THE GEOMORPHIC BASIS OF COLORADO SQUAWFISH NURSERY HABITAT

IN THE GREEN RIVER NEAR OURAY, UTAH

by

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ABSTRACT

The Geomorphic Basis of Colorado Squawfish Nursery Habitat in the Green River Near Ouray, Utah

by

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Nursery habitat availability is considered a bottleneck to successful recruitment of Colorado squawfish (*Ptychocheilus lucius*). Detailed geomorphic studies were conducted in a 1.5-km reach to examine channel response to flows and the geomorphic setting of nursery habitats during a 2-year period. Videography was used to extend relationships in the 1.5-km reach to a longer 10-km reach.

Nursery habitat availability varied yearly with little persistence in location or geomorphic setting of individual habitats for the 2 years of this study. A small number of habitats provided most of the area of high-quality (i.e., deep) habitat, and most of the total area of habitat was formed by three geomorphic classes. Although the 1993 flood reduced the area of available habitat, area of deep habitat increased. The 1994 low-peak flood increased the area of habitat, but most habitats were shallow.

The 1993 and 1994 multi-peaked habitat availability curves for the 1.5-km-reach bank-attached bar were the result of the superposition of curves from habitats in each geomorphic classification, and showed that the discharge that maximized habitat availability changed yearly. A complexity index was evaluated for the 10-km reach as surrogate for habitat availability. Total base-
flow habitat availability was significantly correlated to the complexity index, but deep habitat availability was not.

Measured channel topography was used as input to a flow and sediment transport model. Simulated hydrograph runs produced greater bank-attached bar aggradation and thalweg scour than steady flows, although some unrealistic patterns of scour occurred.

New flow recommendations must include occasional high flows sufficient to rebuild channel topography. Flaming Gorge Dam releases should be used to augment the Yampa River flood peak, but not increase low flood-peak duration. The conceptual model for habitat availability developed here may be used to target the formation and availability of habitats. Base flow recommendations designed to maximize habitat availability should be evaluated annually. Winter flows should be reevaluated for their negative effects on habitat.
ACKNOWLEDGMENTS

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Conversations and field surveys with Melissa Trammel, UDWR, provided valuable insight into the habitats and ecology of juvenile Colorado squawfish. Kelli Stone and Dan Schaad, Ouray National Wildlife Refuge, facilitated our work on the Refuge. Pete Cavalli provided field support far beyond the call of duty. Andrew Rakowski provided computer support at USU and field assistance on many occasions, and Nathan Bentley provided on-call GIS support.

C. L. Rakowski
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INTRODUCTION

Nursery habitat availability is considered a bottleneck to successful recruitment of the endangered Colorado squawfish (*Ptychocheilus lucius*) [Tyus, 1991]. This study evaluated the geomorphic basis of nursery habitat and year-to-year changes in habitat availability in order to improve recommendations for flood flows that form and maintain nursery habitat and for low flows at which these habitats are used.

Nearly every major river in the western United States is controlled by one or more large dams. Much research has shown that the river downstream from a dam adjusts physically, and its waters may change chemically and biologically, after dam completion [e.g., Williams and Wolman, 1984; Tyus, 1992]. These changes affect the downstream river and its floodplain. The dams of the Colorado River basin, such as Flaming Gorge Dam on the Green River, Utah, have greatly altered the river corridor, and these ecosystem changes are believed to be a factor in the decline of endangered fish populations to critical levels [Minckley and Deacon, 1991]. One of the many dam-related factors that may be responsible for the demise of these populations is the availability of nursery habitat for larval fish [Tyus and Karp, 1991]. Consequently, species recovery, as mandated by the Endangered Species Act (ESA), will in part depend on enhancement of available nursery habitat.

The purpose of this research was to evaluate the geomorphic basis of nursery habitat, and to determine if there are annual changes in nursery habitat availability for the endangered Colorado squawfish within the Ouray National Wildlife Refuge (Ouray NWR) near Ouray, Utah (Figure 1). Unlike previous efforts to quantify nursery habitat in the Green River [e.g., Pucherelli et al., 1990], I integrated interdisciplinary data from multiple spatial scales collected during a multiyear period. I used these data to address how nursery habitat characteristics and availability are affected by different flow regimes of the Green River. Results from this research may improve recommendations for releases from Flaming Gorge Dam that form, maintain, and maximize Colorado squawfish nursery habitat. The objectives of this study were to determine the bed- and barforms that create
Fig. 1. General and detailed location maps for the study reaches. North is toward the top of the page, flow is from north to south. (a) The Green River basin spans parts of Wyoming, Colorado and Utah. Below Flaming Gorge Dam, the Green River crosses the Uinta Mountains and flows through the Uinta Basin (b). A 10-km alluvial reach of river within the Ouray NWR (c) was monitored using remotely-sensed data, and a 1.5 km subreach (d) was the site of intensive studies.
nursery habitat, the effect of habitat-forming geomorphic features on the flow field at low flow, the relationship between habitat availability and discharge, and the year-to-year changes in habitat availability caused by different flood flows and subsequent low flows.
LITERATURE REVIEW

Sand-bedded rivers have been the focus of much study, often because of their impact on humans. Early engineering studies focused on reducing the impacts of flooding and migrating rivers on human structures, but more recently geomorphologists have endeavored to improve the understanding of why and how rivers form, migrate, and change. Only recently have geomorphologists combined their efforts with biologists and ecologists to discern the effects of physical attributes and changes in those attributes on the ecology of river systems.

Geomorphology of Sand-Bedded Rivers

Self-Formed Channels

Continually adjusting streams that flow within banks composed of material previously transported by the river are termed self-formed channels and are the focus of long-standing geomorphic research. The Green River within the alluvial Ouray NWR reach is an example of a self-formed channel. For self-formed channels, the channel form at a given cross section is determined by discharge, quantity and character of the sediment in transport, and bank and bed characteristics [Leopold et al., 1964]. Consequently, in channels with a moveable bed and banks, channel form results from the dynamic interaction of bank stability, flow, and sediment transport [Leopold et al., 1964]. This relationship is dynamic because in natural rivers neither bank and bed material nor flow conditions are uniform in space or time.

Classic geomorphic research on self-formed streams such as Watts Branch (Maryland), Brandywine Creek (Pennsylvania), and Baldwin Creek (Wyoming) measured characteristic parameters of streams such as the spacing of pools and riffles, distribution of sediment sizes on the bed, bedload movement, channel shape through meanders, velocity distribution within cross sections, and the relationship between flood recurrence and bankfull channel size [Leopold et al., 1964].
These studies quantified many geomorphic relationships, but they did not reveal the physical processes underlying those relationships. More recent work, at both large (kilometers) and small (meters) scales, has endeavored to study and model the physical processes that create channel form.

Meandering Rivers

Self-formed channels have been classified as straight, meandering, braided, or anastomosing; each planform type is a response to the interaction of discharge, sediment size and availability, and bank and bed characteristics [Rosgen, 1994; Leopold et al., 1964]. Subsequent work has shown that these forms actually describe end-members of a continuum of channel patterns that have many causes [van den Berg, 1995]. Early studies argued that braided streams typically have high sediment loads in relation to transport capacity, straight rivers have low sediment loads, and meandering rivers have approximately equal sediment loads and transport capacity [Leopold et al., 1964].

Much controversy has surrounded the origins of flow meandering. Is meandering caused by the deflection of current around alternate bars, causing additional deposition on the bars and erosion on the exterior of the bend, or are the barforms determined by the flow patterns? What physical properties control meander wavelength and amplitude? Rhoads and Welford [1991] noted that no universal theory of meandering initiation has emerged, although the most promising developments have come from the modeling of fluid dynamics and sediment transport [e.g., Seminara and Tubino, 1989; Nelson and Smith, 1989a,b].

Leopold et al. [1964] noted that the form of meanders varies greatly, and that the amplitude of meanders was probably related to the erosional characteristics of the bank sediments. Ikeda [1989] investigated the sedimentary controls on river form and classified meandering rivers into four types: (1) fixed meanders, (2) restricted meanders, (3) confined free meanders, and (4) true free meanders. The meanders of the Green River through the central Uinta Basin and Ouray NWR are
restricted by resistant deposits of Pleistocene age [Schmidt, 1994]. Ikeda [1989] determined that bar form and characteristic in restricted meander reaches are products of the meandering flow rather than causing the meandering flow.

The Green River in the Ouray NWR is, at high flow, a meandering, single-threaded channel between two well defined banks. In some years, the Green River at low flow is multithreaded, with flow divided by emergent midchannel bars. Consequently, the Green River exhibits characteristics of both meandering and braided rivers.

Bars

There are two dominant research approaches that have considered bar forms. One approach has focused on describing the topographic and sedimentologic features of different systems. Another approach is to determine the physical processes that produce bar features.

Geomorphologic research continues on river bedforms [e.g., Rajaguru et al., 1995; Bridge and Gabel, 1992; Gabel, 1993; Brierley, 1991; Rubin et al., 1990; Crowley, 1983], and the debate on the classification and naming of those features also continues. Many researchers consider the bedforms between ripples and upper plane bed as a continuum of what should be called “dunes” [Ashley, 1990]. These “dunes” have wide-ranging spacing from less than 1 m to greater than 1000 m. However, the terminology commonly understood by ecologists and geomorphologists is defined in the following paragraphs and used to describe the bed- and bar forms of importance to this study.

In sand-bedded rivers, many large-scale geomorphic sediment features form at higher “channel-forming” flows and are exposed by subsequent lower flows [Crowley, 1983]. Many forms of these within-channel features, such as bars, exist [Brierley, 1991]. Bars have lengths of the same order as the channel width, and heights of the same order as the mean depth of the generating flow [Yalin, 1992]. Alternate bars form in both straight and meandering channels, and occur periodically along alternating banks as the thalweg meanders between bars at low flows [Leopold et al., 1964].
Alternate bars may migrate in the downstream direction, or they may be fixed in their location. Point bars occur on the inside of meander bends and are, in part, a product of helical flow in the bend [Leopold et al., 1964; Ikeda, 1989]. Midchannel bars, typically found in braided rivers but also in some meandering rivers, are roughly diamond shaped, and align with and split the low flow [Leopold et al., 1964]. Midchannel bars are transient in nature, but point bars are stationary features. The midchannel and some superimposed bars of the Green River within Ouray NWR are similar to those described by Cant and Walker [1978] in the braided South Saskatchewan River of Canada. Portions of cross-channel bars emergent at low flow accrete additional sediment at low flow, creating sand flats just above base flow level.

In this research, I use the terminology of Brierley [1991] to describe some distinguishing characteristics of these bars (Figure 2). Chute channels are any short-circuiting channel across a bar. A secondary channel is a chute channel that occurs on the shoreward side of a bank-attached alternate bar. Bank-attached bars occur along the margins of the channel although at some discharges these bars may be separated from the bank by secondary channel flows. Bank-attached bars with laterally dissecting chute channels are referred to as bank-attached compound bars, even if the chute channels are inactive at some discharges.

Bars within a channel migrate downstream or are stationary in location. Within the Ouray NWR, the location of bars has been relatively constant over the last 30 years [Andrews and Nelson, 1989]. Ikeda [1989] described two types of stationary bars observed for rivers with restricted meanders: fixed and forced. Ikeda used flume study results to explain the processes that produce each bar type. Migrating alternate bars become fixed when the deflection angle of a meander exceeds a critical value of about 20° [Ikeda, 1989]. Forced bars form only in response to the pattern of flow through a bend [Ikeda, 1989] and are commonly called point bars. Within the Ouray NWR, both fixed bank-attached compound bars and forced point bars exist.
Fig. 2. Detailed topographic maps of the study bar in 1993 and 1994 showing the three units that compose the bar as determined by elevation. Contour interval is 0.25 m and flow is from the top of the page. Dark shading with “plant” pattern indicates the high-elevation area stabilized by vegetation, the stippling indicates white sand, and dark shading shows the dark and wet sand.
Floods

Measuring changes in channel form during flood passage is more difficult than observing the resultant morphology at low flow. Much of our understanding of channel response to flood passage comes from measurements made at USGS cableways. Measurements made at these sites show that sand-bedded alluvial rivers typically scour on the ascending limb and fill on the descending limb of floods, although Leopold et al. [1964] noted that cableway cross sections may be biased by their siting in pool sections of rivers.

