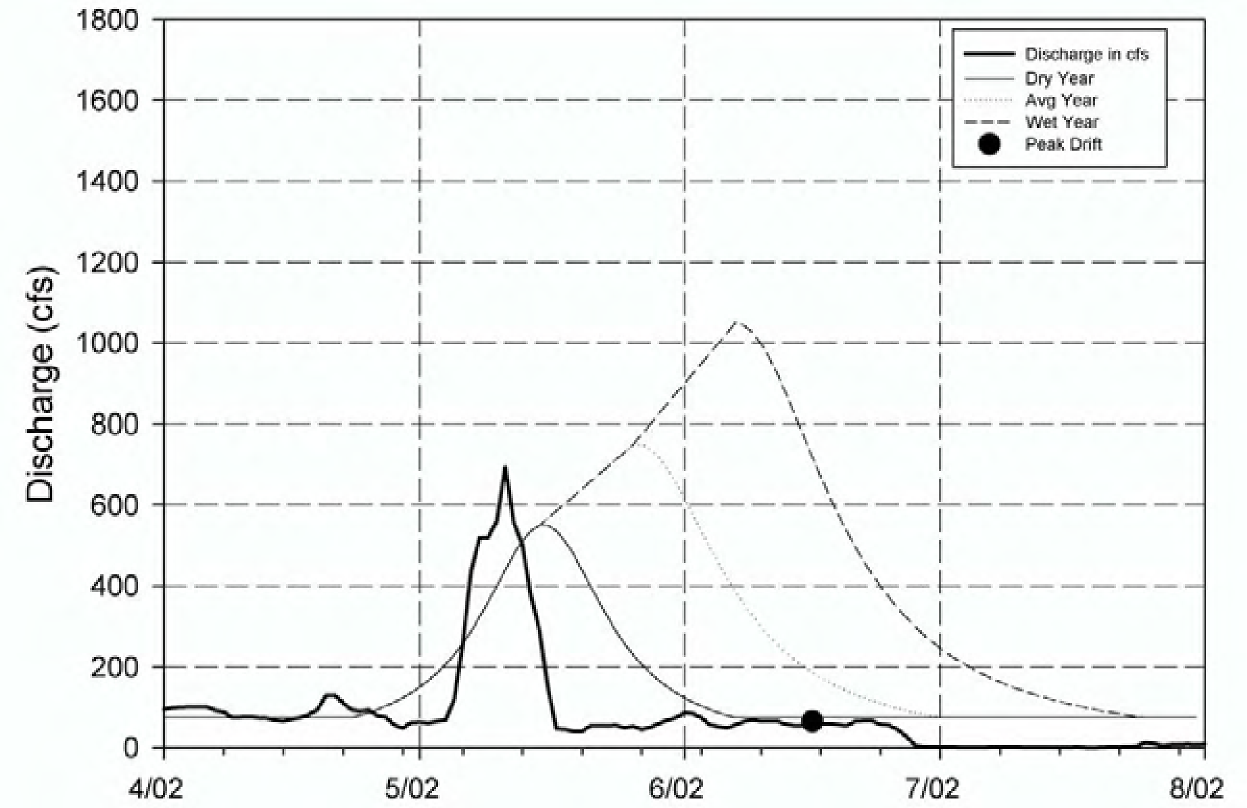

Figure E1. **Plots of recent lower Provo River spring hydrographs and dates of peak larval drift (cont.).**

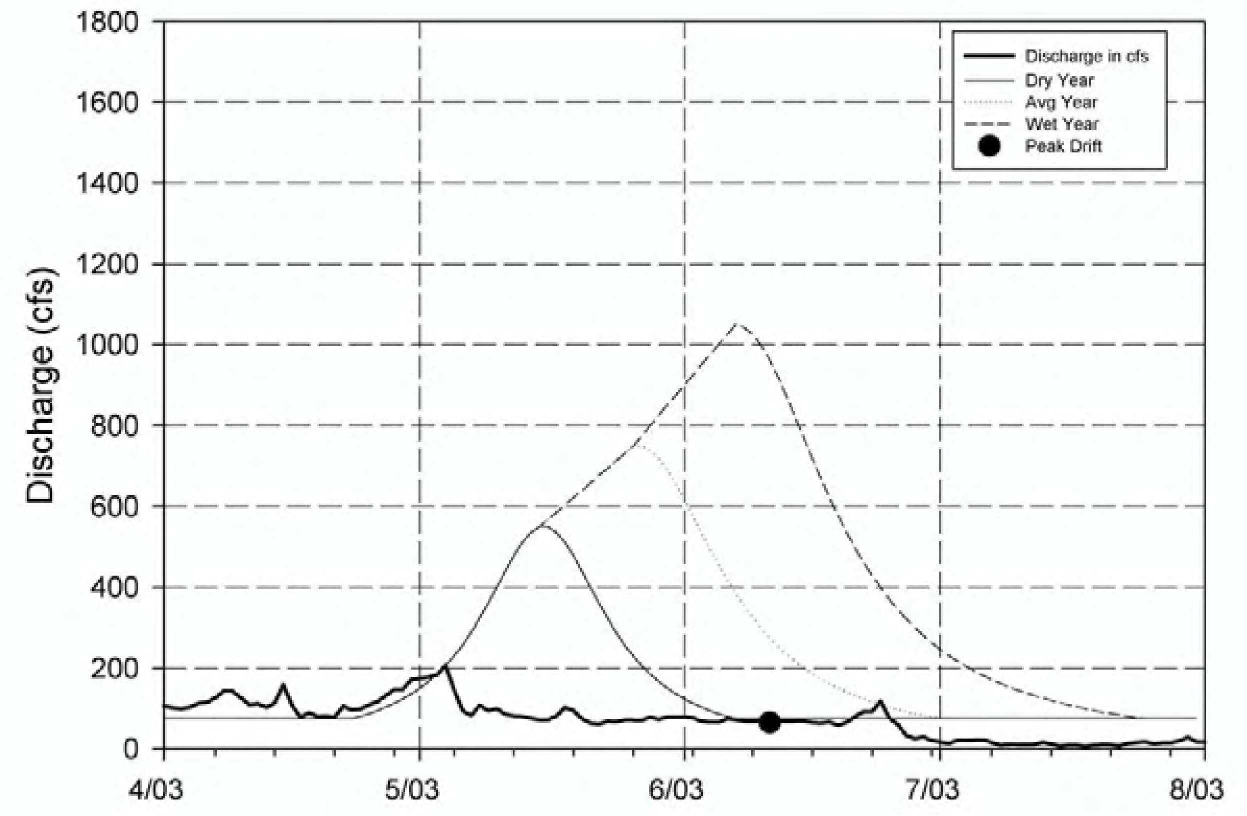

Figure E1. Plots of recent lower Provo River spring hydrographs and dates of peak larval drift (cont.).

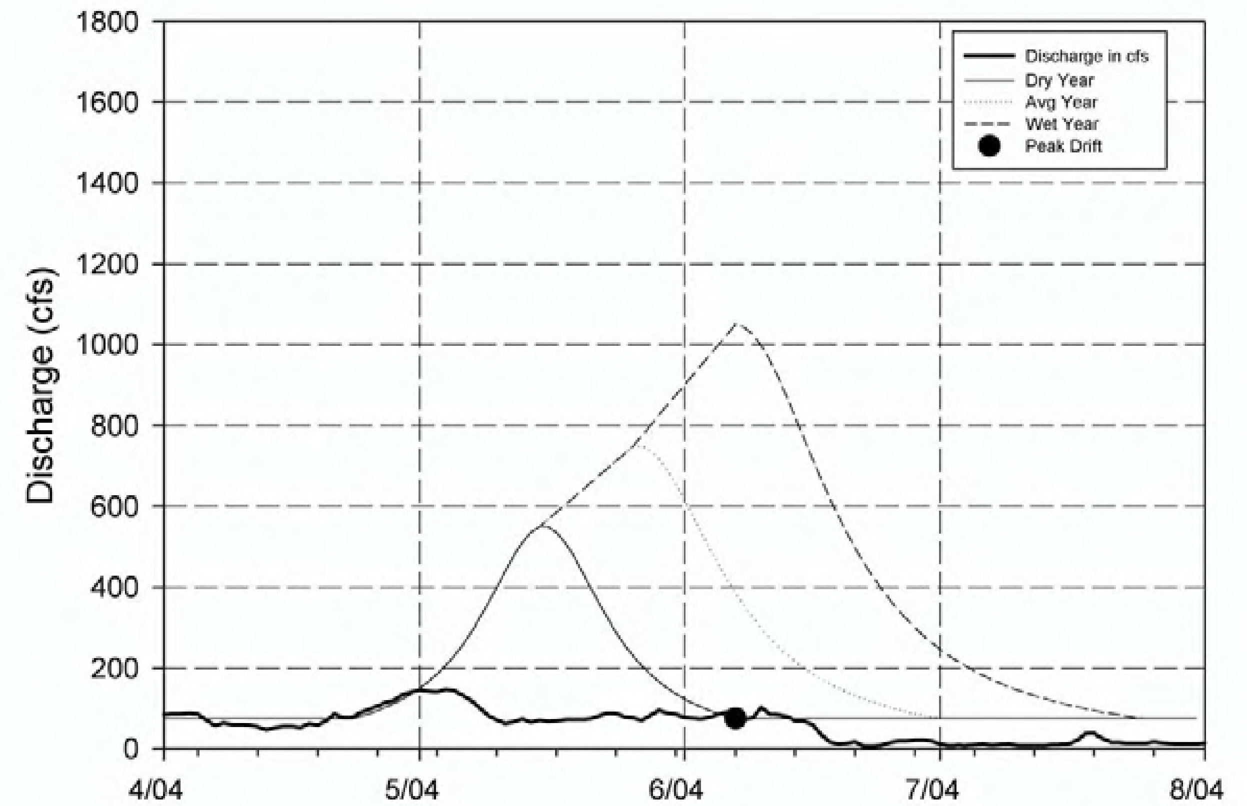

Figure E1. **Plots of recent lower Provo River spring hydrographs and dates of peak larval drift (cont.).**

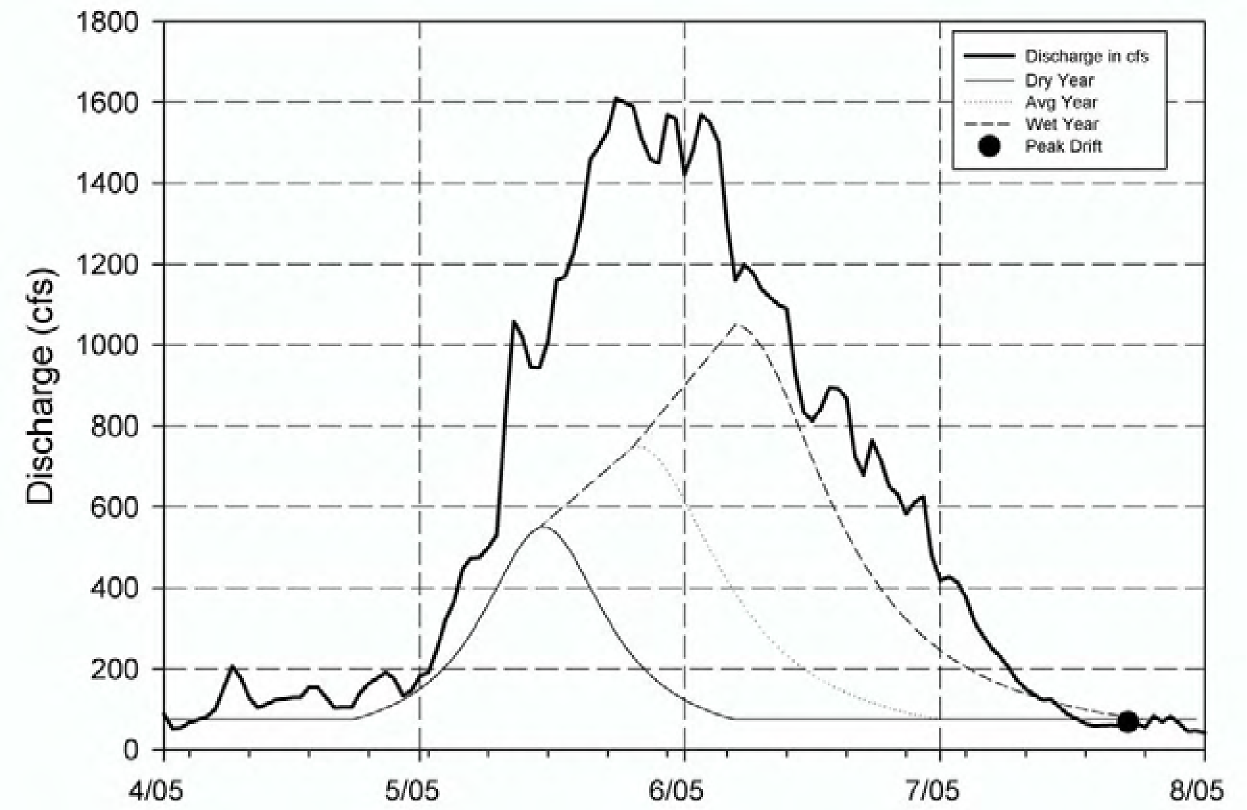

Figure E1. Plots of recent lower Provo River spring hydrographs and dates of peak larval drift (cont.).