Leopold et al. [1964] used the response of the Colorado River at Lees Ferry to the passage of the 1956 spring flood as an example of the typical response of sand-bedded rivers at gaged cross sections. The bed scoured approximately 3 m on the ascending limb of the hydrograph. The maximum depth of scour and the flood peak coincided. The bed subsequently filled on the descending limb to about the pre-flood level [Leopold et al., 1964]. Additional work on the Rio Grande del Ranchos, a tributary of the Rio Grande in New Mexico, and Baldwin Creek and Popo Agie River in Wyoming found net scour at flood peak over long reaches containing both pools and riffles [Leopold et al., 1964]. Colby [1964] found that single cross-section measurements, such as those made at gaging stations, could not be used to characterize the behavior of a stream reach, however. Cross sections within a single reach could be characterized as either filling or scouring cross sections, with fill or scour occurring on both the ascending and descending limb of the flood. In addition, Colby [1964] found that streams typically adjusted to changing discharge by changes in the water surface elevation rather than by scour or fill of the stream bed. Consequently, cross-section studies to characterize river response to flood passage must include cross sections spaced throughout a representative reach.

Discharge measurement records from the discontinued USGS gaging station near Ouray (station number 09307000) surveys were analyzed by Schmidt [1994]. His analysis for the gage
Fig. 3. Water surface and thalweg elevation for the US Geological Survey stream gage Green River near Ouray, Utah for the period 1951 to 1965. The thalweg at the gage scoured on the ascending limb of the flood hydrograph, but quickly returned to its pre-flood elevation. This demonstrates the dynamic nature of the Green River, even at a "stable" site deemed suitable for a USGS gage.

cross section showed an annual scour and fill cycle of about 3 m during the passage of the spring flood (Figure 3). Scour occurred on the ascending limb of the hydrograph, and filling occurred during the descending limb and subsequent low flows. As described below, this pattern of scour and fill was similar to the pattern that was observed at some cross sections within the detailed study reach, both in terms of depth of scour and timing of scour and fill.

For sand-bedded rivers, bedload is typically 10 to 35 percent of the suspended sediment load [Lane and Borland, 1951], so that most sediment is transported by suspension. Bed scour in sand-bedded rivers occurs during floods by the entrainment of bed sediment, and the sediment in motion moves at a much slower rate than the water flow. Increased sediment concentrations reduce water velocities, further decreasing the rate of transport. Thus, large volumes of sediment may be in transport, but the net change in sediment storage within a reach may be small [Leopold et al., 1964]. It should be noted that, even for rivers transporting large quantities of sediment, the amount of
sediment transported is small compared to the amount of sediment stored on the bed, banks, and in the floodplain.

Long-Term Channel Response

The response of rivers to disturbance is of concern to geomorphologists, ecologists, and engineers. A “disturbance” to a river may be either natural, such as the passage of a very large flood, or human induced, such as the closure of a dam. Regime theory considers a river to be an equilibrium expression of the long-term average of the hydrology of a basin [Yu and Wolman, 1987], but on a year-to-year scale natural rivers are highly variable.

Yu and Wolman [1987] developed a conceptual model to simulate the dynamic adjustment of alluvial river width. They modeled channel width as a function of present discharge and past high flow events; the most recent events were given greater weight in the model, and the geomorphic importance of past events decreased with time. Yu and Wolman’s [1987] model simulated channel widening caused by high flow events and the subsequent recovery, or narrowing, during later lower flows. This model shows that the expected channel form of natural rivers varies over time and is not static; increases in channel width occur when certain threshold discharges are exceeded. In addition, channel narrowing continues until the peak discharges are sufficient to maintain or increase channel width.

Prior to dam closure, the higher magnitude, but highly variable, flood peaks of the Green River formed a channel that was wider than that the current river [Andrews, 1986; Lyons et al., 1992]. Channel widening and narrowing have both occurred since closure of Flaming Gorge Dam [Lyons et al., 1992], but the net trend has been narrowing due to lower mean channel-forming flows, a result consistent with the simulation model results of Yu and Wolman [1987].
Numerical Modeling of Flow and Sediment Transport in Natural Channels

To design flood flows that will improve and enhance habitats, it is necessary to predict bar and bed response to high flows and bed evolution during passage of a flood. The 3-dimensional flow of water in rivers is very complex. Empirical models of river flow reduce this complex system to a simpler 1- or 2-dimensional system with empirically derived coefficients. An often employed example of this type of model is the HEC-2 model developed by the US Army Corps of Engineers [HEC, 1982]. Cross-sectional data and a channel roughness coefficient are used in the HEC-2 model to calculate water surface profiles for river reaches. This model assumes steady, uniform flow and predicts water surface elevations. However, this 1-dimensional model provides no information on the lateral distribution of hydraulic properties. More recent modeling efforts recognize that 3-dimensional properties such as topographically induced convective accelerations, secondary circulation, and the distribution of boundary shear stress within the curvilinear 3-dimensional channel are critical to determining patterns of erosion and deposition [e.g., Nelson and Smith, 1989a; Smith and McLean, 1984; Engelund, 1974].

An orthogonal streamwise coordinate system appropriate for 3-dimensional stream models was developed by Smith and McLean [1984]. The Navier-Stokes equations, the equations of motion which consider local and convective accelerations in fluids, were transformed to a streamwise coordinate system and formed the basis of a numerical flow model. Smith and McLean [1984] compared modeled results for bottom shear stress and free surface elevation with those measured in Hooke's [1975] flume experiments in a fixed-bed sinusoidal channel. The Smith and McLean [1984] model produced the same pattern of boundary shear stress, although the maximum boundary shear stress was underestimated and the area of low boundary shear stress extended too far downstream.

Nelson and Smith [1989a,b] refined and expanded the model of Smith and McLean [1984].
The revised model allowed variation in channel width, accounted for the presence of bedforms, and predicted sediment transport. Numerical results for boundary shear stress, sediment transport, and vertically averaged velocity compared well with the field measurements by Dietrich [1982] in Muddy Creek, Wyoming. Nelson and Smith [1989b] used sediment transport equations [Yalin, 1963] to predict bed evolution. This improved approach allowed the simulation of bed evolution and bar genesis in natural channels. Simulation results of the bed evolution model were compared with results from Hooke's [1975] flume experiments. The topography predicted by the model was very similar to that produced in the flume, although location of the deepest scour was predicted downstream rather than upstream from the bend apex. Overall, the agreement between the sediment fluxes and bottom stresses was good.

The expanded model of Nelson and Smith [1989b] was applied to a river reach within the Ouray NWR by Andrews and Nelson [1989]. Cross-section topography measured at a discharge of 275 m$^3$/s was used as model input, and response of the channel was predicted for steady flow at three discharges (50, 275, and 475 m$^3$/s) for 2-day periods. Model results were not validated, but the calculated distribution of unit discharge and sediment transport compared well to field measurements [Andrews and Nelson, 1989]. Model results indicated that the river bed adjusted quickly to changes in discharge.

Channel form and discharge determine the availability of nursery habitat. Because channel form reflects antecedent flows as well as discharge, nursery habitat availability is, in part, a product of antecedent flows. Although it is not possible to experimentally measure the response of the channel to all flow scenarios, it is desirable to predict channel response and, hence, habitat availability for many scenarios. In the Green River basin, only one "experiment" or flood occurs each year, and the magnitude and timing of releases from Flaming Gorge Dam are regulated by many laws. Therefore, each experiment has different antecedent conditions and it is not possible to
conduct an infinite array of scenarios. As an alternative to physical experimentation, a flow and sediment transport model that simulates bed evolution may be used to model bed and bar response to flood passage. The model used by Andrews and Nelson [1989] is an example of such a flow and sediment transport model, and may be an appropriate tool to model changes in channel topography in response to varied flow in the Upper Colorado basin. Stanford [1994] stated that the Andrews and Nelson [1989] model was potentially an appropriate addition to the Upper Colorado basin research program.

Flow Recommendation Research

Historically, instream flow recommendations have been based on the flows necessary for maintaining a suitable amount of fish habitat during base flows [e.g., Tennant, 1975]. More recent work suggests that a suite of flows is necessary to maintain ecological integrity of fish habitat rather than just protecting the habitat at base flows [Hill et al., 1991]. This latter approach is based on the assumption that habitat and nutrient availability for the fishes require maintenance of the linkages between the stream and riparian, floodplain and upland areas.

Two philosophies have shaped the design of instream flow for Colorado River native fishes [Tyus, 1992]. The first philosophy is to provide minimum flows needed for species survival during periods of low river discharge. These minimum flows do not ensure availability of optimal habitat, but seek to maintain and maximize the availability of existing habitat. The second philosophy is to assist species recovery by increasing the availability of optimal habitats, requiring that existing habitat be improved, and restoring "lost" habitats (i.e., habitats that are no longer formed or available as a consequence of flow regulation). "Optimal" habitats under regulated conditions include conditions of altered river hydrology and the presence of exotic species, and are not the pristine river conditions that existed prior to regulation. For example, a habitat that was optimal
prior to river regulation may no longer be optimal due to its use by predatory species. For species recovery to occur in a system as altered, both physically and biologically, as the Green River, the second philosophy, with its emphasis on optimal habitats and increased habitat availability, is the only viable option for species recovery.

**Multiscale, Multiflow Studies**

Ligon et al. [1995] noted the need for multiscale, interdisciplinary studies to quantify and mitigate the downstream effects of dams. Hill et al. [1991] integrated several standard assessment methods into a methodology for determining the suite of flows necessary to maintain ecological integrity and applied their methodology to the Salmon River at Whitebird, Idaho. They noted the need for four flow components: base flows for fish, and channel-, riparian-, and valley-process maintenance flows. Each of these flows inundated different ecosystems (e.g., stream channel and riparian ecosystem), and combinations of methodologies were necessary to evaluate the appropriate flow regime for each component.

**Base Flows**

Habitat availability curves were first developed for cold headwater streams to assess the effects of water diversions on standing crops of fish [Nesler, 1990]. The US Fish and Wildlife Service’s Instream Flow Incremental Methodology (IFIM) and Physical Habitat Simulation system (PHABSIM) [Bovee, 1982] are widely used to predict discharge-dependent changes in area of available habitat. PHABSIM uses suitability curves determined from measurements of physical parameters to model weighted usable area (WUA), a surrogate for the area of available habitat for a target species. This model assumes that a positive, linear relationship exists between WUA and fish biomass, which implies that the target fish population is habitat limited [Mathur et al., 1985].

PHABSIM [Bovee, 1982] was used by Hill et al. [1991] to quantify the low-flow habitat
needs of targeted fish species. Targeted fish species locations were marked while snorkeling, and physical parameters for microhabitat use—depth, velocity, cover, substrate, and distance to cover—were determined for each location. Suitability weighting factors were developed for each parameter and the weighted usable area (WUA) calculated. The stream and the accompanying physical parameters were then modeled for a variety of discharges, and areas of optimal, usable, and unsuitable habitat were calculated for a range of low flows.

Riparian and Valley Flows

Hill et al. [1991] used HEC-2 modeling to determine discharges for bankfull, riparian, and floodplain flows. These modeled discharges were combined with historic exceedance probabilities for peak flows and flow duration curves to determine the magnitude, duration, and hydrograph shape of different flow regimes (for example riparian vs. valley flows). Hill et al. [1991] assumed that the restoration of a "natural" hydrograph would guarantee ecological integrity, but they ignored many of the other consequences of stream alteration such as changes in temperature, sediment load, sediment availability and size distribution, and water quality.

Complexity Indices

Complexity indices based on physical habitat parameters such as depth, water velocity, and substrate size have been related to habitat complexity in cold water streams [Bovee, 1982]. In that light, some river ecologists have used a "bank coefficient" [Gosse, 1963, as cited in Sedell, 1989] to measure river heterogeneity and hence, habitat heterogeneity or complexity [Sedell, 1989]. The "bank coefficient" is the ratio of shoreline length to channel centerline length, and quantifies the relative amount of shoreline per unit length of river [Gosse, 1963, cited in Sedell, 1989]. High values of the bank coefficient indicate the presence of islands and/or bank irregularities. Consequently, a complexity index such as the bank coefficient reflects within-channel morphology.
In the context of nursery habitat, the convoluted nature of the shoreline may be indicative of the area of low or no velocity areas within the channel. The Green River near Ouray includes midchannel bars and some very large vegetated islands. As is shown below, these features greatly increase the length of shoreline, but do not necessarily contribute to nursery habitat area, and the "bank coefficient" of Gosse [1963] may be only weakly correlated to habitat availability in this reach. Consequently, a complexity index that, to some degree, minimizes the effects of midchannel bars and large islands may be more desirable for reaches such as Ouray NWR.