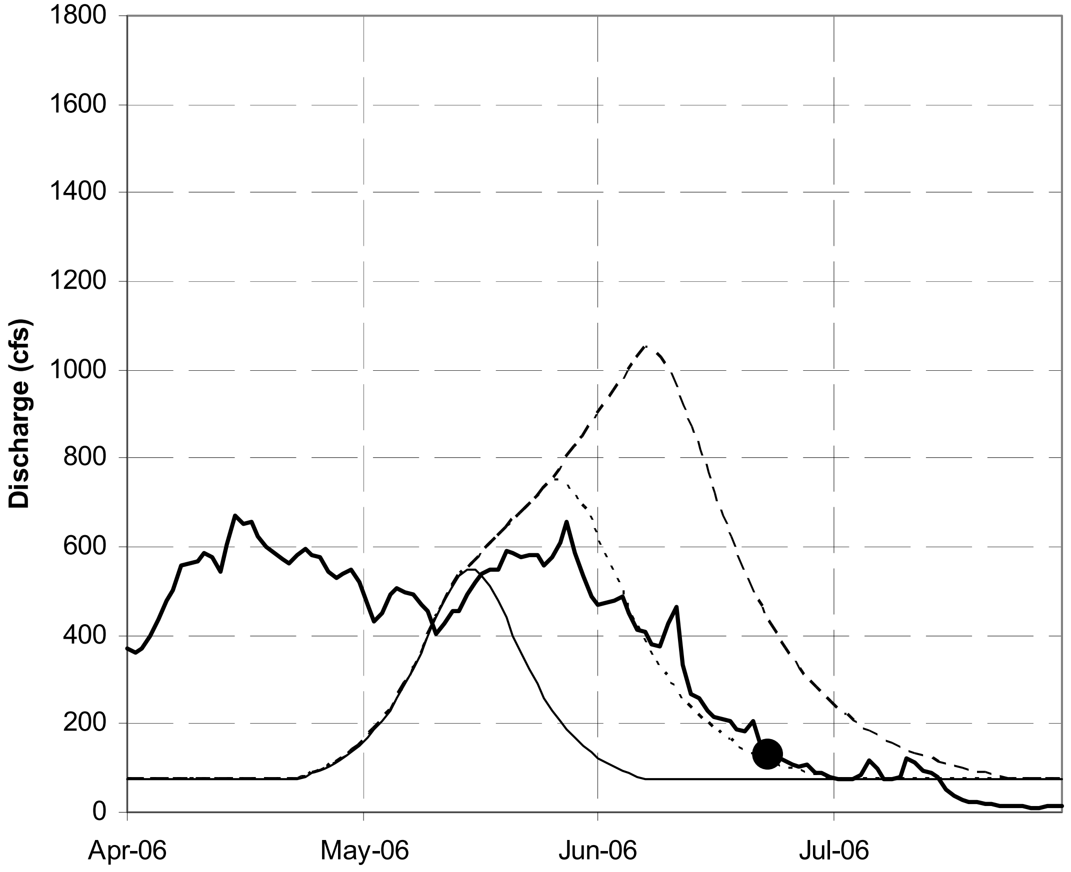

Figure E1. **Plots of recent lower Provo River spring hydrographs and dates of peak larval drift (cont.).**

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[UDWR] Utah Division of Wildlife Resources. 2002. Monitoring Adult June Sucker populations in Utah Lake and the Provo River in 2001. June Sucker Recovery Program 2001 Report Project Number V.01.06. UDWR, Central Region, 1115 North Main Street, Springville, UT 84663. 29 p.

[UDWR] Utah Division of Wildlife Resources. 2003. Monitoring Adult June Sucker populations in Utah Lake and the Provo River in 2002. June Sucker Recovery Program 2002 Report Project Number V.02.06. UDWR, Central Region, 1115 North Main Street, Springville, UT 84663. 17 p.

[UDWR] Utah Division of Wildlife Resources. 2004b. Monitoring Adult June Sucker populations in Utah Lake and the Provo River in 2003. June Sucker Recovery Program 2003 Report Project Number V.03.03. UDWR, Central Region, 1115 North Main Street, Springville, UT 84663. 15 p.

[UDWR] Utah Division of Wildlife Resources. 2005. Monitoring Adult June Sucker populations in Utah Lake and the Provo River in 2004. June Sucker Recovery Program 2004 Report Project Number V.04.04. UDWR, Central Region, 1115 North Main Street, Springville, UT 84663. 10 p.

[UDWR] Utah Division of Wildlife Resources. 2006. Monitoring Adult June Sucker populations in Utah Lake and the Provo River in 2005. June Sucker Recovery Program 2005 Report Project Number V.05.02. UDWR, Central Region, 1115 North Main Street, Springville, UT 84663. 24 p.

[UDWR] Utah Division of Wildlife Resources. 2007. Monitoring Adult June Sucker populations in Utah Lake and the Provo River in 2006. June Sucker Recovery Program 2006 Report Project Number V.06.02 and VI.06.01. UDWR, Central Region, 1115 North Main Street, Springville, UT 84663. 23 p.

APPENDIX F: WETTED PERIMETER INFLECTION-POINT ANALYSIS

WETTED PERIMETER INFLECTION POINT ANALYSIS

Introduction

The wetted perimeter is the cumulative distance along the streambed and banks from one wetted edge to the other. Like wetted channel width, the wetted perimeter of a cross section typically increases rapidly with increasing discharge until flows reach the streambanks, and then the value increases relatively slowly until the banks are overtopped. The "breakpoint" or "inflection point" at which this rate change occurs provides an indication of the flow that fully inundates the bottom of the channel. Maintaining this flow level limits vegetation establishment within the low-flow channel, and helps maintain channel capacity. We pursued a wetted perimeter-inflection point analysis to characterize an "anti-vegetation encroachment" flow for the lower Provo River.

Methods

We completed a wetted perimeter analysis at two transects within the lower Provo River. The first transect is located within Provo River Flow Study Site 1 (Figure 5.2; see Olsen et al. 2003 for specific location of Site 1 bedload modeling transect), and will be referred to as the "Site 1 Cross Section." The second analysis transect is located within Provo River Study Site 2 (Figure 5.2; see Olsen et al. 2003 for specific location of Site 2 bedload modeling transect), and will be referred to as the "Site 2 Cross Section". Both analysis transects are located in riffles, and were surveyed as part of the Provo River Flow Study (Olsen et al. 2003). Calibrated hydraulics information (slope, roughness, measured water surface elevations, etc.) previously developed for the Provo River Flow Study was used to calculate wetted perimeter at different discharge increments. Wetted perimeter was then plotted against discharge for each transect, and the inflection point was visually identified.

Results

As seen in Figures F1 and F2, the wetted perimeter inflection point occurs at approximately 27 cfs at the Site 1 Cross Section, and at approximately 80 cfs at the Site 2 Cross Section. Plots of the two analysis cross sections are shown in Figures F3 and F4. These results provide an indication of the range of minimum growing-season flows that would protect against vegetation encroachment in the lower Provo River.

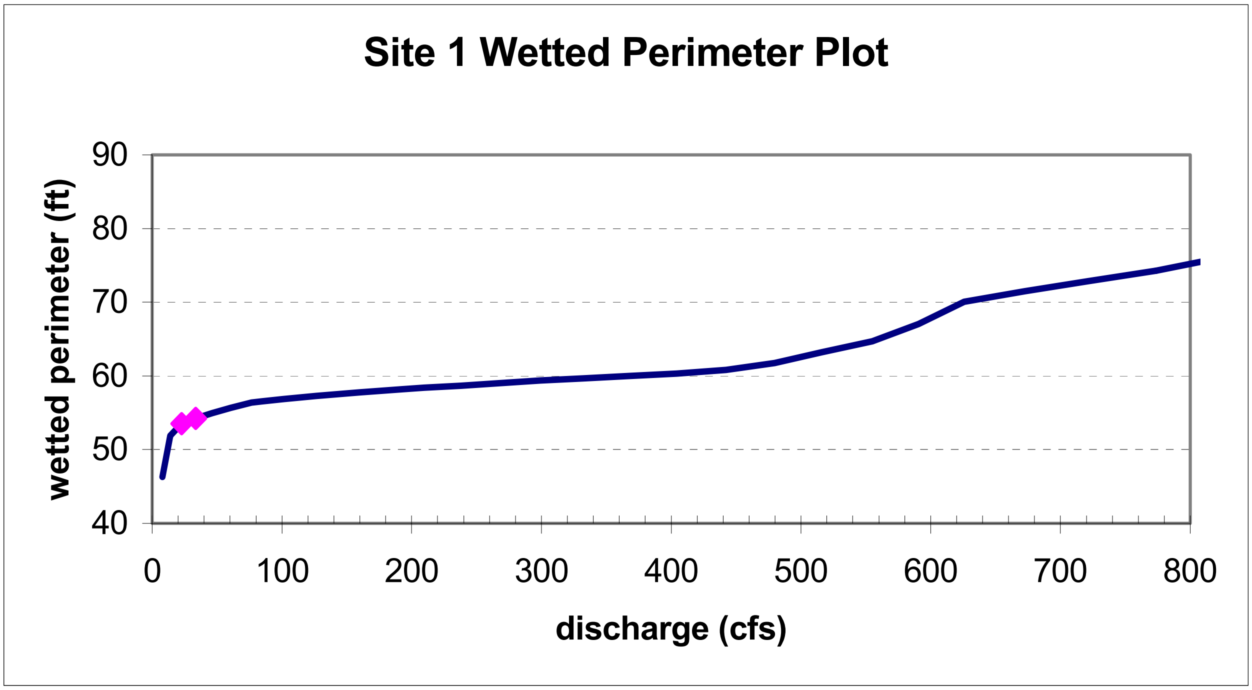

Figure F1. Wetted perimeter plot for Site 1 Cross Section. Pink dots indicate inflection point, which occurs at approximately 27 cfs.

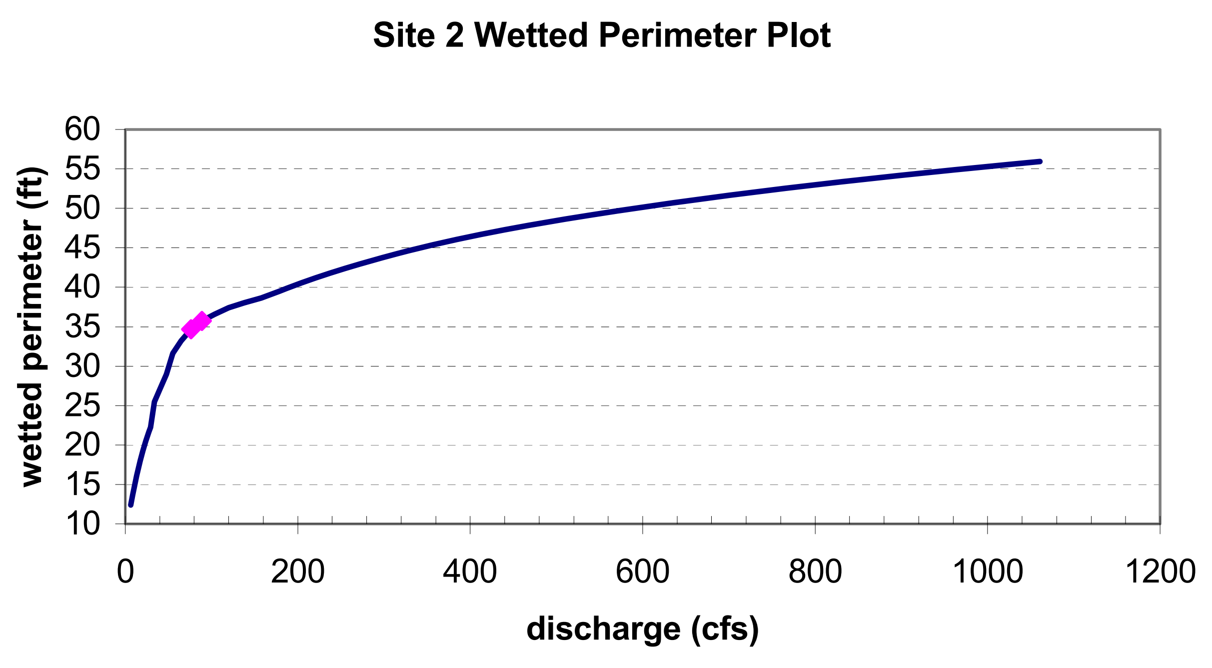

Figure F2. Wetted perimeter plot for Site 2 Cross Section. Pink dots indicate inflection point, which occurs at approximately 80 cfs.

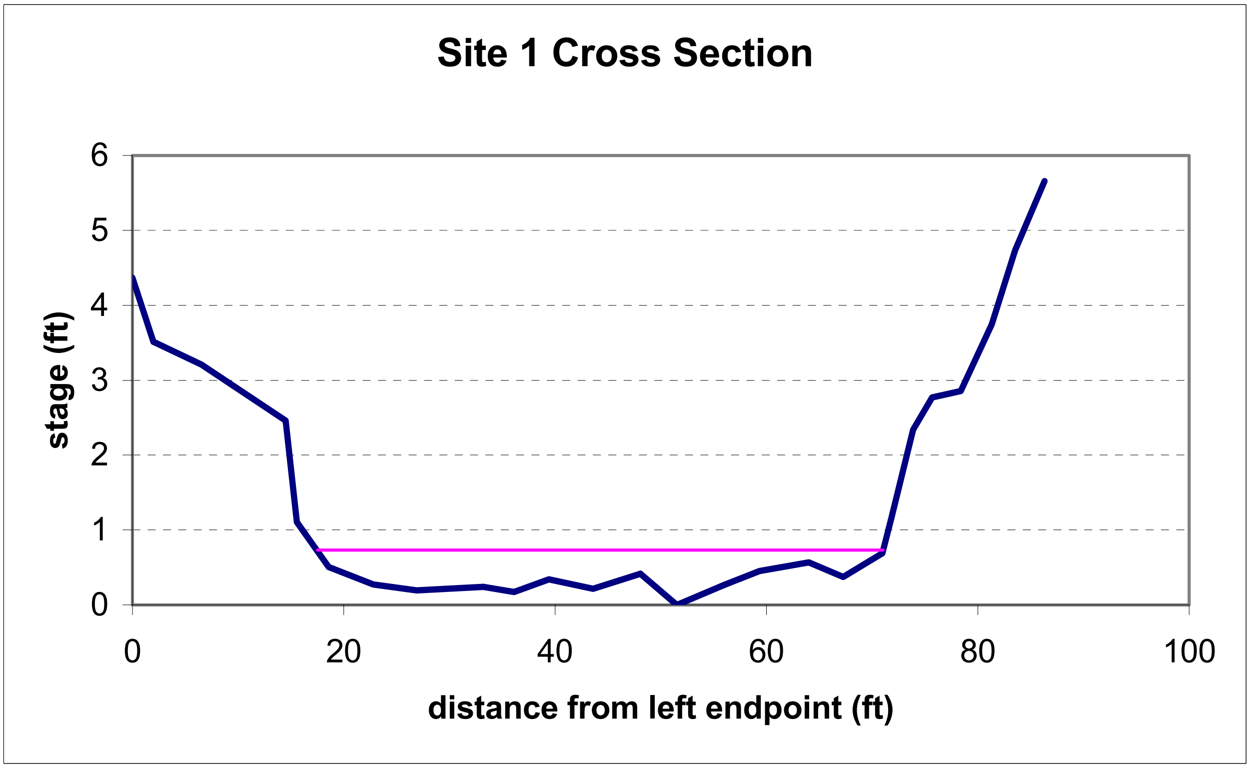

Figure F3. **Plot of Site 1 Cross Section. Pink line indicates stage below which wetted perimeter drops rapidly with decreasing flow.**

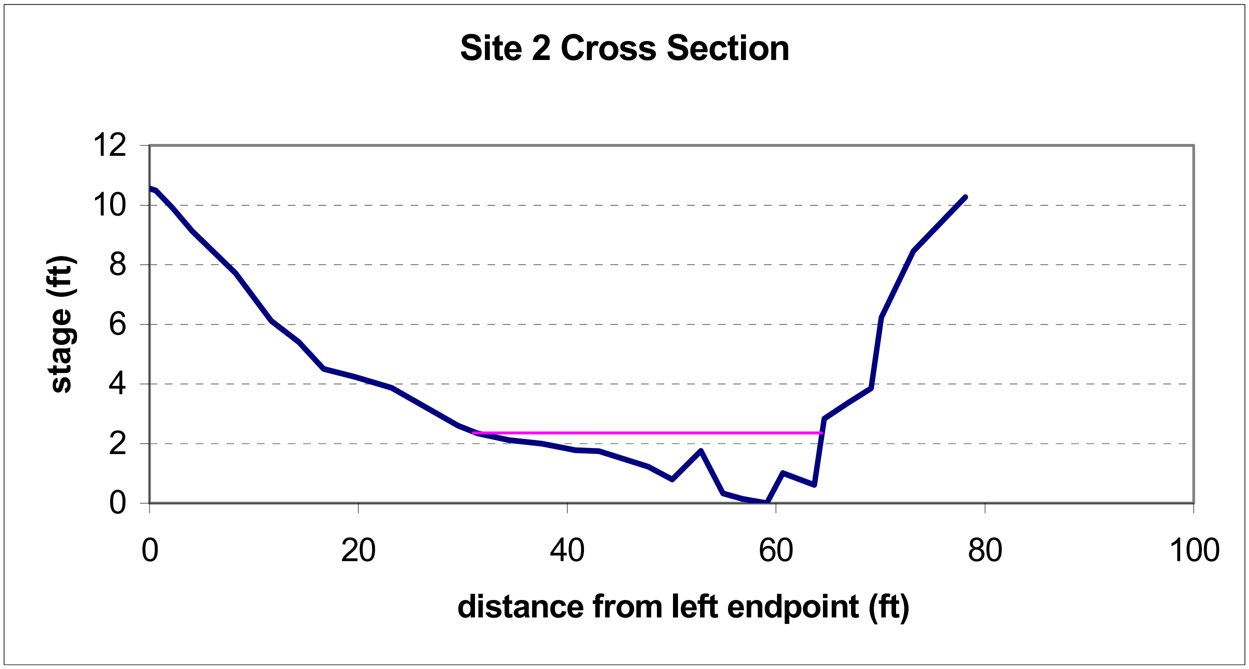

Figure F4. **Plot of Site 2 Cross Section. Pink line indicates stage below which wetted perimeter drops rapidly with decreasing flow.**

APPENDIX G: ANALYSIS OF SUMMERTIME WATER TEMPERATURE AND STREAMFLOW

APPENDIX G: ANALYSIS OF SUMMERTIME WATER TEMPERATURE AND STREAMFLOW

Introduction

The lower Provo River is designated as a cold water fishery, and as such the Utah Division of Water Quality (DWQ) standard for maximum water temperature is 20 degrees C (DWQ 2005). It is not uncommon for water temperatures to reach and exceed this standard during low flow periods in the summertime. Therefore, an empirical analysis of the relationship between flow and temperature was undertaken to help identify a minimum flow that would be protective of the temperature standard. In addition, we wanted to review existing temperature data to determine whether water temperatures ever reach the chronic level lethal to June sucker (approximately 28 degrees C for 60 days; Kindschi et al. 2005).

Initial Analysis and Results

Hourly water temperature and streamflow data collected on the lower Provo River by the Central Utah Water Conservancy District (CUWCD) between 2002-2006 were obtained and analyzed. These data were available for the time periods of 9/3/02-10/3/02; 4/7/03-7/28/03; 4/26/04-6/18/04; 4/5/05-11/7/05; and, 4/6/06-8/6/06. In addition, available DWQ data from 1976-2000 (non-continuous data) and 15-minute thermistor data collected during the spring and summer of 2002 as part of the Provo River Flow Study were analyzed.

After initial review of the complete data set, a subset of the data containing only July and August flows less than 100 cfs were analyzed in greater detail. This is the time period and flow conditions when temperature exceedences are most common.

As evident in Figure G1, temperatures very rarely approach the 28 degree chronic lethal level, and only remain that high for a period of 1 to 2 days. Therefore, avoidance of temperatures lethal to June sucker will not be a driving factor in recommending minimum base flows.

Maintaining water temperature below the 20 degree fishery standard is a greater concern. As seen in Figure G1, once flows drop below about 40 cfs, water temperatures above 20 degrees become quite common. At flows greater than about 65 cfs, temperatures almost never exceed 20 degrees.