Previous Green River Instream Flow Studies

Although sand-bedded rivers and the response of these rivers to flow regulation have been the focus of much study over the past three decades, many questions remain unanswered. The response of channels to disturbance was studied by Andrews [1986], Lyons et al. [1992], and Yu and Wolman [1987]. The first two studies addressed the long-term downstream effects of Flaming Gorge Dam and the latter study modeled the response of channels to flood passage, but all of these studies used channel width, not within-channel distribution of bars, to measure channel response. Colorado squawfish use habitats formed in the lee of within-channel bed- and barforms. Consequently, the long-term measurements used to assesses the effects of dams (i.e., changes in channel width) measure neither changes to within-channel geomorphic features nor the impact of channel changes on habitat availability.

Changes in nursery habitat availability within five alluvial reaches of the Green River were quantified by Pucherelli et al. [1990]. They used remotely gathered data from five different discharges over a 4-month period in 1987 to develop a correlation between habitat availability and discharge, but found the relationship between habitat availability and discharge at Ouray to be the weakest of the five reaches. Backwaters next to the bank were much more abundant than
midchannel-bar backwaters, and there were more very large (>1000 m$^2$) backwaters in the Ouray reach than in the other sampled reaches. Stanford [1994] noted that the relationship developed by Pucherelli et al. [1990] for a single year's topography would only be valid for that year, and would likely change in subsequent years as the channel morphology changed in response to flood peaks. Habitat availability at base flow is a product of channel morphology, and within-channel morphology in this dynamic system may vary greatly from year to year. Thus, from a geomorphic point of view, annual variability in habitat availability is expected.

Need for a New Methodology

Multiscale methodologies are necessary to determine flows that maintain low-flow habitat availability and the large magnitude floods that form habitats. Neither PHABSIM nor the methodology of Pucherelli et al. [1990] accounts for the dramatic changes in channel morphology that occur from year to year in alluvial rivers, nor do they consider competition and predation pressures [Mathur et al., 1985] that are presumed to be significant in the Green River [Tyus, 1992]. These methods are inappropriate tools for the Green River [Tyus, 1992]. Thus, a new methodology must be developed to determine the effect of low-flow variation on habitat availability. The 2-dimensional HEC-2 modeling and historic hydrology do not provide information on channel response to flood passage, but a 3-dimensional flow and sediment transport model can simulate the response of channel topography to flood passage. The long-lived endemic Colorado River fishes, including the Colorado squawfish, are adapted to not require successful recruitment each year for species survival [Minckley and Deacon, 1991]. Consequently, the short-term high-discharge disturbances necessary to maintain long-term channel structure may be viewed as a viable river management tool.
OVERVIEW OF GREEN RIVER PHYSIOGRAPHY, HYDROLOGY, AND RESPONSE TO FLAMING GORGE DAM

Physiography

The Green River is the longest tributary of the Colorado River, draining approximately 115,800 km² (Figure 1). The mainstem of the Green River has its headwaters in the Wind River Range of Wyoming. The Yampa River, the Green River’s largest tributary, has its headwaters in the Park Range of Colorado and supplies almost half of the Green River’s water. Flaming Gorge Dam, located 662 river kilometers upstream from the Green River’s confluence with the Colorado River, has regulated the flow of the mainstem of the Green River since October 1962. The Yampa River remains largely unregulated.

The longitudinal profile of most large rivers is generally concave up [Leopold et al., 1964], and has larger bed material and steeper gradients in the headwaters and lower gradients and smaller grain size downstream. The Green River below Flaming Gorge Dam passes through formations of differing erosional resistance [Schmidt and Rubin, 1995], such as the harder, resistant Uinta Mountain group in Dinosaur National Monument [Hansen, 1986], the less resistant Duchesne and Uinta Formations of the central Uinta Basin, and the more resistant Mesa Verde sandstone in Gray Canyon. The channel shape and gradient are partly adjusted to these varying resistances [Grams and Schmidt, in press]. Downstream from Flaming Gorge Dam, the Green River has steep-gradient, eddy-dominated canyon reaches with large bed material interspersed with low-gradient, sand-bedded alluvial reaches and forms a complex longitudinal profile (Figure 4) [Schmidt, 1994; Schmidt and Rubin, 1995]. The Green River in the central Uinta Basin is the area of interest for this study. In this area, the Green River has the lowest gradient of any reach of the Green River in Utah, and is sand-bedded. The study reach is located within the Ouray National Wildlife Refuge.
Hydrology

Dams are used to store peak flows for later release during low flow periods for irrigation and other "beneficial" uses. Although the magnitude and duration of peak and base flow have changed dramatically, the total annual stream flow \(3.9 \times 10^9 \text{ m}^3\) of the Green River is essentially unchanged by Flaming Gorge Dam [Andrews, 1986].

The annual hydrograph (Figure 5) of the Green River near Jensen, Utah, is characterized by a spring flood which typically occurs in April, May, and June. The water for this flood originates as snow melt in the headwaters of the Yampa and upper Green River basins. The US Geological Survey (USGS) gage near Jensen (station number 09261000) provides the best measure of flow conditions for the Green River as it flows through the Ouray NWR because no large tributaries enter the river downstream from the gage [Andrews and Nelson, 1989].

Fig. 4. Longitudinal profile of the Green River between Flaming Gorge Dam and the confluence with the Colorado River. Adapted from Schmidt [1994].
Fig. 5. Average annual hydrographs for the Yampa River and the Green River near Jensen, Utah. The effect of Flaming Gorge Dam (FGD) on mainstem flow, and the contribution of the Yampa River to the Green River are demonstrated by comparison of the periods 1947 to 1962 (thin lines) and 1963 to 1994 (thick lines) which represent pre- and post-dam conditions, respectively.

Floods

The magnitude of the spring flood near Jensen, Utah, has been reduced since the closure of Flaming Gorge Dam (Figure 6) [Schmidt, 1994]. The 2-, 5-, and 10-year recurrence floods have been reduced by 26, 19, and 13 percent, respectively, from the period prior to dam closure (1923 to 1962) compared to the period after dam closure (1963 to 1993) (Table 1) [Schmidt, 1994]. Schmidt [1994] used correlations between the USGS gage near Jenson and other gages to extend the Jensen gage record to include the period 1923 to 1947.

Prior to this study, 6 years of drought occurred in the study area (Figure 7). The annual peak flows of 1993 and 1994, the period of this study, were each less than the pre-dam 2-year recurrence flood (622 m$^3$/s). The magnitude of the 1993 flood (570 m$^3$/s), with an estimated recurrence of 4.5 years for the post-dam period, caused flooding through much of the central Uinta Basin. The flood peak of 1994 was 331 m$^3$/s and was similar in magnitude to those of the period between 1987 to 1992.

<table>
<thead>
<tr>
<th>Years</th>
<th>Recurrence Interval (years)</th>
<th>1.25</th>
<th>2</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
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<tr>
<td>1923-1962</td>
<td></td>
<td>446.4</td>
<td>622.1</td>
<td>791.6</td>
<td>869.6</td>
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<tr>
<td></td>
<td></td>
<td>(15764)</td>
<td>(21967)</td>
<td>(27952)</td>
<td>(30707)</td>
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<tr>
<td>1963-1993</td>
<td></td>
<td>326.3</td>
<td>463.0</td>
<td>640.5</td>
<td>753.3</td>
</tr>
<tr>
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<td>(11521)</td>
<td>(16347)</td>
<td>(22617)</td>
<td>(26598)</td>
</tr>
</tbody>
</table>

Fig. 6. Recurrence interval of instantaneous peak flow for the Green River near Jensen, Utah. Adapted from Schmidt [1994].
Fig. 7. Annual peak discharge for the Green River near Jensen, Utah. Five-year moving average is shown by the solid line [adapted from Schmidt, 1994].

US Geological Survey gage records show that, prior to dam closure, the Yampa River provided slightly less than half of the volume of water for the annual peak discharge. Since the closure of Flaming Gorge Dam, the Yampa provides, on average, three-quarters of the volume of water for the annual peak discharge (Figure 5).

Base Flows

The summer base flows for the period between 1970 and 1990 were much greater than had occurred prior to construction of Flaming Gorge Dam. Since dam closure, September typically has had the lowest mean monthly discharge of the year (Figure 5), although prior to dam closure, December and January typically had the lowest monthly mean discharge of the year. Prior to dam closure, September base flows were typically less than 40 m³/s (Figure 8). After closure of Flaming Gorge Dam, base flows were as high as 85 m³/s and were never less than 55 m³/s between 1970 and
Fig. 8. Five-year moving average of September mean monthly discharge. Prior to dam closure, the September mean discharge was typically the lowest of the year. While the mean September discharges of the 1990s are closer to pre-dam levels than those of the 1970s and 1980s, they still exceed the historic mean discharge for September.

Flaming Gorge, September base flows have been about 42 m$^3$/s. These September flows are more similar to pre-dam conditions.

Winter base flows (i.e., December, January, and February) have also increased since closure of Flaming Gorge Dam (Figure 9). The average winter discharge has more than doubled (Figure 5), and is greater than the current recommended summer discharges, which is between 31 and 51 m$^3$/s. The current flow recommendations establish target summer low flows, but allow a much greater range, between 22.7 and 133.1 m$^3$/s, for winter flows. Overwinter habitat stability and availability are components of successful recruitment, but large discharge variations do not contribute to habitat stability.

Sediment Transport

Within the Green River basin, the sources of water and sediment do not coincide. Most of the water originates in the mountainous headwater regions, whereas most of the sediment is
Fig. 9. Five-year moving averages of mean monthly discharge for December, January, and February. Winter discharges have greatly increased since closure of Flaming Gorge Dam.

Contributed by the lower elevation semiarid regions [Iorns et al., 1965]. Although the peak flows that have the capacity to transport large quantities of sediment are reduced by Flaming Gorge Dam, sediment contributions to the Green River are not strongly regulated by the dam because sediment-laden tributaries enter downstream from the dam. Consequently, the Green River downstream from the unregulated Yampa River is not a sediment-starved system like the Colorado River immediately below Glen Canyon Dam.

Sediment load has been estimated using sediment rating curves and discharge records. Andrews [1986] demonstrated that the sediment rating curve near Jensen, Utah, has not changed since the closure of Flaming Gorge Dam, but that peak discharges and duration of large discharges have been significantly reduced. As a consequence, the mean annual sediment discharge near Jensen, Utah, has decreased by 54 percent to $2.91 \times 10^9$ kg. Andrews [1986] estimated that the sediment transported into the Green River in the reach between the Yampa River confluence and the White and Duschesne Rivers, including the Ouray NWR, is equal to the sediment exported from that reach.
Sediment mass balance thus appears to be maintained for the Green River within the central Uinta basin.

Channel Change Since Flaming Gorge Dam

Two studies have measured or described channel change in the Green River below Flaming Gorge Dam. Andrews [1986] considered the Green River between Flaming Gorge Dam and its confluence with the Colorado River, and Lyons et al. [1992] studied the Green River through the Uinta basin. The following discussion highlights those results applicable to the reach that includes Ouray NWR.