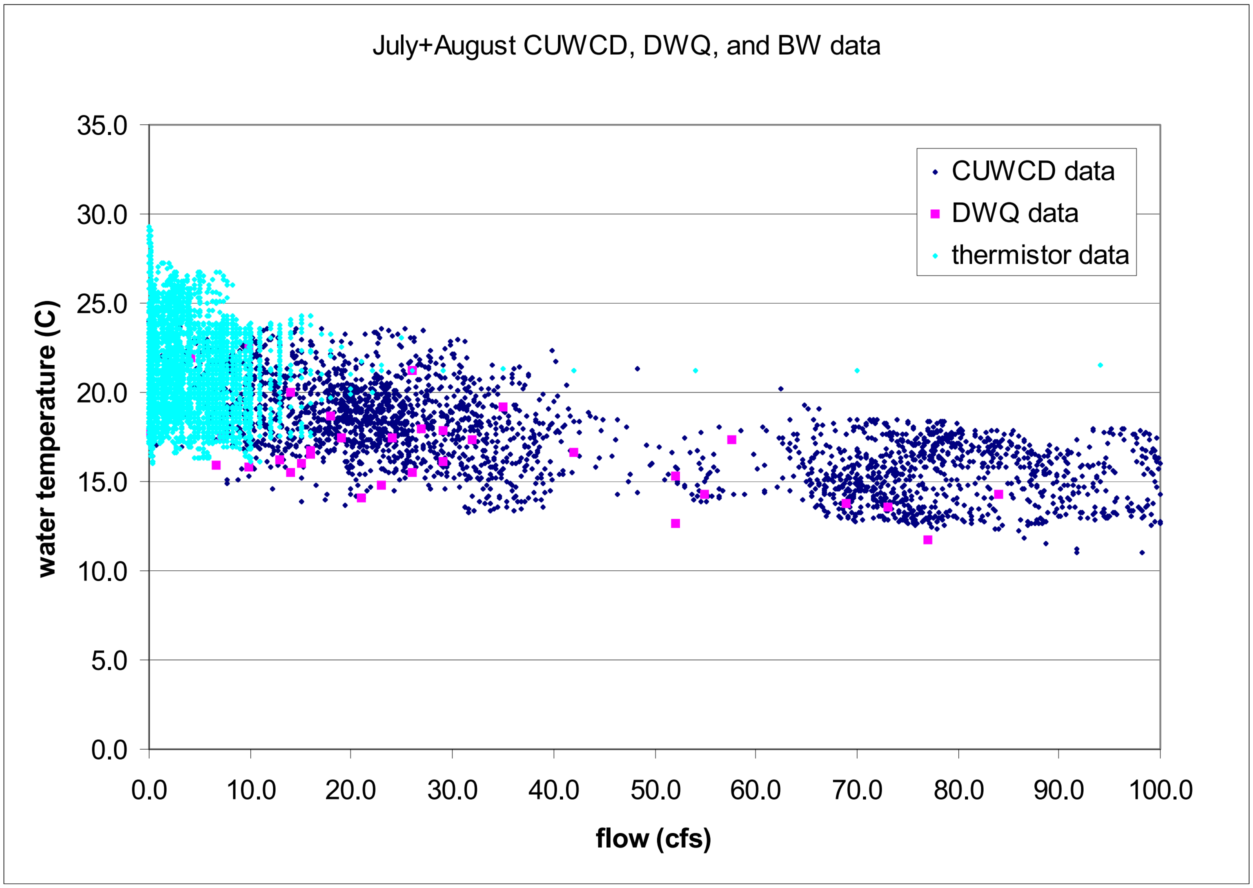

Figure G1. Plot of lower Provo River summertime flow and temperature data.

Experimental Summer Releases in 2007

Based on the results of the initial analysis described above, test releases were conducted during July and August, 2007. The intent of these experimental releases was to provide a minimum flow of 40 cfs in the lower Provo River while monitoring water temperature to determine whether 40 cfs is adequate to maintain water quality. The Utah Division of Wildlife Resources (UDWR) installed two temperature thermistors in the lower river: one at the UDWR fish weir and one at the drift site approximately 1/4 mile upstream of the fish weir. The UDWR fish weir is located about 1.6 miles upstream from the Provo River mouth. The thermistor at the drift site collected data from July 13, 2007 to September 30, 2007. The thermistor at the weir site collected data from July 13, 2007 to August 2, 2007. Flow and water temperature data were also collected by the CUWCD at their Harbor Drive gage.

As evident in Figure G2, the experimental releases were generally successful at providing flows of 40 cfs or greater in the lower river, and were also generally successful at maintaining mean daily water temperatures below 20 degrees C. Daily flow records at the USGS gage near Geneva

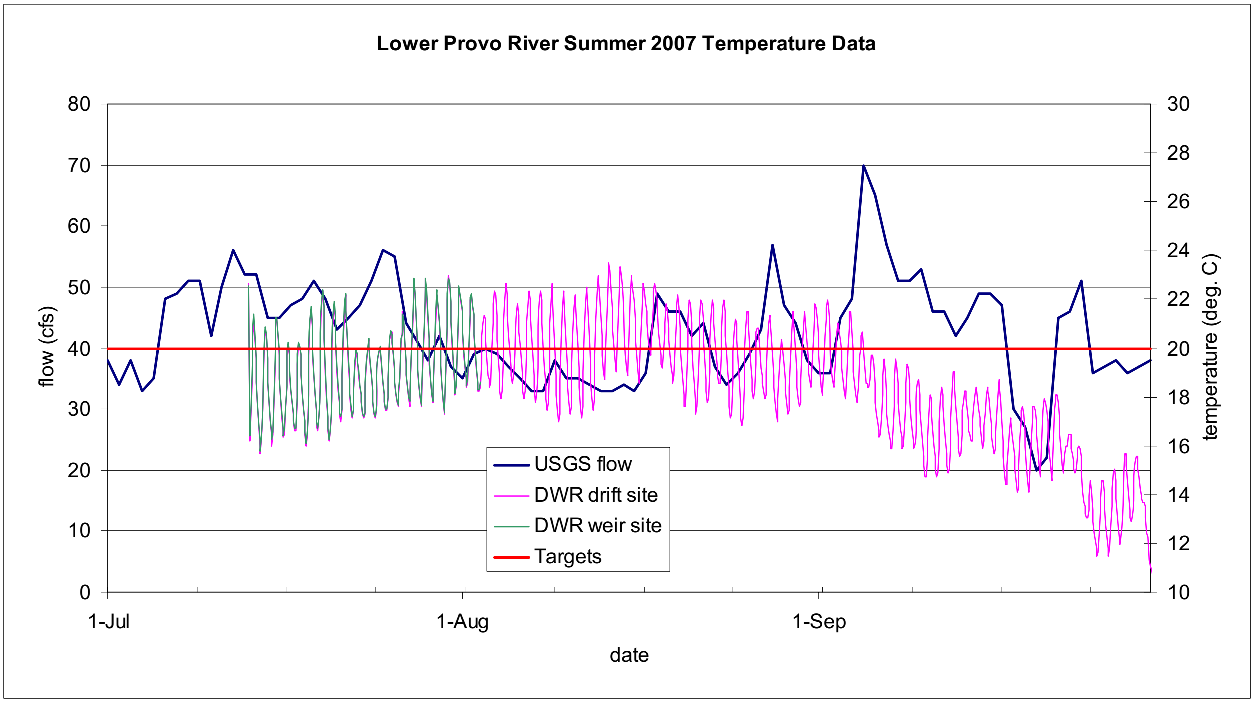

Figure G2. **Summer 2007 water temperature and flow data collected by the UDWR and USGS.**

Road indicate that flows did drop below the 40 cfs target to about 34 cfs for about 2 weeks at the beginning of August. However, mean daily water temperatures did not begin to exceed 20 degrees C until the later part of this 2 week period. In addition, temperatures dropped quickly once flows increased. This suggests that temperature conditions rebound quickly, and that brief (2- to 3-day) periods of flows lower than 40 cfs are unlikely to cause immediate temperature problems. However, if air temperature is especially high or if flows remain low for extended periods of time, water temperature problems are likely to occur.

The data collected by the CUWCD show patterns similar to those observed in the USGS and UWDR data (Figure G3). Flows recorded at the CUWCD Harbor Drive gage are somewhat higher than the values recorded at the USGS gage, which is located about 0.8 miles upstream. Return flows from pumped drain water enter the river between the two gages at the Provo pump station, accounting for some of the difference between the two data sets.

Based on the results of the 2007 experimental releases, we recommend that the target minimum flow be raised to 50 cfs as measured at the CUWCD Harbor Drive gage. This higher target flow would ensure that even the maximum daily water temperature would generally remain below 20 degrees. Continued monitoring of summer water temperature is recommended for the future, along with additional experimental flow releases to maintain summertime water quality.

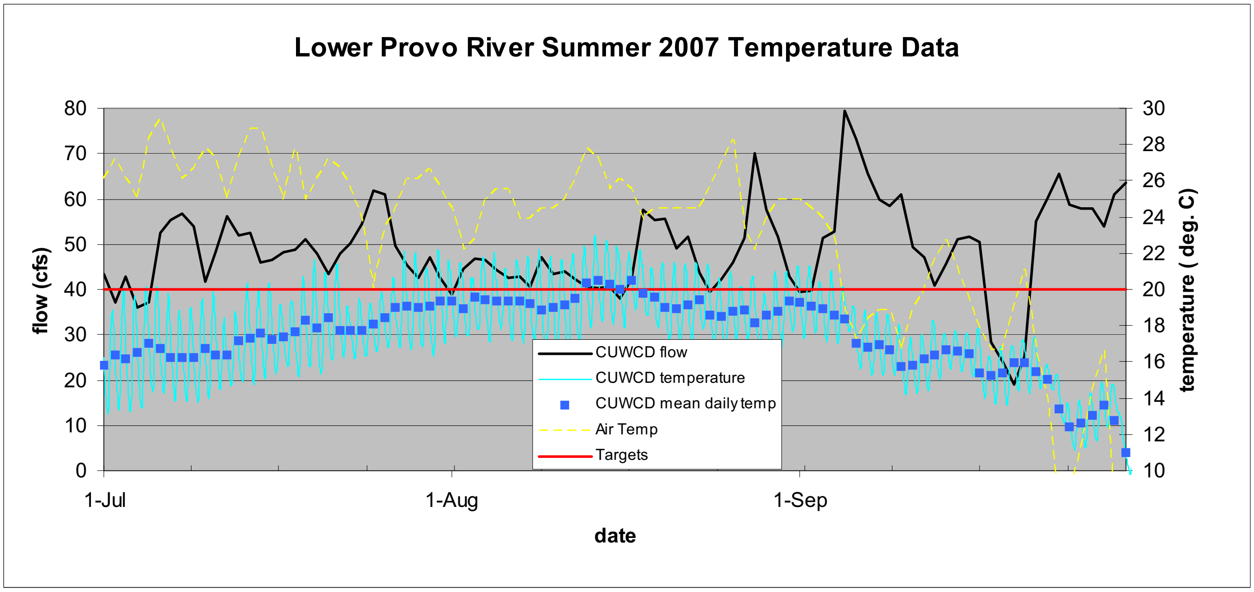

Figure G3. **Summer 2007 water temperature and flow data collected by the CUWCD.**

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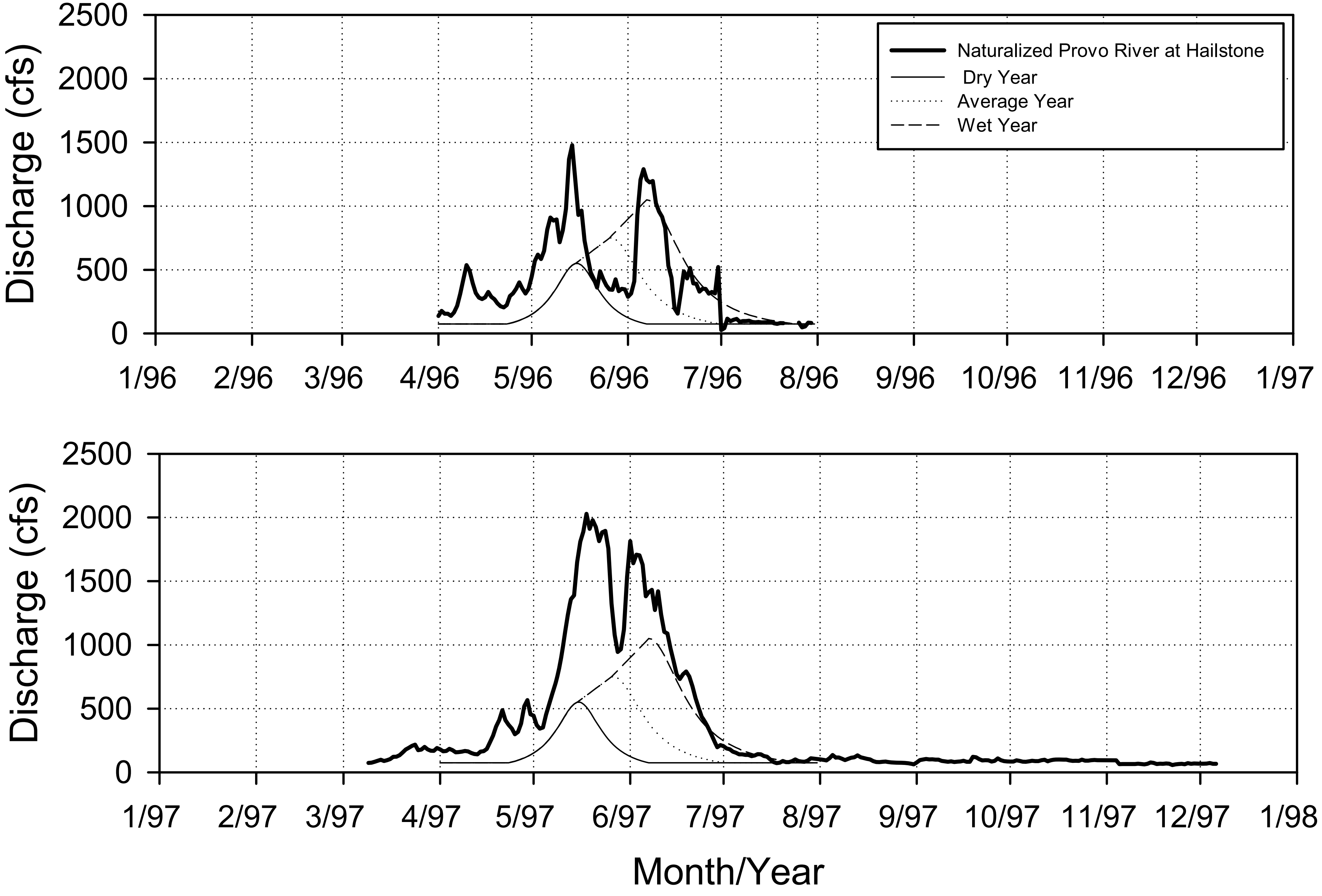
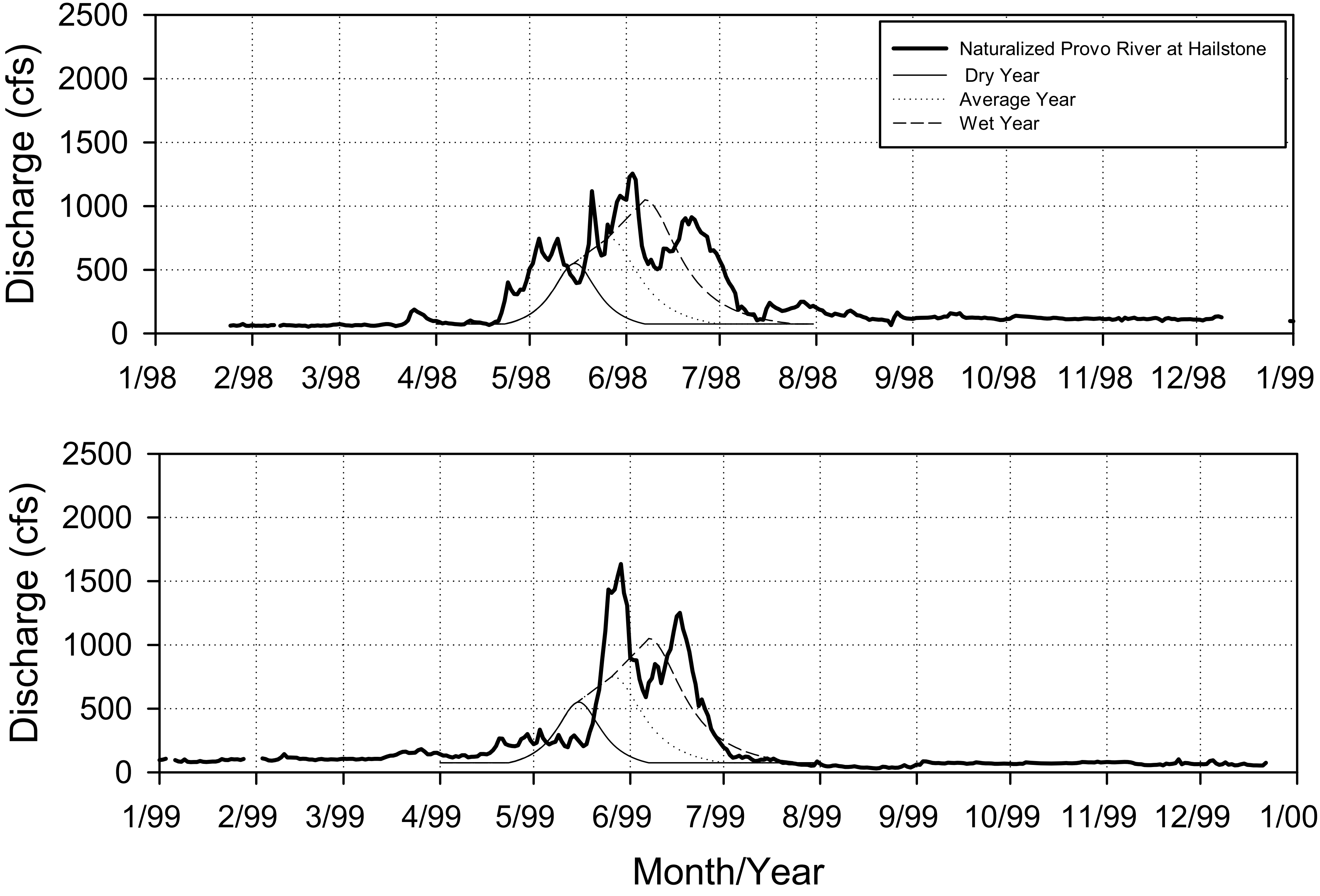
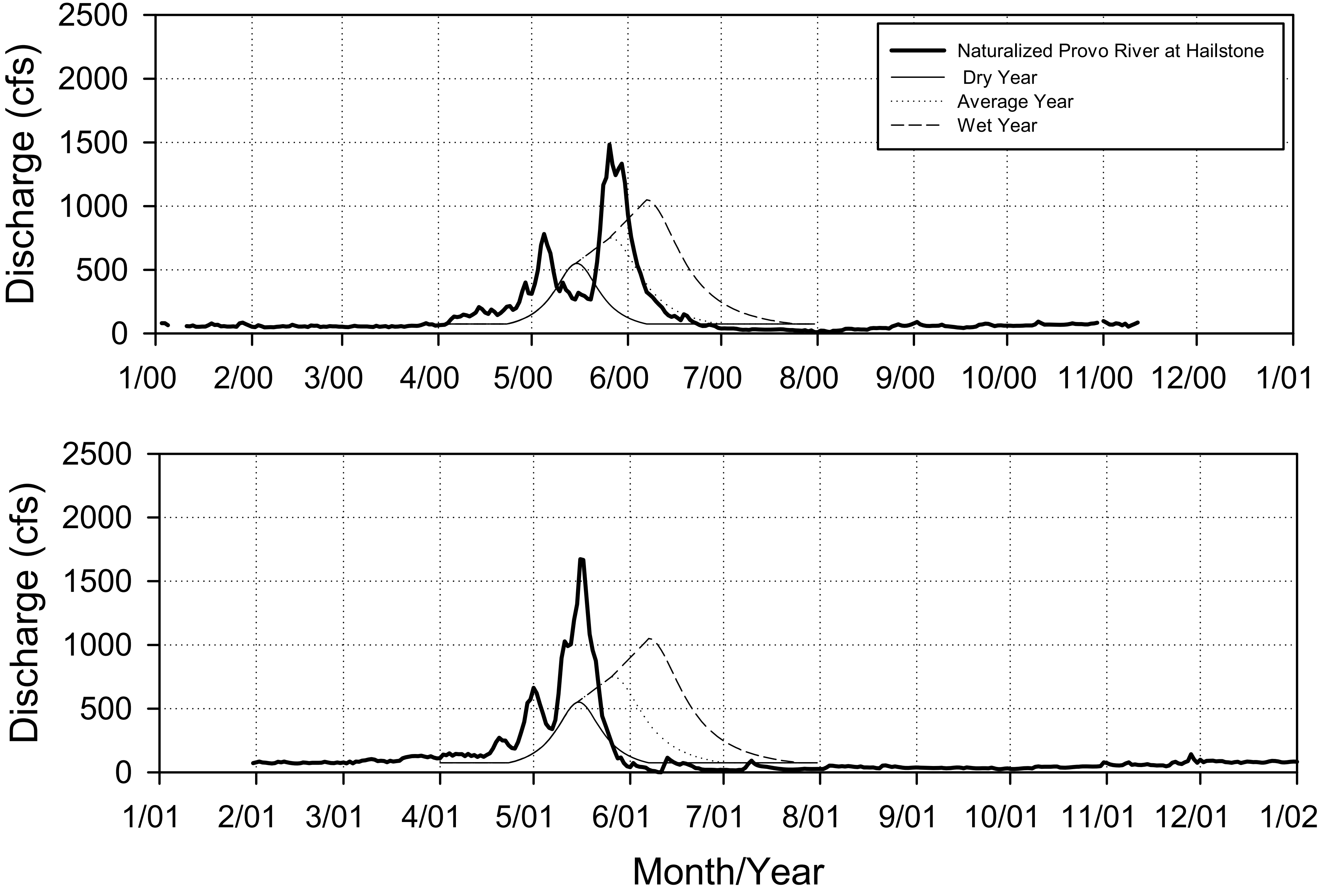
[DWQ] Utah Division of Water Quality. 2005. Standards of Quality for Waters of the State. R317-2, Utah Administrative Code. Salt Lake City (UT):Utah Department of Environmental Quality, Division of Water Quality.

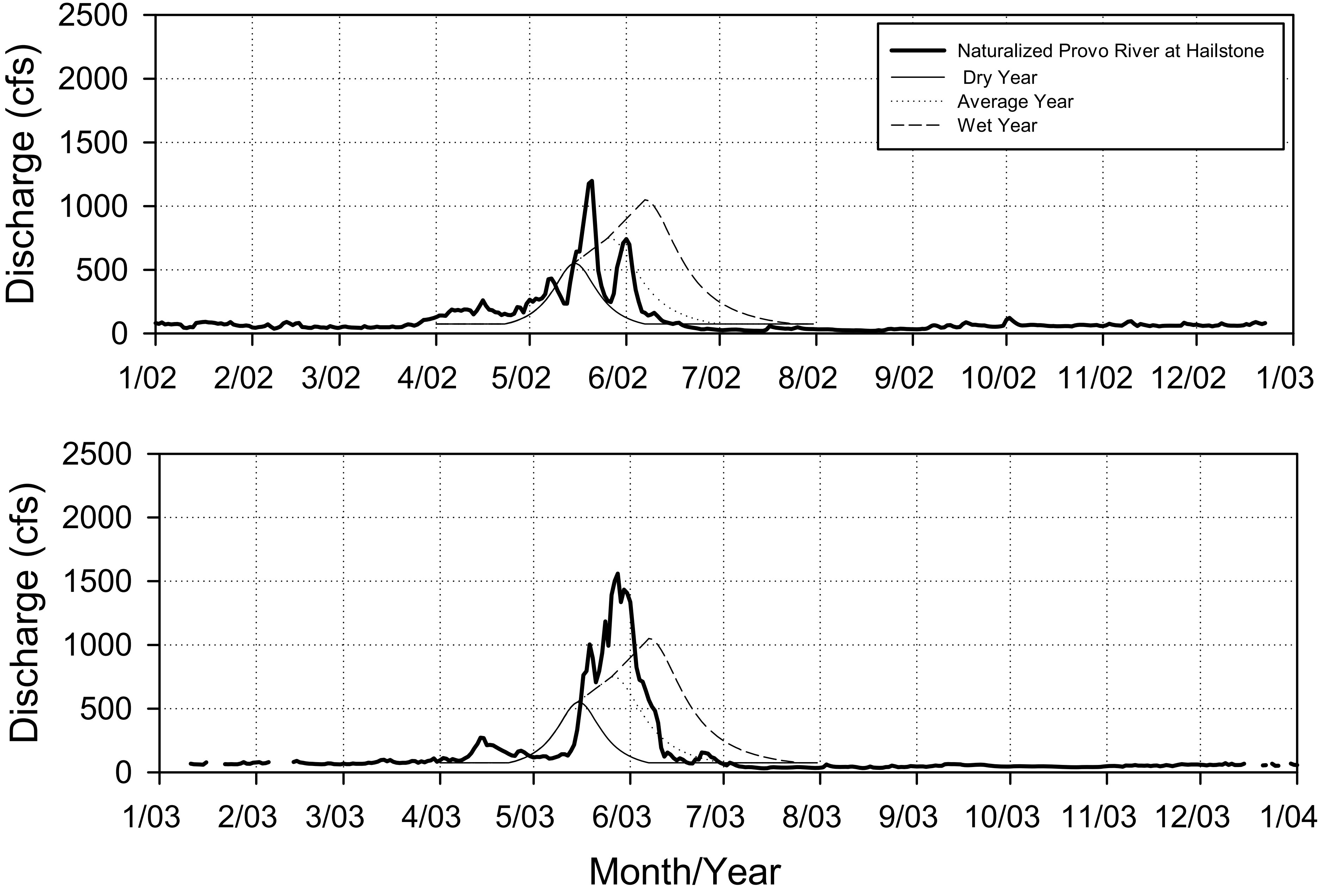
APPENDIX H: PLOTS OF NATURALIZED PROVO RIVER AT HAILSTONE FLOWS VERSUS EXISTING TARGET HYDROGRAPHS