Andrews [1986] used USGS gage records for the station near Jensen, Utah, for the period 1947 to 1981 to calculate the changes in sediment mass balance and discharges since closure of Flaming Gorge Dam. A sediment-discharge rating curve relates the quantity of sediment in transport to river discharge, and a flow-duration curve shows the relationship between discharge and the percent of time that discharge is exceeded. These two curves may be combined to show the relationship between annual sediment load and discharges which transport the sediment. The effective discharge, the modal value of this sediment load and flow duration curve, was reduced by 44 percent from 580 m$^3$/s to 325 m$^3$/s after closure of Flaming Gorge Dam. No significant change in the sediment rating curve for the sand-sized fraction occurred during this period. In addition, Andrews [1986] compared aerial photographs taken in 1964 and 1978 to assess changes in bankfull width at 15 cross sections within a 97-km reach that included the Ouray NWR. Andrews [1986] determined that, on average, the channel had narrowed by 13 percent from 213 m to 186 m, and much of the narrowing resulted from accretion of islands to the bank [Andrews and Nelson, 1989]. Andrews [1986] estimated that channel narrowing would be complete when the average channel width was 160 m, based on hydraulic geometry relations. He estimated that channel narrowing
Lyons et al. [1992] recalculated effective discharge and measured channel change in the Uinta basin. Using more extensive photo-interpretation, and discharge and sediment records that extended to 1987, they concluded that channel narrowing had been completed by 1974, and was not as great as reported by Andrews [1986]. Andrews [1986] did not include data from the large floods that occurred on the Green River between 1983 and 1986, but Lyons et al. [1992] showed that these floods did increase channel width within the central Uinta basin. Although Lyons et al. [1992] largely confirmed Andrew’s [1986] findings, they argued that a sediment mass balance quasi-equilibrium has already been reached in the Uinta basin, and channel widening and channel narrowing would occur in the future as short-term adjustments to periods of high and low discharge. Although high flows such as occurred between 1983 and 1986 caused some channel widening, Mayers and Schmidt [1994] found that these post-Flaming Gorge Dam floods did not widen the channel to pre-dam conditions.

The invasion of saltcedar (Tamarix sp.) has probably exacerbated channel narrowing. This exotic species has dominated much of the riparian community in the Colorado River basin [Graf, 1978]. Vegetation, such as saltcedar, can be an important factor in channel narrowing [Friedman et al., 1996]. Vegetation stabilizes bank deposits with its roots and colonizes within-channel sand deposits, the latter causing additional deposition by vertical accretion [Friedman et al., 1996]. Graf [1978] believed that the saltcedar invasion was responsible for a large degree of channel narrowing on the Colorado River prior to the 1950s, but Fisher et al. [1983, cited in Stanford, 1994] provided evidence that the unregulated Yampa River did not narrow after saltcedar invasion. Fisher et al. [1983] argued that if a river’s peak discharge is insufficient to scour and remove young saltcedar deposits become stabilized, and the added roughness slows water velocities and causes additional sediment deposition. Along the Green River in the Uinta basin, a new saltcedar-covered floodplain,
formed in response to flow regulation by Flaming Gorge Dam, is inset within a higher terrace dominated by cottonwoods [Mayers and Schmidt, 1994].
LIFE HISTORY AND HABITAT NEEDS OF LARVAL COLORADO SQUAWFISH

The life history of the Colorado squawfish has only been investigated since the closure of the major dams in the Colorado River basin. Consequently, we only know what habitat is used in the altered, fragmented river system. This long-lived, large, endemic minnow was once widespread and abundant throughout the Colorado River basin, but is now found only in the upper Colorado basin. Within that basin, the largest known concentrations of squawfish are found in the Green River [Tyus and Haines, 1991].

The Colorado squawfish has a complex life history and spawns on gravel bars in two canyon sections: Yampa Canyon on the Yampa River and Gray Canyon on the Green River. These fish migrate long distances [Tyus, 1990] and spawn on the descending limb of the spring snow melt hydrograph, apparently cued by temperature [Tyus, 1990]. After the eggs hatch, the larval fish are transported downstream for 3 to 15 days [Nesler et al., 1988]. In the downstream reaches, the larval fish move or are entrained into "backwaters" in low-gradient alluvial reaches. Backwaters, as described by aquatic ecologists, are embayments along river margins having low or no velocity [McAda and Kaeding, 1989]; these areas are the nursery habitat for age-0 Colorado squawfish. The Green River, in the Ouray NWR in the Uinta basin, is an area of known Colorado squawfish nursery habitat [Tyus and Karp, 1991]. Tyus and Haines [1991] found larval squawfish in embayments that were relatively warm, deep, and large in this reach.

T. A. Crowl (Dept. of Fisheries and Wildlife, Utah State University, pers. comm., 1994) has suggested that habitat depth partly determines habitat quality. Crowl defined deep habitats as those with a depth greater than 0.5 m at any location within the habitat, and has noted that the deepest area is typically near the interface between flowing and low- or no-velocity zones. When predators were excluded, the deep, more productive habitats were preferred by Colorado squawfish during one
study. More recent work has shown that the preferred habitats (deep or shallow) are not the same from year to year and may be dependent on river temperature and predatory pressures. Low-flow river temperature is influenced by the cold, hypolimnetic Flaming Gorge Dam releases [Tyus, 1991]. Consequently, the sun-warmed shallow habitats were preferred Colorado squawfish habitat in years of greater base-flow Flaming Gorge Dam releases, whereas deep habitats were preferred in years with warmer river temperatures.

Backwaters were categorized into process-based geomorphic classifications (J.C. Schmidt, Utah State University, unpublished presentation at the Upper basin Endangered Fish Research Meeting, Grand Junction, 1993). These classifications link habitats to the bed and bar features that form them at low flow. Schmidt's study was the first step toward determining flood flows that form the channel features and habitats important to juvenile Colorado squawfish.
SPECIFIC STUDY DESIGN

Field, photographic, and numerical computations were employed at three spatial scales in order to understand the effect of low- and flood-flow variation on habitat availability. Geomorphic studies within a 1.5-km reach, called the study reach, focused on a large, bank-attached compound bar, called the study bar, and were used to study the geomorphic processes that determine channel form and habitat availability. Large-scale videography from the 10-km reach were used to quantify differences in habitat availability at base flow in years with different flood magnitudes.

Achieving the goals of my study required consideration of multiple scales. The habitat of concern occurs at a scale of 10's of meters, the geomorphic processes that forms these habitats occur at a scale of 100's of meters, and the flows controlling these geomorphic processes occur at a scale of 10's of kilometers. Habitat availability also displayed annual and seasonal variation. Consequently, a multiscale assessment strategy appropriate for the Green River was implemented, and addressed each spatial and temporal scale and the linkages between them. Multiyear, large-scale data are needed to determine overall channel response to flood passage and the reach-scale change in habitat availability. Small-scale data, collected on the scale of individual habitats, are needed to assess the relationship of habitat availability to channel form and determine the response of channel form to flood passage. Data from an intermediate scale are necessary to determine the physical processes that link habitat availability to channel form and, ultimately, to flood and base flow variability.

Channel response to flood passage was assessed at three scales. At the largest, 10-km scale, videography taken at low flow was used to determine large-scale changes in emergent bars. Cross-section surveys within a 1.5-km reach were used to characterized patterns of scour and fill during flood passage and subsequent low flows. Detailed topographic surveys of the study bar showed the response of individual bed- and barforms to flood passage.
The effect of channel, specifically bar, topography on flow field and habitat availability was determined at both small and large scales. At the habitat scale, field maps of flow patterns and available habitats for longer reaches of the river and the detailed topographic surveys of the study bar were used to determine typical flow patterns around bars. Detailed topographic studies from 2 years were used to measure the change in habitat availability as a function of discharge and as the study bar topography changed in response to flood passage. These observation were related to changes in channel form determined from the 10-km videography.

Large-scale, year-to-year changes in habitat availability were determined from videography from three different years for 10 km of river. On the video maps, habitats were identified, delineated, and classified by the bed- or barform that caused flow stagnation. Habitat depth, as determined from field measurements, was also noted. The videography was used to link the changes in topography and habitat availability measure at the study bar to the changes in channel form within the 10-km reach. Surrogates for habitat availability, in the form of shoreline complexity indices were also evaluated.
METHODS

Channel Response to Flood Passage and

Patterns of Sediment Storage

Nursery habitat was formed by bar- and bedforms that were created by high flows and were emergent at low flow. Consequently, it was necessary to characterize channel response to flood passage at a scale representative of bar-forming processes. The study reach, a 1.5-km reach that included the study bar, was the site of repeated cross-section measurements between November 1992 and October 1994 (Table 2).

Cross-section measurements were used to characterize bed response to flood passage, calculate changes in bed elevation for individual cross sections, determine changes in sediment storage, and as input to a numerical flow and sediment transport model developed by Andrews and

TABLE 2. Dates of Cross-Section Surveys and Discharge at the Time of the Surveys. The May 21, 1993 Survey Was Conducted at High Flow, and Only Water Surface Stage and Maximum Channel Depth Were Measured at Each Cross Section. Asterisks Indicate That Field Maps of Flow Patterns Were Made Within the 1.5-km Reach

<table>
<thead>
<tr>
<th>Water Year 1993</th>
<th>Discharge (m$^3$/s)</th>
<th>Days since Jan. 1, '92</th>
<th>Water Year 1994</th>
<th>Discharge (m$^3$/s)</th>
<th>Days since Jan. 1, '92</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 6, 1993</td>
<td>44.5</td>
<td>310</td>
<td>Nov. 20, 1993</td>
<td>81.3</td>
<td>689</td>
</tr>
<tr>
<td>May 21, 1993*</td>
<td>546.6</td>
<td>505</td>
<td>March 17, 1994</td>
<td>70.0</td>
<td>806</td>
</tr>
<tr>
<td>June 10, 1993*</td>
<td>422.0</td>
<td>526</td>
<td>April 30, 1994</td>
<td>237.3</td>
<td>850</td>
</tr>
<tr>
<td>June 22, 1993*</td>
<td>430.5</td>
<td>538</td>
<td>May 14, 1994</td>
<td>213.8</td>
<td>864</td>
</tr>
<tr>
<td>August 15, 1993*</td>
<td>49.6</td>
<td>592</td>
<td>May 28, 1994</td>
<td>305.9</td>
<td>878</td>
</tr>
<tr>
<td>June 16, 1994*</td>
<td>155.8</td>
<td>897</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July 16, 1994*</td>
<td>44.7</td>
<td>927</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>October 8, 1994</td>
<td>46.4</td>
<td>1011</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 10. Hydrograph of mean daily discharge for the study period showing dates of cross-section measurements and Reclamation video overflights. Table 2 lists the number of days since January 1, 1992 for each sampling date.

Nelson [1989]. In 1992, we occupied 6 of the 10 cross sections established by Andrews and Nelson [1989]. In 1992, four cross sections were added within the reach; and in November 1993, two additional cross sections were added on the upstream end of the study reach. Surveys were made during peak flows and at base flow (Table 2, Figure 10). Cross-section surveys were conducted in November 1992 and at peak flow, twice on the descending limb and at base flow conditions in 1993. A complete survey was not conducted at peak flow (May 21, 1993), but water surface elevation and maximum depth of scour were measured. In 1994, seven cross-section surveys were conducted; the first survey was prior to the spring flood, then surveys were made every 2 weeks during flood passage. Eleven stage measurements for discharges between 45 and 500 m³/s were used to develop a stage-discharge relationship for this reach (Figure 11). One day of travel time was estimated for water to pass from Jensen, Utah, to Ouray NWR.
Fig. 11. Stage/discharge relationship developed for the 1.5-km study reach.

Cross-Section Measurements

Each cross section was monumented by pairs of rebars and fenceposts. All rebars were surveyed from a single point so that the relative location of each rebar was known. To survey each cross section, a wire cable, marked by a colored bead at 3.05-m (10-ft) intervals and supported at the ends by fenceposts, was stretched taut across the river. A laser theodolite was used to survey the parts of the cross section less than about 1 m in water depth. Points were surveyed at all breaks in slope and edges of water, and survey points were not separated by more than 6 m. A motorized raft equipped with a recording depth sounder was used to survey the deeper portions of the channel. A recording depth sounder was used to record channel depth during the six passes, three in each direction, made at each cross section. The depths were continuously recorded on a moving strip chart, and the trace marked by the depth sounder operator at 3.05-m intervals marked on the wire cable. The trace from the depth sounder was read at each 3.05-m mark, the values for each mark averaged, and the depth of the transducer below the water surface added to give the actual channel depth.
The two types of information about channel cross sections—depth measurements separated by 3.05 m and survey data—were then integrated. The calculated depths were subtracted from surveyed water-surface measurements to give an elevation from an arbitrary datum. The location of points within the cross section was measured in distance from the river-left rebar, and was calculated from the survey data. The surveyed cable marks for the beginning and ending of the depth sounder trace were used to adjust the lateral position of channel depths. The resulting cross-section data were reduced to a two-column array: distance from the river left rebar and elevation.

Sediment Storage

The cross-section data were used to calculate total change in sediment storage within the study reach and the longitudinal change in the location of sediment storage. A FORTRAN program was used to calculate the average bed elevation of each cross section (Appendix A). These average bed elevations were used to determine the changes in sediment storage at individual cross sections, and to estimate the change in sediment storage within the study reach.

The change in sediment stored at a single cross section was calculated by multiplying the change in average bed elevation by cross-section width. Calculating the change in reach-averaged bed elevation, and hence the change in sediment volume, for the study reach was more complex. The calculated change in sediment volume used the August 1993 cross-section measurements as the baseline. The average cross-section elevation and the area that the cross section represented were used to estimate sediment volumes. The effects of uneven cross-section spacing and variation of channel width were taken into account by this “represented area”; thus, the resultant reach-average bed elevation indicated the change in sediment volume in the 1.5-km reach. Individual cross sections were considered to be representative of the area from the cross section to half the distance to the adjacent cross sections. As such, an appropriate width and length was calculated for areas above and below the cross section. For the area above the cross section, the effective width was calculated as:
where $W_{\text{eff}}$ is the effective width, $W_n$ is the width of the cross section, and $W_{n+1}$ is the width of the cross section upstream. The length used for the channel area calculation was half the distance between cross section “n” and cross section “n+1,” and the depth was the average cross-section depth. The process was repeated for the area below the cross section, and for each cross section. This approach assumed that the error associated with the curvature is small, that the channel width changes slowly, and that the cross section’s average elevation is representative of the area above and below the cross section.

Flow and Sediment Transport Modeling


The Andrews and Nelson [1989] model was originally used in the reach for 2-day, steady-discharge simulations of bed evolution. In this study, flood simulations were made using unsteady hydrographs for longer periods. These simulations were used to understand how the channel topography, and hence nursery habitat availability, responded to the passage of floods.

Cross-section data were used by the model to generate a 41x13 computational matrix. Cross-section data were smoothed, and the depths at evenly spaced intervals were determined for each cross section. These smoothed cross sections were then used to interpolate the up- and downstream bed elevations of the computational matrix. This matrix of topography was then used to calculate the channel topography in the sloped coordinate system of the reach-averaged energy gradient; the elevation of the bed was given in depth below the water surface. A known discharge, starting at an appropriate upstream stage, was routed down the channel and the channel roughness adjusted until the reach water surface slope was accurately predicted by the model. The topography, discharge, and roughness were used to calculate vertically averaged velocities and shear stress.
These velocities were then used to calculate discharge at each point in the matrix and the centerline water slope such that the same amount of water flowed out of the reach as flowed into the reach.

In the sand-bedded Green River, Andrews and Nelson [1989] used a single roughness coefficient for the reach that included all forms of roughness such as grain, bedform, and barform roughness. The roughness calculated at each computational node was scaled with flow depth. This single-roughness coefficient approach was used for cases where bedform geometries were unknown and was valid when sediment transport rates were similar over much of the bed [Andrews and Nelson, 1989]. The error associated with using one roughness parameter to describe the whole channel affected the spatial distribution of roughness within the channel rather than the total roughness of the whole reach [Andrews and Nelson, 1989]. Consequently, the roughness due to bars, bedforms, and saltating grains was distributed throughout the channel rather than being restricted to the locations where the roughness elements extract momentum from the flow.

The Engelund-Hansen [1967] sediment transport equation, as formulated by Andrews and Nelson [1989], was used for these Green River simulations:

\[
\frac{q_s}{\sqrt{\frac{\left(\frac{\rho_s}{\rho} - 1\right) g d^3}} = 0.8 \tau^* f}
\]

where \(q_s\) is the volumetric transport rate per unit width, \(\rho_s\) and \(\rho\) are the densities of the sediment and water, respectively, \(g\) is the acceleration due to gravity, \(d\) is the sediment size, \(\tau^*\) is the dimensionless shear stress, and \(f\) is the drag coefficient. The Engelund-Hansen relationship was developed for dunes in sand-bedded rivers, but has been shown to be valid for flows over the range of bedforms including dunes, transition, standing waves, anti-dunes, and chute-and-pool flows [Engelund and Hansen, 1967]. During this study, only ripples and dunes were observed in the sedimentary
structures of the bank-attached bar and on the fathometer traces. Unlike Yalin's [1963] transport equation, the Engelund-Hansen equation for suspended load does not require additional bedform information such as amplitude and wavelength. This approach was necessary for the Green River where a variety of bedforms, from ripples to dunes superimposed on barforms, was present across the channel. The shear stress values were calculated at all nodes of the computational matrix, then used in the sediment transport equation to determine the areas of erosion and deposition. It was assumed that the modeled reach was in sedimentary equilibrium, that is, exactly as much sediment as was transported into the reach was transported out of the reach.

Although the Andrews and Nelson [1989] model was a physically based 3-dimensional numerical model, there were several conditions for which this model did not function well (J. Nelson, USGS, pers. comm., 1994). These conditions included:

1) when any part of the bar was emergent and where split flow around an island existed, and
2) low-flow conditions where areas of recirculation or stagnation existed.

J. Nelson (USGS, pers. comm., 1994) also noted that calibration of the model is necessary for each river reach to which it is applied. As a consequence of the first condition, only flows whose stage exceeded the elevation of the highest elevation bar were modeled. The second condition prevented the prediction of the locations of backwater habitat at low discharge. Thus, the model was run only to predict the rate and style of bar building.

Model Modifications

J. Nelson (USGS, pers. comm., 1994) made modifications to the model to allow its use for the cross sections and topography surveyed in 1993. Changes to the boundary conditions were necessary because the original version of the model used by Nelson and Smith [1989b] for the bed evolution model was designed for channel reaches where the most upstream and downstream cross-section topographies were identical, and the downstream cross section's flow distribution was used.
as input at the top of the reach. The study reach within Ouray NWR did not satisfy this condition. I made additional code changes to allow the discharge to vary. In my approach, I used initial topography and a discharge that overtopped the bars. Unsteady flow conditions were simulated by using the field-measured stage-discharge relationship from the Ouray site to determine the stage change necessary for each simulated discharge change. In addition, model modifications were made to allow the roughness to vary with discharge, such that the roughness was adjusted to maintain a nearly constant average water surface slope for the reach. Field-measured slope through the study reach was approximately 0.0002 m/m at all discharges; the flow model maintained this slope within a 2-cm tolerance such that the average slope was between 0.000191 to 0.000213 m/m during all model runs.

There were some limitations to this approach. Initial topography was calculated at a lower discharge, then flow depth was appropriately increased or decreased for the change in discharge during each iteration. This approximation implied that vertical banks were assumed for the channel at higher discharges. This was an appropriate assumption for the channel topography measured in the study reach. The radius of curvature for each cross section was not recalculated for each change in discharge. While the radius of curvature does change with changes in discharge, the greatest changes occur for lower discharges that expose midchannel and bank-attached bar deposits. These lower discharge conditions were prohibited in this model formulation. This approach also assumed that the average water surface slope was relatively constant for a range of discharges. Although this assumption would not be appropriate for shorter or higher gradient reaches, it was a reasonable assumption for the 1.5 km study reach.

It was necessary to include the additional upstream cross sections to increase model stability during the longer simulations of this study. The earliest date for which complete cross-section data were available for discharges above base flow was May 14, 1994. These survey data, measured at
256 m$^3$/s, were used for all flow simulations.

Longer model runs were made for three flood scenarios: (1) a steady discharge of 400 m$^3$/s (11 days), (2) a flood hydrograph peaking at 500 m$^3$/s for 3 days (total run time 11 days), and (3) a flood hydrograph peaking at 575 m$^3$/s for 3 days (total run time 17 days) (Figure 12). In the latter cases, the hydrograph was ramped at 25 m$^3$/s/day with the discharge and stage incremented for each 200-s iteration. This ramping rate was similar to the daily differences in discharge measured at the USGS Green River near Jensen gage during the 1993 flood (Figure 12). The third flood scenario was similar to the 1993 flood peak of 570 m$^3$/s. These flood scenarios have post-dam recurrence intervals of about 1.8 years, 2.8 years, and 3.5 years, respectively, and pre-dam recurrence intervals of less than 2 years. Final topography for day 11 for the first 2 runs and day 17 of the third run were compared.

Fig. 12. Simulation hydrographs. Run 1 used a steady discharge of 400 m$^3$/s, run 2 peaked at 400 m$^3$/s, and run 3 peaked at 575 m$^3$/s. Discharges were increased or decreased by 25 m$^3$/s/day, with the model proportionally incrementing the discharge at each time step. A portion of the 1993 flood hydrograph is shown for comparison.
Fig. 13. Comparison of model-generated and field-measured average cross-section longitudinal bed elevation for May 1994. The bed elevations for each cross section were calculated as described in Appendix A for field-measured cross sections (X's) and model-generated cross sections. The model data are calculated with (+'s) and without (boxed X's) the endpoints on each section. The model cross sections with end points are biased higher by the inclusion of points up to the 95.75 m elevation along the channel margin, and the field-measured cross-section calculations do not include points on the channel margin. See Figure 15 for field cross-section locations.

Topographic Resolution and Sediment Transport Rates

Model inputs and results must be evaluated for relevance to the real world. In my work, cross-section data was transformed into a data set that was more sparse in the cross-stream direction, but more dense in the downstream direction. The adequacy of this transformation must be evaluated. The model routed water on the surveyed channel topography and calculated the resulting areas of erosion and deposition; these data were used to simulate bed evolution. The model calculated sediment transport rates for the reach. These transport rates were compared to sediment transport rates measured at the USGS gage near Jensen, Utah, and this comparison was used to indicate model adequacy.
Average bed elevation from the model adequately reproduced the average bed elevation of the cross sections (Figure 13). Data from the portion of the channel delineated as detailed in Appendix C were used to calculate the average bed elevation for the surveyed cross sections. These calculations did not include elevation data points above 94.0 m found near the channel margin. The model topography was for the whole channel, and included points up to 95.4 m. Consequently, the calculated average bed elevation from the model was biased to be higher than the average bed elevation calculated from the surveyed data. This bias was demonstrated by removing the end points for each cross section from the calculated average bed elevation. The model data with and without end points bracket the average bed elevation calculated from the surveyed cross sections, as expected (Figure 13).

Comparisons of model-generated topography and mapped field data were made to evaluate model resolution of real channel features. A contour map of splined topography generated from the cross sections was compared to the pseudo-elevations generated from the video prints (discussed below) and the detailed topography of the study bar (Figure 14). Channel topography generated by splining the cross-section data described the large scale topographic features of the study reach such as the location of the bank-attached and point bars and the thalweg. Comparison of the study bar's 1994 detailed topography and the July 1994 model topography (Figure 14) demonstrated that the spacing of the cross sections of this study was not sufficiently close to resolve the finer details and complexity of topographic features including those that, in some years, form nursery habitat.

The model predicted reasonable sediment transport rates for this reach. Sediment transport rates between 3300 and 11,050 tons/day were calculated by the model for discharges between 400 and 575 m³/s. These transport rates fell within the 2000 to 20,000 tons/day range for these reported discharges [Andrews, 1986] from the rating curve for the Green River near Jensen, Utah. The Jensen data are comparable to the rating curve of the Ouray, Utah, USGS gage [Lyons et al., 1992].
Fig. 14. Comparison of the topography interpolated by the numerical flow model in relation to the detailed bar topography and 1.5-km reach topography determined from video data in July 1994. Dark shading with "plant" pattern indicates the high-elevation area stabilized by vegetation, the stippling indicates white sand, and dark shading shows the dark and wet sand. Although the model topography reproduces the gross topography of the channel, the spacing of the cross sections for this study was too great for the interpolated topography to accurately represent the features of the bars that form nursery habitat.
The Study Bar and Colorado Squawfish Habitat

Detailed Topography of the Study Bar

Detailed topographic maps were used to determine the relationship between barform and habitat availability, the year-to-year changes in habitat availability at base flow and at higher discharges, and bar response to flood passage. The study bar was intensively surveyed in August 1993 and July 1994. I created a detailed topographic map for the study bar in 1994, similar to the 1993 map of Krider [1994]. A laser theodolite was used to survey many points and features across the study bar’s surface, and the surveyed points were later plotted by hand on graph paper at a scale of 1: 2362.2 in 1993 and 1: 1574.8 in 1994. The plotted points were used as a base for the hand-drawn 0.25-m contour lines, the water line, and nursery habitats that were mapped in the field. To simplify the comparison of the 1993 and 1994 maps, the field maps were digitized into ARC/INFO, a geographic information system (GIS), as contour line maps (Figure 2). It was then possible to interpret and analyze these maps for additional information.