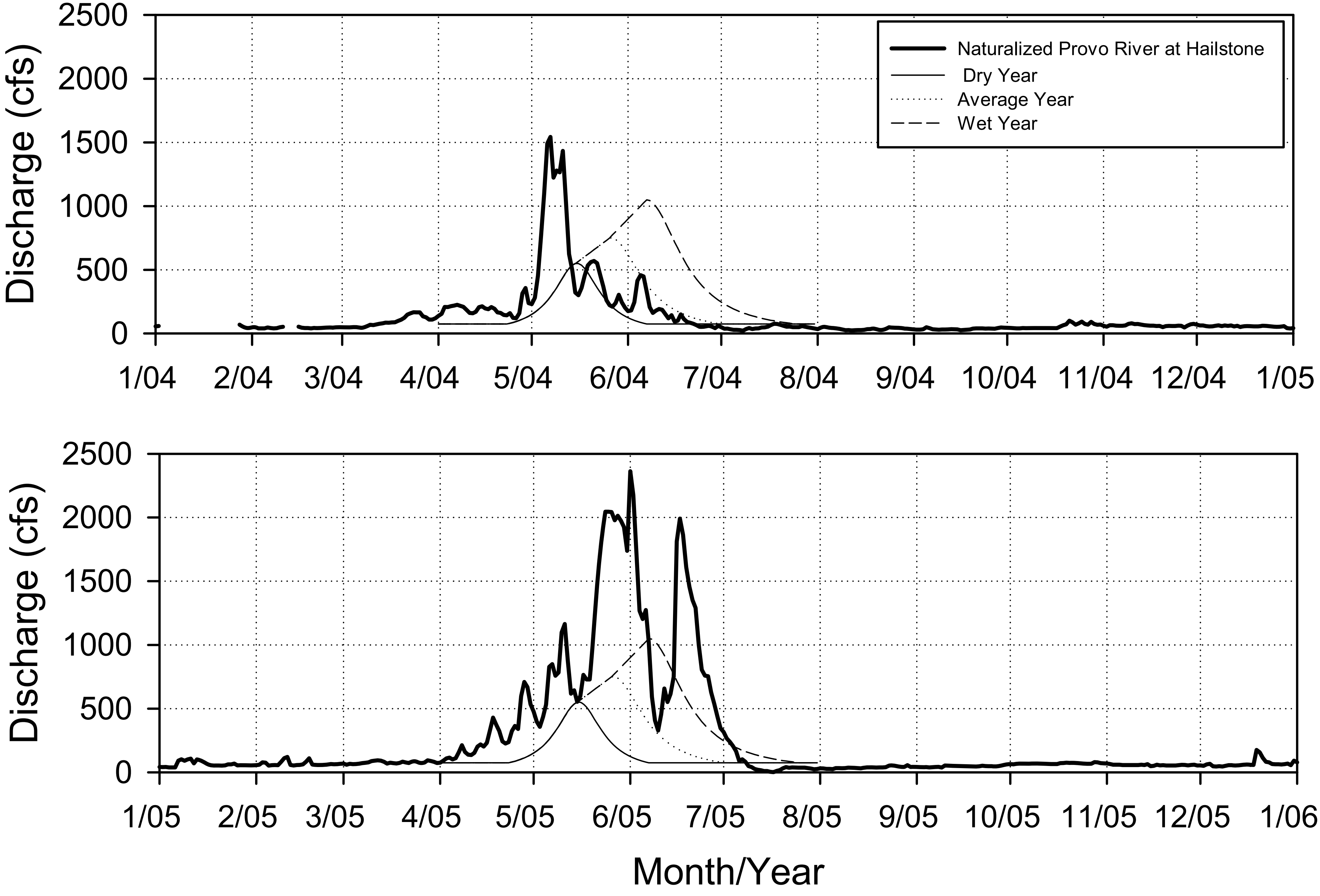

Naturalized Provo River at Hailstone
Dry Year
Average Year
Wet Year
Discharge (cfs)
2500
2000
1500
1000
500
0
1/96
2/96
3/96
4/96
5/96
6/96
7/96
8/96
9/96
10/96
11/96
12/96
1/97
Discharge (cfs)
2500
2000
1500
1000
500
0
1/97
2/97
3/97
4/97
5/97
6/97
7/97
8/97
9/97
10/97
11/97
12/97
1/98
Month/Year

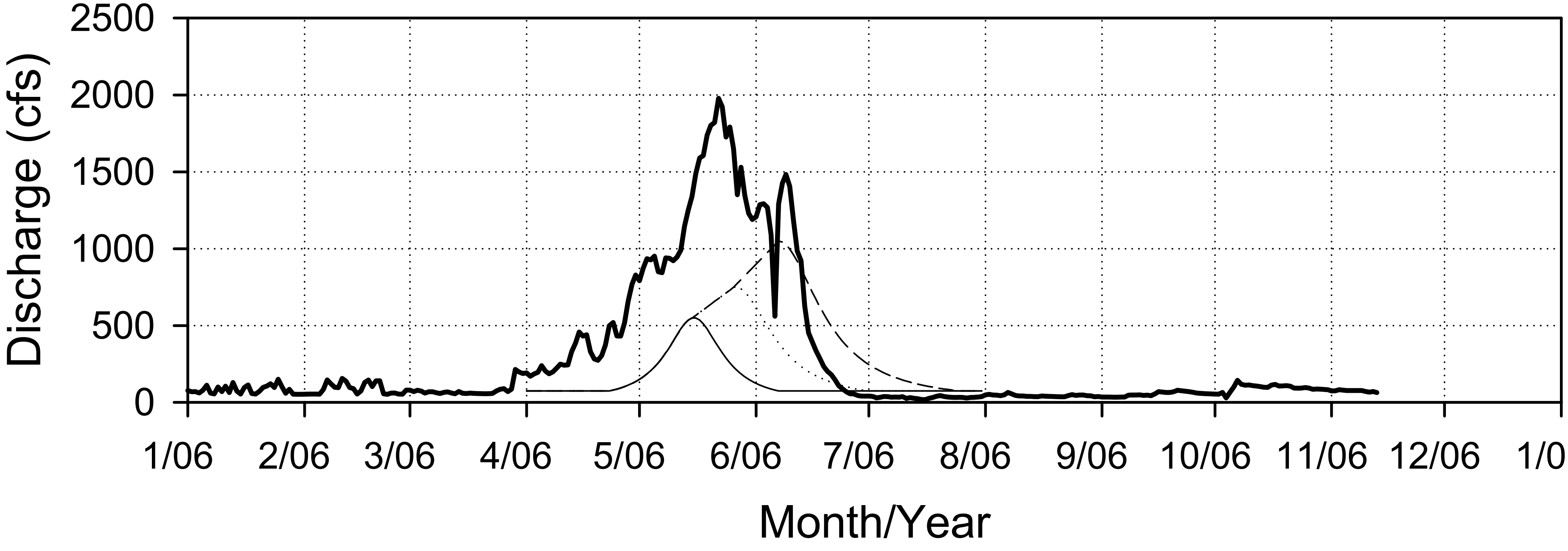


Naturalized Provo River at Hailstone
Dry Year
Average Year
Wet Year
Discharge (cfs)
2500
2000
1500
1000
500
0
1/98
2/98
3/98
4/98
5/98
6/98
7/98
8/98
9/98
10/98
11/98
12/98
1/99
Discharge (cfs)
2500
2000
1500
1000
500
0
1/99
2/99
3/99
4/99
5/99
6/99
7/99
8/99
9/99
10/99
11/99
12/99
1/00
Month/Year

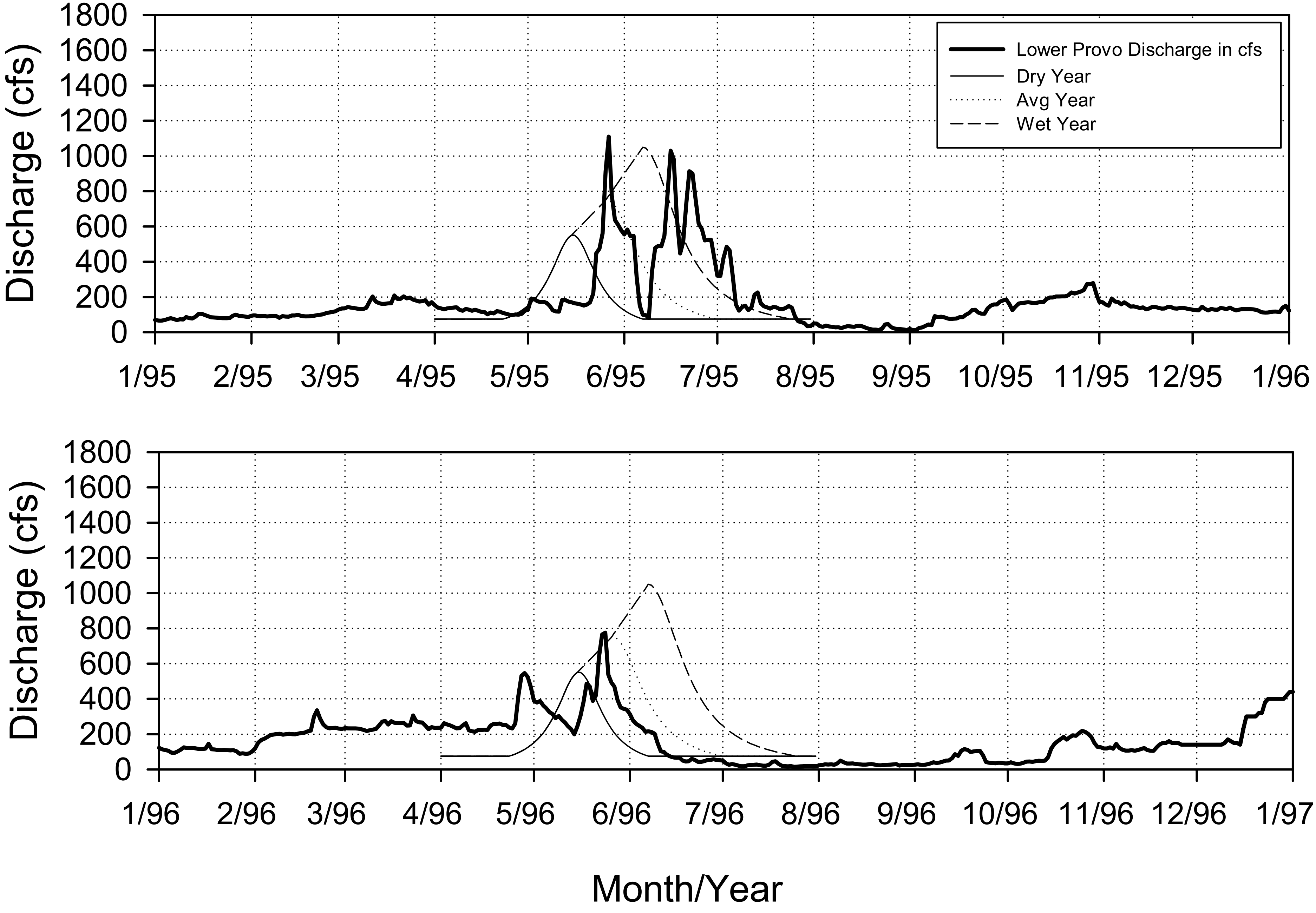

Naturalized Provo River at Hailstone
Dry Year
Average Year
Wet Year
Discharge (cfs)
2500
2000
1500
1000
500
0
1/00
2/00
3/00
4/00
5/00
6/00
7/00
8/00
9/00
10/00
11/00
12/00
1/01
Discharge (cfs)
2500
2000
1500
1000
500
0
1/01
2/01
3/01
4/01
5/01
6/01
7/01
8/01
9/01
10/01
11/01
12/01
1/02
Month/Year