Habitat Availability Curves

The area of available habitat at base flow was a function of discharge, although that function was not constant from year to year. To quantify the change in habitat availability as a function of discharge at the study bar, overlay maps of available habitat were created for each contour line of the detailed topographic map (Figure 15). Area statistics from these habitat maps were used to create localized Habitat Availability Curves (HAC’s) for 1993 and 1994.

The field maps of current patterns and nursery habitats, described below, and field observations aided the interpretation of the area of habitat that would be available at different water stages. Flow patterns were surmised for each contour, and areas of low velocity or stagnant flow delimited. Each interpreted habitat area was geomorphically classified, digitized into the GIS, and
Fig. 15. Detailed topographic map of the study bar in 1993 and 1994. Each successive level is highlighted (A-H) and the interpreted habitat area is shown in cross hatches. The geomorphic classification of each habitat is labeled in lower case letters. Descriptions of these codes are listed in Table 5.
Fig. 15. Continued

93.5 METER CONTOUR

(B)
Fig. 15. Continued
Fig. 15. Continued
Fig. 15. Continued
94.5 METER CONTOUR

(F)

Fig. 15. Continued
Fig. 15. Continued

94.75 METER CONTOUR

(G)
Fig. 15. Continued

95.0 METER CONTOUR

(H)
the area of available habitat calculated. The total area of habitat for each contour level was then calculated.

An HAC requires the relationship of discharge, not stage, to the area of available habitat. The stage-discharge relationship was used to convert the topographic elevations of the contours maps to equivalent discharges. These discharges were then used to plot the area of habitat available for each contour against the contour’s equivalent discharge, thus producing the localized HAC.

Surrogates for Habitat Availability at the Study Bar

Topographic complexity has been considered to be an indicator of habitat heterogeneity. I evaluated if shoreline complexity was an adequate surrogate for habitat availability. Statistics from the GIS of detailed bar topography were used to calculate Gosse’s [1963] complexity index, the ratio of line length to total reach length, for each contour of each year. The simple index of Gosse [1963] was used for the study bar because, while this bar was representative of other bank-attached bars within the 10-km reach, it was not representative of the whole 10-km channel.

Current Maps

Field maps of flow patterns and habitats were valuable for both small- and large-scale studies. Field maps of individual habitats were used to geomorphically classify habitats at the study bar and within the 10-km reach. Habitats and patterns of flow were mapped within the study reach on six dates: May 22, June 11, June 23, and August 13, 1993; and June 17 and July 16, 1994. Flow patterns of October 28, 1993, were mapped for River Mile (RM) 252.8 to 253.7, below the study reach; flow patterns for RM 256 to RM 257, upstream from the study reach, were mapped on October 28, 1993 and July 16, 1994. Mylar or tracing paper were overlaid on US Bureau of Reclamation (Reclamation) video prints (discussed below), and habitats and flow patterns mapped onto the overlays. The video prints from the overflight immediately previous to the mapping date
were used because these prints most closely resembled the channel condition at the time of mapping. The main thalweg, shallow, and low or no velocity areas were mapped. Particular attention was given to the location of shear zones that separated the main flow from areas of recirculating or stagnant flow.

**Analysis of Video Prints**

Videography was used to assess the large-scale changes in low-flow channel form and habitat availability as a function of discharge and in response to flood flows. In addition, the videography was used to link the relationships of channel form and habitat availability that were evaluated within the study reach to habitat availability in the 10-km reach.

**Pseudo-Topographic Units**

Topographic and video-imagery data covered different time periods, and the data were collected on different dates. Integration of these data into one synthesis provided the opportunity to obtain the broadest perspective about geomorphic change in the study reach. Interpretation of topographic changes from the video prints also permitted analysis of topographic changes at sites where field surveys were not made. Topographic data can only be interpreted from video imagery by inferring that the geomorphic units--areas of vegetation and areas of white, dark, and wet sand--visible on the video prints occur at different elevations. If this assumption is true, then the contacts between different geomorphic units represent pseudo-topographic lines.

Detailed surveys were compared to video prints of the study bar for both August 1993 and July 1994 (Figure 16). These comparisons showed that assuming a topographic relationship between the geomorphic units was reasonable. The topographic data were more detailed, so the contours were grouped by elevation into three categories--dark sand, white sand, and vegetation as mapped in the field on the contour map--to permit comparison with the video prints. Areas above 95.0 m in
Fig. 16. Comparison of pseudo-topographic units interpreted from the video prints to the detailed topographic maps (Figure 15). For the map derived from the 1993 detailed topography (A), the areas shown as vegetation (dark shading with "plant" pattern) are above 95.0 m, as white sand (dot and dash pattern) are between 94.0 and 95.0 m, and as dark sand (dark shading) are between 93.5 and 94.0 m. For 1994 (B), the white sand/dark sand boundary is at the 93.75 m contour.
Fig. 16. Continued.

Isolated pools formed by horseshoe vortices

Superimposed bar

Chute channel

Isolated pool in secondary channel

Video print
July 1994

Derived from topographic map
July 1994

(B)
elevation were compared with the area of vegetation shown on the video prints. The areas of the bar covered by white sand changed from year to year; the area of white sand on the video prints was compared with the area surveyed between 94.0 and 95.0 m in 1993 and between 93.75 and 95.0 m in 1994. Areas below 94.0 m and 93.75 m in 1993 and 1994, respectively, were compared to the areas of dark sand, wet sand, and isolated pools depicted on the video prints. The contacts between these map units were generally similar, and the interpretation of topography from video prints was therefore considered to be consistent with interpretations based on surveyed topography, especially for the water/dark sand and dark sand/white sand contacts. Consequently, the reach scale maps from the interpreted video prints were used as maps indicating generalized bar topography, and deposit classification was considered indicative of deposit elevation. The major discrepancy in the data is the presence of a large area above the 95.0 m contour surveyed in July 1994 that did not appear to be vegetated in the video print (Fig. 16); however, video images taken in September 1994 show sparse vegetation occupying this area. Also, dark sand was interpreted from the July 1994 video print for a long area in the upstream third of the bar and a small area just upstream of the chute channel. These deposits were actually at a higher elevation than other dark sand areas in July 1994: The dark coloring resulted from silt settling from the water column when these areas were isolated from main channel flow.

Base Maps

The US Bureau of Reclamation provided color prints of the river corridor, each print covering approximately 0.2 km of river. These prints were frame captures from video overflights conducted between spring 1992 and fall 1994 (Table 3). Although these prints were neither scaled nor rectified, they were projected and adjusted to a common base. Reclamation provided us with a mosaic of stitched images from the August 1993 overflight. This “video base map” was produced by registering approximately 70 prints to a geographically referenced, rectified map. US Geological
<table>
<thead>
<tr>
<th>Date</th>
<th>Days since Jan. 1, 1992</th>
<th>Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 18, 1992</td>
<td>77</td>
<td>68.5</td>
</tr>
<tr>
<td>July 29, 1992</td>
<td>210</td>
<td>45.9</td>
</tr>
<tr>
<td>September 23, 1992</td>
<td>266</td>
<td>35.4</td>
</tr>
<tr>
<td>August 10, 1993</td>
<td>587</td>
<td>45.6</td>
</tr>
<tr>
<td>September 27, 1993</td>
<td>635</td>
<td>51.0</td>
</tr>
<tr>
<td>April 5, 1994</td>
<td>825</td>
<td>55.5</td>
</tr>
<tr>
<td>July 29, 1994</td>
<td>940</td>
<td>44.7</td>
</tr>
</tbody>
</table>

Survey 1:24,000 orthophoto maps and intermediate 1:6,000 scale aerial photography were used to register the video images. These maps were termed "video base maps" by Reclamation so that no implication of accuracy was made. The residual error for the common points used in making the base map was less than the national map accuracy standard for the 1:24,000 orthophoto on which this mosaic was based (K. Fenton, US Bureau of Reclamation, pers. comm., 1995). The mosaic of images for the river was split into four sections by Reclamation. The software used to split the map into sections did not preserve the coordinate system between sections, but did preserve the projection of the maps (K. Fenton, US Bureau of Reclamation, pers. comm., 1996). Scale was verified using USGS 7.5-minute quads.

**Interpretation and Transfer**

At USU, the video prints were interpreted, and the resultant lines transferred onto a base map mylar overlay. The interpretation consisted of separating each image into geomorphically meaningful units (Table 4). On the video prints, the coloring of the within-channel deposits was indicative of composition and moisture content of the deposit. The deposits near base flow were
TABLE 4. Interpreted Geomorphic Units for Video Prints. Habitat Units Are Defined in Table 5

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>Main channel with no visible sand bed.</td>
</tr>
<tr>
<td>ss</td>
<td>Submerged sand visible through the water. This indicates shallow bars but to some extent, is dependent on the clarity of the water.</td>
</tr>
<tr>
<td>ip</td>
<td>Isolated pools. Found at river level, but separated by bar deposits from the main channel.</td>
</tr>
<tr>
<td>wt</td>
<td>Wet sand. Found near flow level, darker than submerged sand with a visible shoreline, particularly apparent during turbid periods when the water is orange/brown and deposits are more gray.</td>
</tr>
<tr>
<td>ds</td>
<td>Dark sand. Usually found near base flow level, within the level of fluctuation; deposited by low summer floods caused by thunderstorms.</td>
</tr>
<tr>
<td>ws</td>
<td>White sand. This sand is deposited at high flow, typically occurs about 1 m above base flow.</td>
</tr>
<tr>
<td>s/v</td>
<td>Sand and vegetation. These deposits are higher than ws and areas have sparse vegetation.</td>
</tr>
<tr>
<td>veg</td>
<td>Vegetated deposits within the channel. These are typically higher deposits stabilized by older vegetation.</td>
</tr>
</tbody>
</table>

typically darker sand, the color derived from moisture and the darker silts and fines mixed with the medium sand that composed the bars. Higher bar deposits were primarily medium sand and white in color. The highest elevations of the bars were in the process of being colonized by vegetation. Consequently, these geomorphic units are indicative of bar topography and are referred to as “pseudo-topographic” units.

Prints for 10-km of river within the Ouray nursery habitat reach from seven overflights (Table 3) were interpreted and digitized (e.g., Figure 17). Each individual interpreted video print was transferred onto a mylar overlay on the video base map, and the difference in the transferred lines between individual video prints was smoothed by eye. The resulting overlay mosaic was then digitized into an ARC/INFO GIS on a Sun Microsystems Unix platform. The digitized map was
Fig. 17. GIS map of the 10-km study reach for July 1994. River miles (denoted by numbers between 251 and 257), are those used by others conducting research within the Green River basin, and were taken from Reclamation video prints. The location of persistent bank-attached bars are labeled as BA1 to BA10, and the location of point bars is shown by P1, P2 and P3 labels. Flow is from the top of the page. Stippled areas are emergent bars at low discharge. The study bar is BA3.
composed of polygons described by the pseudo-topographic geomorphic units of Table 4. The coverage was later georeferenced using the Lambert conformal conic coordinates from the Reclamation video base maps.

**Enumeration of Bars**

The long-term behavior of the channel and bars was determined from the GIS maps. For summarizing the overall behavior of bars, each bar was classified as a midchannel, point, or bank-attached compound bar. Some discharges may dissect bank-attached compound bars, but only a small portion of the flow was carried by these dissecting chute channels at discharges that do not overtop the bars.

**Integration of the UDWR Nursery Habitat Surveys**

Utah Division of Wildlife Resources (UDWR) conducted nursery habitat sampling three times each year in conjunction with the Reclamation video overflights. Information about the location, size, and depth of available habitat was added to the GIS maps of the channel. Field observations of available habitat were combined with the video data to generate statistics from the GIS for the area of total, deep, and shallow habitat available.

In the spring, prior to the snow melt flood, UDWR sampling assessed the location, condition and densities of fish after winter low flows. Typically, discharge at that time was 1.2 to 1.6 times the summer base flows. Sampling also occurred in late July and early August after larval fish had been transported into the study reach and again in September. The discharge during these latter sampling trips were near base flow (50 m$^3$/s).

UDWR field crews seined fish and measured physical parameters at each sampled habitat. Physical measurements included temperature, length, and width at the mouth, middle, and upper part of each backwater. The depth of the water and depth to firm substrate was measured at three evenly
spaced points on each width transect. All data were recorded on standard data sheets, and the location and extent of habitat marked on the video prints. UDWR provided data sheets from all nursery habitat sampling trips made between 1992 and 1994. Marked video prints were provided for the 1993 and 1994 trips. Data sheets also included the number of identified Colorado squawfish found in each habitat.

These UDWR data were used as follows. First, the sampled habitats were delimited and geomorphically classified on the video prints taken in conjunction with the UDWR sampling; the difference in time between video prints and sampling was typically less than 4 to 6 days in 1994, and less than 3 days in 1992 and 1993. Second, the maximum depth of the sampled backwater was used to classify each backwater as deep (> 0.5 m) or shallow (< 0.5 m). Lastly, the presence or absence of Colorado squawfish as noted by UDWR personnel for each backwater was included in the GIS database. Most of the sampled fishes were too small for field identification, so these samples were sent to the Colorado State University Larval Fish Laboratory for later identification. The attributed presence or absence of fish in the GIS may be updated when final data are available from the Colorado State University Larval Fish Laboratory, but this revision is beyond the scope of this thesis.

A five-character code for the delineated habitats was used to describe the sampled habitat's geomorphic setting, its depth classification, and the presence or absence of squawfish. The first three characters of the five character attribute coded the geomorphic setting of the habitat (Table 5). Bank-attached compound bar habitats begin with “b” and midchannel bars with “m.” Horseshoe vortices (hsv) were scour holes associated with the upstream end of stabilized deposits, and isolated pools (ip) were most often associated with bank-attached bar secondary channels or horseshoe vortices separated from the main channel by sand deposits (see Figure 15). Isolated pools were not sampled by UDWR personnel. The fourth letter of the code identified if depths were greater (d) or
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>bsd</td>
<td>the downstream end of a secondary channel associated with a bank-attached bar</td>
</tr>
<tr>
<td>bsu</td>
<td>the upstream end of a secondary channel associated with a bank-attached bar</td>
</tr>
<tr>
<td>bsb</td>
<td>a superimposed bar found along a bank-attached bar margin</td>
</tr>
<tr>
<td>bds</td>
<td>stranded dunes on a bank-attached bar margin</td>
</tr>
<tr>
<td>bsc</td>
<td>chute channel across a bank-attached bar</td>
</tr>
<tr>
<td>ip</td>
<td>isolated pool on a bank-attached bar</td>
</tr>
<tr>
<td>mcb</td>
<td>midchannel bar</td>
</tr>
<tr>
<td>hsv</td>
<td>horseshoe vortex</td>
</tr>
<tr>
<td>oth</td>
<td>other</td>
</tr>
</tbody>
</table>

less (s) than 0.5 meters. The fifth letter identified if Colorado squawfish were present (p) or absent (n).

Validation of Habitat Area Measurement
Determined from Videography

It was necessary to examine the appropriateness of using a GIS for evaluating 10 km of river and the use of the GIS to measure a small-scale feature such as nursery habitat, which is 100’s of square meters in extent. As such, the habitat areas interpreted from the video prints were compared to the field-mapped habitat areas from the 1993 and 1994 detailed topographic survey maps. The video prints used were for dates most closely associated with the 1993 and 1994 bar surveys within the study reach, namely August 1993 and July 1994. The discharges associated with the overflights were 50 and 59.5 m³/s, respectively.

Surrogates for Nursery Habitat Availability

Quantifying the area of available habitat from the video prints was a labor-intensive project
that evaluated only 10 km of river. If a surrogate, determined from remotely sensed data, for habitat availability existed, it would reduce the cost and time needed to assess the river each year. Schmidt (1996, unpublished manuscript) proposed using geomorphic mapping units to systematically measure habitat complexity and to map habitat attributes on a series of aerial photos taken in 1963. Differences in shoreline complexity and habitat attributes were related to the characteristics of each river reach. These interpreted photos were digitized into a GIS and scaled to USGS quad maps. Schmidt's (1996, unpublished manuscript) methodology was adapted to compare variation in channel edge complexity as a function of time and changing discharge, and to relate a remotely sensed measure of complexity to actual habitat availability. Rather than comparing behavior of alluvial and canyon reaches of the Green River as Schmidt (1996, unpublished manuscript) had done, the 10-km reach within the Ouray NWR was evaluated multiple times to determine the seasonal and discharge variation in channel complexity. In addition, I used the video data to discern if:

1) a positive, significant correlation between the calculated complexity indices and the area of available habitat existed, and

2) given a correlation, if the relationship varied from year to year with changing channel morphology.

If such a correlation were to exist, it would be possible to use remotely sensed data rather than more costly field studies to quantify the availability of habitat.

Line length and area statistics necessary for determining complexity indices were calculated by the GIS. Shoreline complexity was calculated for the flow at the time of the video overflight, and the pseudo-topographic units were used to simulate the channel form at greater discharges. Areas and perimeters were calculated for each pseudo-topographic elevation by melding it and all lower "elevation" polygons into a single polygon, and its area and perimeter determined. The resulting polygons simulated the shape of the channel if the discharge's stage were to coincide with the highest
The "shoreline development" index of Wetzel [1983] was employed as a complexity index:

\[ C = \frac{\text{Perimeter}}{2x(\pi \times \text{Area})^{1/2}} \]

This index is the ratio of the perimeter of the water to the circumference of a circle of the same area. The shoreline development index was calculated from the GIS data for the water and submerged sand units of the GIS and compared to the area of available habitat in the 10-km reach for each sampling date. This index was used to compare the length of the shoreline to the area of water and indicates the degree of convolutedness of the shoreline edge. Although developed for lake and reservoir systems, this type of index was appropriate for discerning shoreline convolutedness for this alluvial system. Rivers are linear systems, so the length of the reach greatly influences this calculated complexity index. If reaches of river of different lengths are compared, this non-dimensional complexity index must be normalized. Comparison of indices for reaches of the same length of similar width or comparison of changes to a single reach, such as the 10-km study reach, over time required no normalization.

Comparison to Habitat Availability Prior to Flow Regulation

The channel form digitized from aerial photos taken in the late summer of 1963 [Schmidt, 1994] was considered to be the channel in its pre-dam condition. The 1963 data for the 10-km reach within the Ouray NWR were extracted from the larger data set of Schmidt (1996, unpublished manuscript). The discharge at the time of these photos was between 9.6 and 27.8 m³/s. The analysis of channel complexity described above was performed, the digitized image was interpreted for areas of nursery habitat, and summary statistics generated. The scale of the maps developed from the 1963
aerial photos was proportionally adjusted. The magnitude of the adjustment was determined by comparing centerline lengths for the 10-km reach from the USGS quads and the Reclamation base map Lambert Conformal Conic projection to the digitized 1963 maps. The USGS quad and Reclamation base maps yielded similar lengths, but it was necessary to multiply the length statistics from the 1963 maps by a factor of 1.27 and the area statistics by 1.62 to maintain proper proportionality.
RESULTS

Representativeness of the 1.5-km Reach

The study reach was considered representative of the alluvial Ouray reach by Andrews and Nelson [1989]. The focus of that study was on channel form and sediment transport only, so the representativeness of this short study reach was reevaluated within the broader scope of this study.

Generally, the geomorphic characteristics of the 1.5-km reach are representative of the form and sediment transport within the 10-km reach. The study reach was approximately eight bankfull channel widths in length. The width varied from 130 to 220 m at bankfull stage, but was as narrow as 50 m wide at base flow. Bank-attached compound-, point-, and mid-channel bars and a meander restricted by bedrock occurred in the 1.5-km reach and throughout the 10-km reach. The average bankfull width of the 10-km reach was about 175 m. Field observations and videography maps showed that the behavior and channel form of the 1.5-km reach were similar to those of the 10-km reach. USGS maps (scale 1:24,000) indicate that the slope of the 10-km reach is about 0.0003 m/m, 50 percent steeper than the measured slope of 0.0002 m/m for the 1.5-km reach.

Geomorphology

Nursery habitats occurred in the lee of emergent bed- and barforms at base flows. Consequently, we evaluated year-to-year changes in the distribution of bed- and barforms in order to understand why year-to-year changes in habitat availability occurred.

Bank-attached compound bars were the predominate barform and most consistent contributor to available nursery habitat in the 10-km reach (Figure 17). The study bar within the 1.5-km reach was a persistent channel feature whose maximum elevation was up to 1.75 m above base-flow stage during the period of this study. The point bar in the downstream part of the reach (Figure
Fig. 18. The detailed study reach in July 1994 based on interpreted Reclamation video prints. Cross-section locations are shown. Within-channel deposits were characterized as: (1) higher-elevation vegetated deposits shown as sand and vegetation or vegetation indicated by "plant" pattern on white or dark stipple, respectively, (2) high elevation white sand deposited by floods indicated by the dot and dash pattern, and (3) dark and wet sand near base-flow level indicated by dark shading. Flow is from the top of the page.
18) was a lower elevation deposit (<0.75 m above base flow) that changed greatly in emergent area at base flow during this study.

Geomorphic Characteristics and Changes of the Bank-Attached Compound Bar in the Upstream Part of the 1.5-km Reach

The study bar was composed of three distinct units: vegetated sand, white sand, and dark sand (Figure 2). The highest elevations of the study bar (> 95.0 m) were stabilized by saltcedar and willow. The main bar platform (94.0-95.0 m in 1993, 93.75-95.0 m in 1994) was composed of bare white sand that had been deposited or reworked during high discharges. The lower bar platform (93.5-94.0 m in 1993 and 93.5-93.75 m in 1994) was composed of wet, white, or silty dark sands and was inundated by discharges less than about 100 m$^3$/s.

This bar was first surveyed in 1986 and was completely unvegetated at that time [Andrews and Nelson, 1989]. The bar also extended further downstream in 1986 than in any subsequent survey. These conditions presumably were the result of the high annual discharges that occurred in the study area between 1983 and 1986. Vegetation had colonized the high elevation part of the study bar by September 1990.

The study bar had several geomorphic features. A chute channel dissected the bar between cross-sections 7 and 8 (Figure 2) in 1993 and 1994. A secondary channel followed the bank on river right when facing downstream. Other features of the study bar in 1993 and 1994 included isolated pools formed by horseshoe vortices at the head of the stable vegetated island between cross-sections 10 and 11, a deep pool within the secondary channel between cross-sections 8 and 9, and superimposed bars along the margin of the study bar (Figure 2).

The elevation, shape, and topographic organization of the study bar changed from year to year. Cross-section surveys and data inferred from the digitized detailed bar topography and video prints were used to measure small- and large-scale bar changes.
The 1992 survey data depict the general setting of the study bar prior to onset of the spring 1993 snow melt flood. The September 1992 video image shows that the bar was more intricately dissected by chute channels, and that there were three emergent areas at a low discharge of 35 m$^3$/s (Figure 19). The largest emergent area included a higher-elevation vegetated area, was attached to the bank, and occurred at the upstream end of the study bar. White sand and vegetation also occurred on the downstream emergent feature. Chute channel flow entered the secondary channel, and the secondary channel was not an area of stagnant flow at this discharge. In November 1992, all surveyed cross-section points on the bar were lower than 94.5 m, and the overall bar platform was lower in elevation than in subsequent years.

1993 - Channel Cross-Section Measurements

Substantial aggradation of the study bar occurred during the 1993 flood. Maximum flood stage was 1.5 m greater than the highest elevations of the bar surveyed in November 1992. A smooth-edged, high-elevation bar emerged after flood recession (Figure 2). By June 10, immediately after passage of the flood peak but before bar emergence, the bank-attached bar and its secondary channel had aggraded 0.6 m in most locations and the thalweg had scoured about 1 m. The chute channels on the bar accumulated up to 1.7 m of sediment.