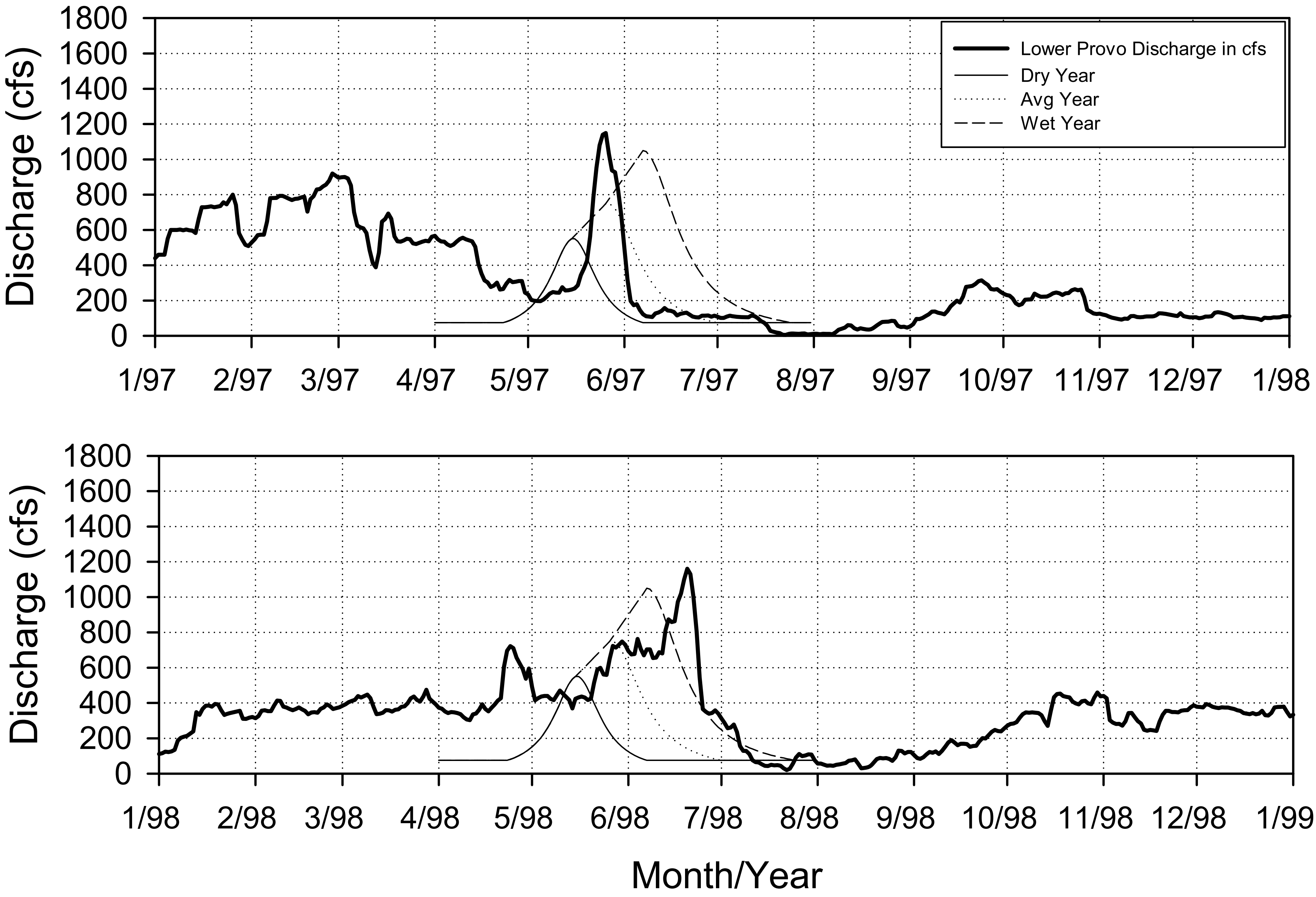

Naturalized Provo River at Hailstone
Dry Year
Average Year
Wet Year
Discharge (cfs)
2500
2000
1500
1000
500
0
1/02
2/02
3/02
4/02
5/02
6/02
7/02
8/02
9/02
10/02
11/02
12/02
1/03
Discharge (cfs)
2500
2000
1500
1000
500
0
1/03
2/03
3/03
4/03
5/03
6/03
7/03
8/03
9/03
10/03
11/03
12/03
1/04
Month/Year

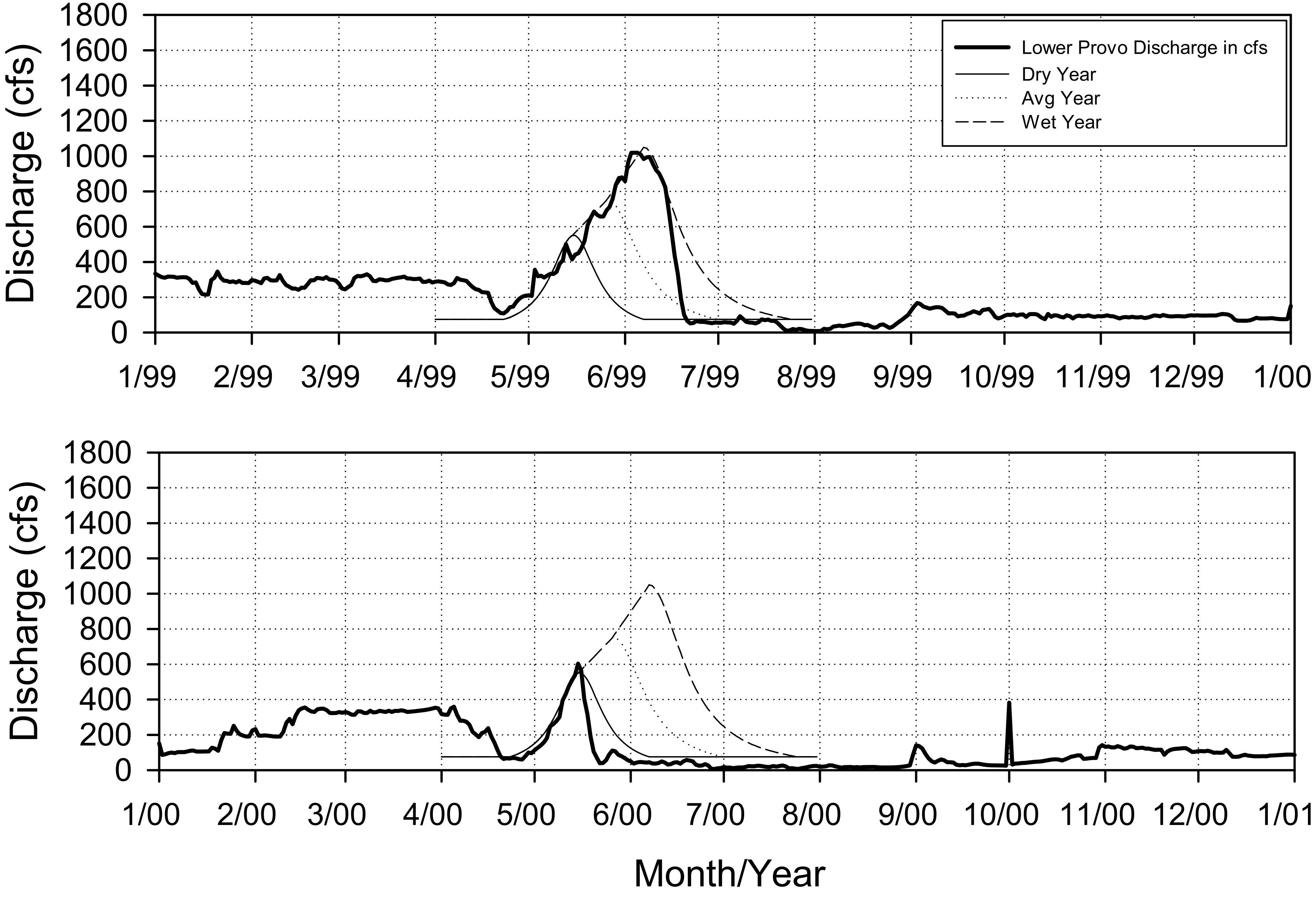

Naturalized Provo River at Hailstone
Dry Year
Average Year
Wet Year
Discharge (cfs)
2500
2000
1500
1000
500
0
1/04
2/04
3/04
4/04
5/04
6/04
7/04
8/04
9/04
10/04
11/04
12/04
1/05
Discharge (cfs)
2500
2000
1500
1000
500
0
1/05
2/05
3/05
4/05
5/05
6/05
7/05
8/05
9/05
10/05
11/05
12/05
1/06
Month/Year


Discharge (cfs)
2500
2000
1500
1000
500
0
1/06
2/06
3/06
4/06
5/06
6/06
7/06
8/06
9/06
10/06
11/06
12/06
1/07
Month/Year

APPENDIX I: PLOTS OF ACTUAL LOWER PROVO RIVER FLOWS VERSUS EXISTING TARGET HYDROGRAPHS


Lower Provo Discharge in cfs
Dry Year
Avg Year
Wet Year
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/95
2/95
3/95
4/95
5/95
6/95
7/95
8/95
9/95
10/95
11/95
12/95
1/96
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/96
2/96
3/96
4/96
5/96
6/96
7/96
8/96
9/96
10/96
11/96
12/96
1/97
Month/Year


Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/97
2/97
3/97
4/97
5/97
6/97
7/97
8/97
9/97
10/97
11/97
12/97
1/98
Lower Provo Discharge in cfs
Dry Year
Avg Year
Wet Year
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/98
2/98
3/98
4/98
5/98
6/98
7/98
8/98
9/98
10/98
11/98
12/98
1/99
Month/Year


Discharge (cfs)
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1600
1400
1200
1000
800
600
400
200
0
1/99
2/99
3/99
4/99
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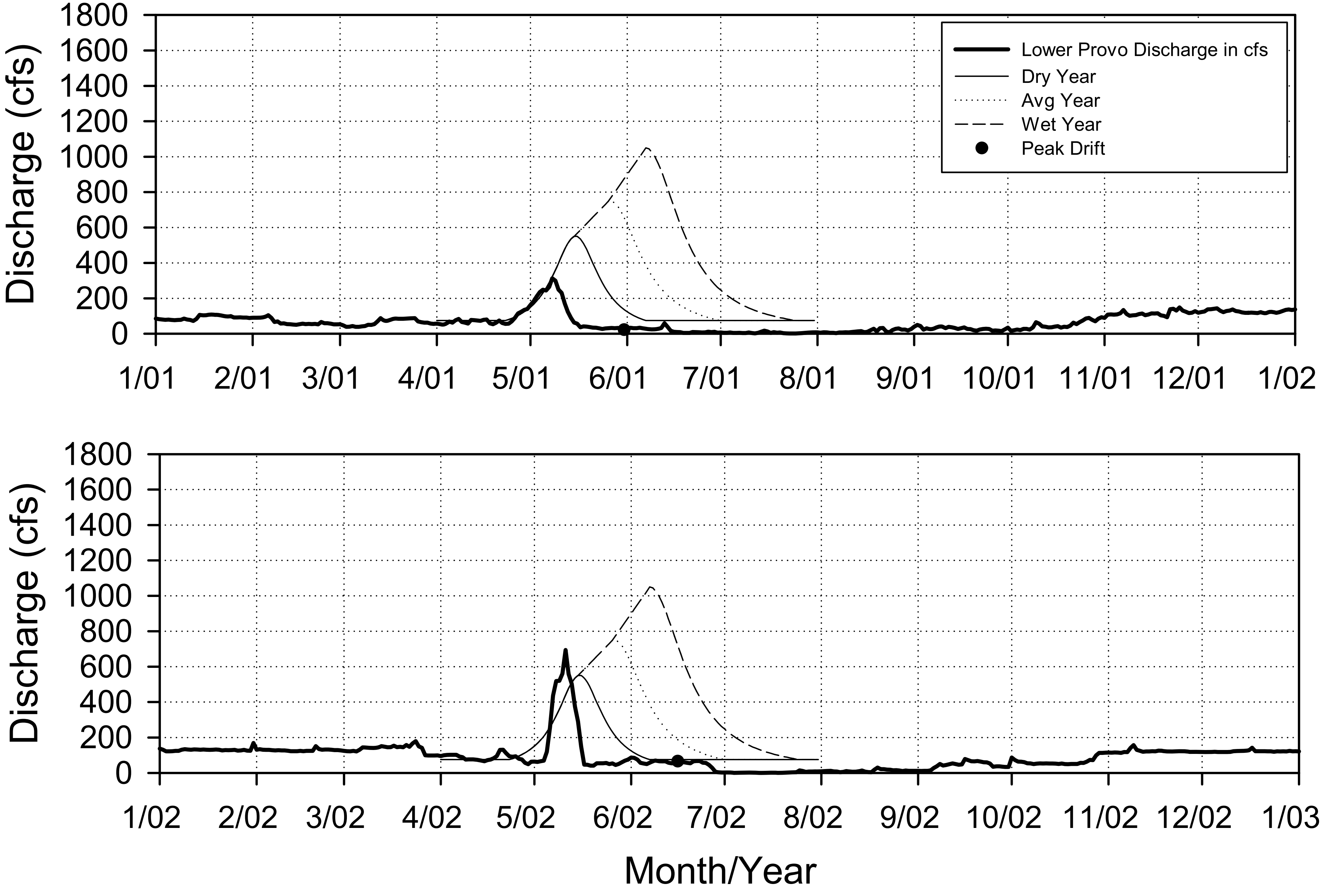
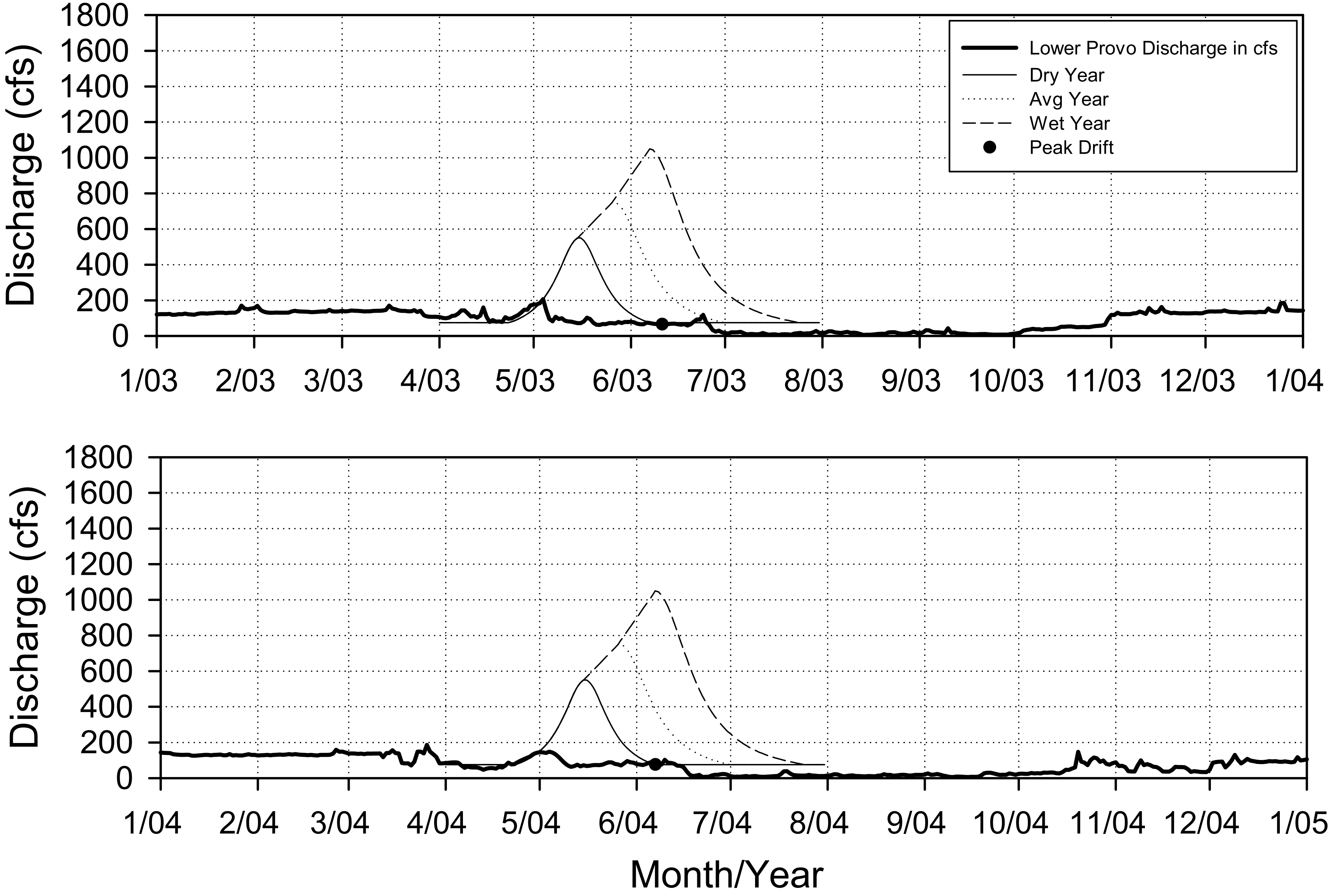
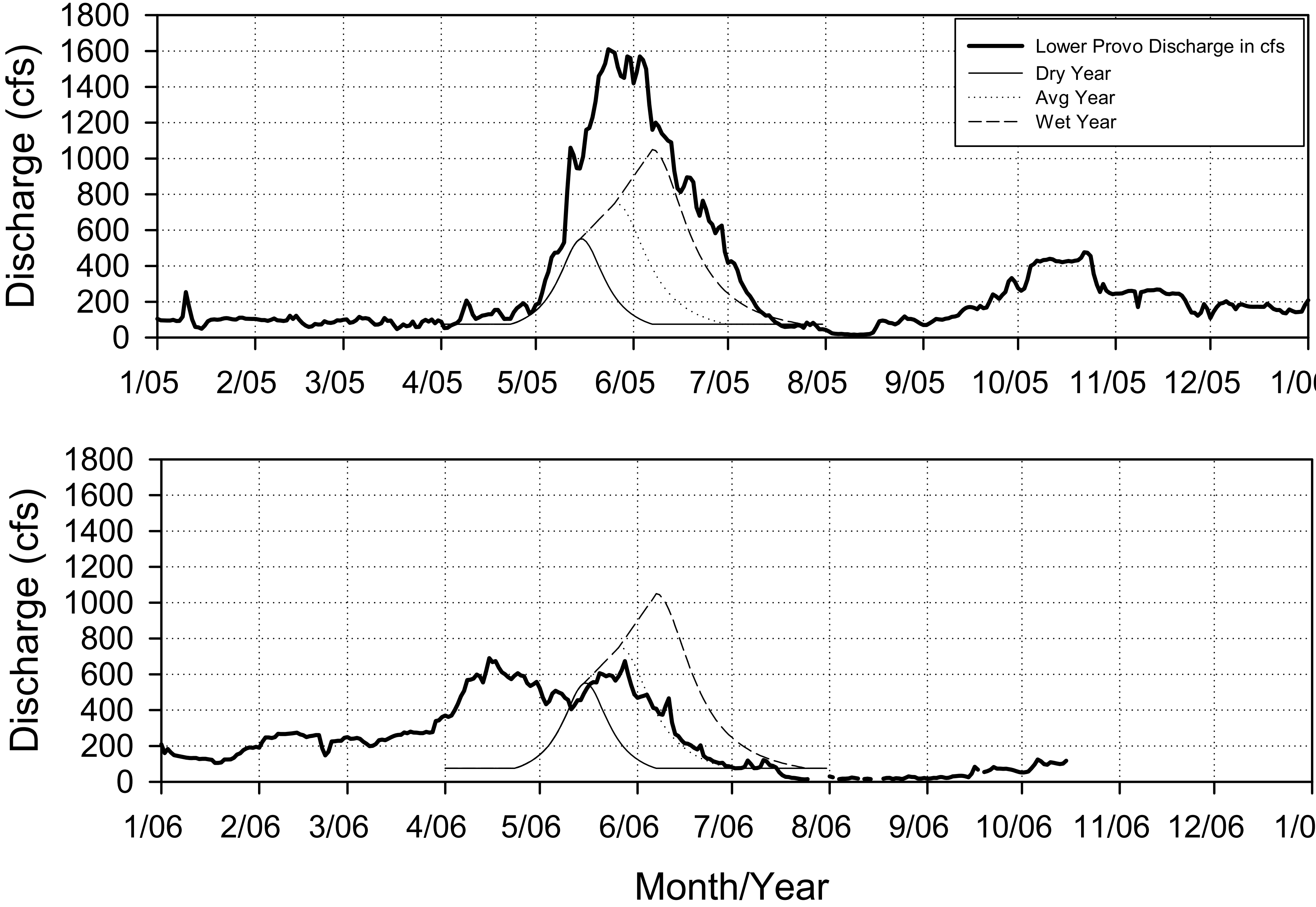
6/99
7/99
8/99
9/99
10/99
11/99
12/99
1/00
Lower Provo Discharge in cfs
Dry Year
Avg Year
Wet Year
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/00
2/00
3/00
4/00
5/00
6/00
7/00
8/00
9/00
10/00
11/00
12/00
1/01
Month/Year


Lower Provo Discharge in cfs
Dry Year
Avg Year
Wet Year
Peak Drift
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/01
2/01
3/01
4/01
5/01
6/01
7/01
8/01
9/01
10/01
11/01
12/01
1/02
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/02
2/02
3/02
4/02
5/02
6/02
7/02
8/02
9/02
10/02
11/02
12/02
1/03
Month/Year


Lower Provo Discharge in cfs
Dry Year
Avg Year
Wet Year
Peak Drift
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/03
2/03
3/03
4/03
5/03
6/03
7/03
8/03
9/03
10/03
11/03
12/03
1/04
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/04
2/04
3/04
4/04
5/04
6/04
7/04
8/04
9/04
10/04
11/04
12/04
1/05
Month/Year


Lower Provo Discharge in cfs
Dry Year
Avg Year
Wet Year
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/05
2/05
3/05
4/05
5/05
6/05
7/05
8/05
9/05
10/05
11/05
12/05
1/06
Discharge (cfs)
1800
1600
1400
1200
1000
800
600
400
200
0
1/06
2/06
3/06
4/06
5/06
6/06
7/06
8/06
9/06
10/06
11/06
12/06
1/07
Month/Year