Between June 10 and 22, rain in the Yampa basin caused a short-term rise in discharge during the overall descending limb of the flood. The discharge increased 85 m$^3$/s over a 6-day period, and then the descending limb resumed its systematic decrease. During this period, the upstream end of the study bar eroded 0.5 m (Appendix C). The middle and downstream end of the study bar remained at about the same elevation, but a large dune was deposited on the river offshore side of the secondary channel at the downstream end of the bar.
Fig. 19. Study bar in September 1992 based on interpreted Reclamation video prints. Flow is from the top of the page. Areas of nursery habitat are hatched. Dark sand, white sand, and vegetation are indicated by dark stippled, dots and dashes, and dark stippled with "plants," respectively.
The study bar became emergent between the June 22 and August 15 surveys. During this period, only small changes in morphology were measured on the top of the study bar. The thalweg filled at all cross sections within the reach that included the study bar. The bar shoulders, which are the submerged bars between the emergent point or bank-attached bar and the thalweg, were eroded throughout the study reach.

During the base-flow period of summer and fall 1993, the thalweg in the study reach continued to fill and erosion occurred on the bar shoulders. The study bar was reduced in elevation by 0.1 to 0.2 m during this period at cross-section 8 (Appendix C), possibly by the high winds observed during this period and which are common [Andrews and Nelson, 1989].

1993 - Emergent Barform

After flood recession, the emergent form of the study bar was very different than it was in 1992. The net aggradation of the bar measured during the 1993 field season was approximately 0.5 m in the secondary channel, and between 0.5 and 1.0 m on the surface of the bar platform. The chute channels that formerly had crossed the upstream portion of the bar in 1992 no longer existed. Although the vegetated area upstream of cross-section 8 scoured sufficiently to remove existing vegetation (compare Figure 19 and Figure 16a), the saltcedar and willows were not removed from the downstream vegetated area just upstream from cross-section 7. The area of the bar above 95.0 m increased from 0 to 3540 m². These results are consistent with those of Krider [1994].

Krider [1994] analyzed the sedimentary structures of the newly aggraded study bar. He showed that the bar platform and secondary channel aggraded at least 0.3 m, with aggradation occurring by deposition of low-amplitude (0.1 to 0.2 m) migrating dunes at high flows, and by deposition of climbing ripples during the descending limb of the hydrograph. The downstream and lateral increases in bar extent were accommodated by the advance of slipfaces. These slipfaces had heights up to 1 m in some locations and were formed with sediment supplied from downstream-
migrating dunes on the bar platform.

1994 - Channel Cross-Section Measurements

The channel form changed greatly between November 1993 and March 1994. Spring 1994 field observations showed that winter flows had eroded the downstream end of the study bar (near cross-section 7), that small midchannel bars became emergent near cross-sections 7 and 10, and that the location of the thalweg had migrated from river left to the bar margin in the vicinity of cross-sections 9 and 10.

In 1994, flood flow barely inundated the highest elevations of the study bar. Consequently, although localized areas of scour and fill occurred on the bar platform, the most dramatic response to flood passage occurred in the deepest portions of the channel. Immediately prior to flood passage, the thalweg was located on river left at cross-sections 12 and 11, crossed to the bar margin on river right above cross-section 10, then crossed back to river left between cross-sections 8 and 7. During the ascending limb of the hydrograph, the thalweg moved up to 50 m with the resultant thalweg following the river left channel margin for most of the length of the bar and crossed to river right near cross-section 7. One to 2 m of scour and fill occurred during the lateral migration of the thalweg in this reach (Appendix C).

Changes observed across the bar platform in 1994 were much less dramatic. About 0.25 m of fill occurred on the upper platform near cross-section 9, with scour of about 0.25 m occurring on the upstream end of the bar (Figure 2). The higher portions of the secondary channel, as measured by surveys of cross-sections 8, 9, and 10, aggraded on the ascending limb, but scoured during flood recession.

1994 - Emergent Barform

The large-scale topography of the study bar changed little from that of 1993, but the
topographic complexity substantially increased. The net effect of the reworking of bar platform sediments was to increase the area of the bar above 95.0 m from 3,540 to 11,730 \( m^2 \), but to decrease the area of the bar between 94.0 and 95.0 m by about 50 percent, from 61,620 to 30,270 \( m^2 \). Upon bar emergence, three low-amplitude bars were superimposed on the shoulder of the compound bar. These superimposed bars made the topographic form of the bar, especially at base flow stage of about 93.5 m, more complex than it had been in 1993 (Figure 2). No vegetation on the bar was removed by scouring. The secondary channel accumulated about 0.25 m of sediment in the depression between cross-sections 8 and 9, although net scour occurred at the measured cross sections, and it accumulated more than 1.0 m of sediment at the downstream end. About 0.25 m was eroded from the upstream portion of the bar. This portion of the bar blocked throughflow into the secondary channel. This overall flattening of the secondary channel topography greatly reduced the range of discharges at which water, but not throughflow, occupied portions of the secondary channel. In 1993, this range was from less than 45 m\(^3\)/s to a discharge greater than 136 but less than 170 m\(^3\)/s. In 1994, the range of these flows was more narrow and was between 76 m\(^3\)/s and 136 m\(^3\)/s. It is important to note that the minimum flow necessary to inundate the secondary channel in 1994 was greater than normal base flows. Thus, the channel was not a backwater habitat at the mandated base flow. Throughflow was initiated in the secondary channel at a discharge less than 170 m\(^3\)/s in 1993 and less than 136 m\(^3\)/s in 1994 (the 94.5 and 94.25 m elevations, respectively). These discharges, and hence throughflow, occurred only during the floods.

Analysis of sedimentary structures of the newly aggraded parts of the study bar showed that the low-amplitude bar near cross-section 8 was superimposed on the previous year's deposit. The lateral extent of the bar platform was greater at this location in 1993. This area of the bar scoured below the stage of average base flows, and the low-amplitude bar was superimposed on the scoured deposit. The low-amplitude bars had superimposed 3-dimensional downstream-migrating dunes and
downstream-migrating ripples.

Geomorphic Characteristics and Changes in the 1.5-km Study Reach

The location of the study and point bar within the study reach was fixed, but the location of midchannel bars and the thalweg was transient. The study bar was located between cross-sections 7 and 12, and was truncated in its downstream extent by the shift of the thalweg from the river-left bank to the river-right bank. The point bar was highly variable in its extent at base flow from year to year. Although detailed topographic maps were not developed for the point bar, cross-sections 1 through 6 described this feature. During and after flood passage, the thalweg meandered from river left to river right through the length of the reach, and the cross-over point occurred between cross-sections 6 and 8. The meandering of the thalweg was more complex after the winter base flows of 1993-1994, although a cross-over point persisted near cross-section 7 throughout this study. No field observations of thalweg location were made after the 1992-1993 winter flows prior to the passage of the 1993 flood.

The passage of the 1993 flood greatly rearranged the within-channel sediment. The channel scoured at least 3 m at cross-section 2 between May 21 and June 10, a period extending from near the flood peak of 570 m$^3$/s to midway on the descending limb of the flood (422 m$^3$/s). Aggradation of 1.5 m occurred on river left near cross-sections 1 and 3 and a midchannel bar was removed. The aggradation and the resulting low-flow emergent bar reduced the 1992 split flow to single-threaded flow on river right in 1993. Between June 10 and June 22, aggradation continued at the downstream point bar. Between June 22 and August 15, the point bar and the upstream study bar became emergent. The midchannel bar between cross-sections 2 and 3 was removed prior to the return to base flow. The thalweg filled during this period everywhere in the reach except just below the cross-over area where 2 m of scour was measured. Filling of the thalweg, increased thalweg
meandering, and lateral erosion of the bank-attached bar occurred during the remainder of the year.

Sediments were rearranged by the 1993-1994 winter flows. A midchannel bar was emergent between cross-sections 11 and 12, and a low-elevation bar was emergent near the study bar margin upstream from cross-section 7 during the March 1994 survey.

During passage of the 1994 snow melt flood, the thalweg between cross-section 4 and 8, inclusive, filled 1 to 2 m during the ascending limb and subsequently scoured on the descending limb. After flood passage, the thalweg filled to approximately the same elevation as had existed on November 20, 1993. The most downstream portions of the point bar, between cross-sections 1 and 3, scoured throughout the passage of the 1994 flood. The upstream portion of the point bar, between cross-sections 4 and 6, had approximately 0.5 m of fill.

Sediment Budget Within the 1.5-km Reach

The average bed elevation of the 1.5-km reach increased 0.15 m for the period between November 1992 and October 1994. Net reach-scale aggradation primarily occurred during the 1993 flood and to a lesser degree during the 1994 flood (Figure 20).
Examination of the spatial distribution of the sediment storage on the bed and bars showed that sediment aggradation did not occur throughout the reach. The average elevation of the bed increased in the upstream end of the study reach (Figure 21) during the 1993 flood. A large quantity of sediment moved into the upstream portion of the reach during the passage of the 1993 flood and was stored on the study bar that occupied most of the channel.

Just as the average bed elevation did not constantly decrease through the reach (Figure 21) because of the existence of pools and shallows, the change in sediment storage within the study reach was unevenly distributed (Figure 22). The 1993 flood resulted in increased sediment storage in the wide, upstream part of the reach. This upstream increase was entirely due to aggradation on the study bar, because the thalweg scoured then filled to its previous elevation with the subsequent low flows. As will be shown below, the elevation of the upstream portion of the bar determined the base flow that maximized secondary channel habitat availability. There was little change in average bed elevation or sediment storage in the downstream part of the study reach during this study (Figures 21
Fig. 22. Longitudinal changes in sediment storage within the 1.5-km reach. August 1993 survey (+'s) was used as the baseline. Sediment accumulated in the upper portion of the reach with the passage of the 1993 flood. By July 1994 (X’s), the sediment had been re-distributed in a pattern similar to that of 1992 (filled X’s) although a greater amount of sediment remained in the upper cross sections of the reach.

and 22). Rearrangement of the bar platform sediments by the 1994 flood resulted in a slight decrease in the average elevation of the entire bed. In the downstream portions of the study reach, the average cross-section bed elevations after the 1994 flood were more similar to those that had existed prior to passage of the 1993 flood (Figure 21).

Geomorphic Characteristics and Changes in the 10-km Study Reach

Fourteen sites in the 10-km study reach were consistently occupied by bank-attached compound bars or point bars during the study period (Appendix D, Table D-1). In addition to these spatially stable bars, there were many transitory midchannel bars. The stable channel deposits were associated with 10 bank-attached compound bars, most with some stabilizing vegetation, three point bars, and a deposit upstream from a flood return channel that was active only during high flows (Figure 17). The low-flow morphology of these deposits varied greatly from year to year, but the
location of these deposits changed little during this study. J. Mayers (USU, pers. comm., 1995) determined that location of these deposits has changed little since 1966.

In 1992, during summer low flow, the channel in the 10-km reach had many midchannel bars. These conditions were similar to the conditions in the study reach. In July 1992, there were nine midchannel bars, and 4 of the 10 bank-attached bars were dissected by one or more chute channels (Appendix D). The channel form was complex and had many flow-dissecting features. The September 1992 videos were made during a period of lower discharge, about 35 m³/s, than the other video flights (Table 3). The September videos show that the lateral extent of bars visible in the July 1992 videos (46 m³/s) appeared to have increased, but there was no change in their location. This indicates that visible changes in morphology were probably an artifact of the lower discharge at the time of the September 1992 Reclamation overflight.

After the 1993 spring flood, the number of midchannel bars and deposits dissected by chute channels at low flow was reduced from 14 to 3; two of these were associated with dissected bank-attached bars. This reduced midchannel bar population and maps of the reach (Appendix D), show that the 1993 flood simplified channel morphology. Midchannel deposits were removed and bank-attached compound bars or point bars were consolidated into single bank-attached units such as occurred within the 1.5-km study reach (Appendix D).

The winter low flows of 1993-1994 increased the number of midchannel bars to 18 by April 1994. Deposits were emergent at 55.5 m³/s in 8 midchannel locations whereas no deposits were emergent at 51 m³/s in September 1993. There was an apparent overall decrease in the lateral extent of the bars, and this lateral erosion was confirmed by cross-section surveys in the 1.5-km reach (Figure 23).

The gross planform of the channel changed little as a result of the passage of the low flood peak in 1994. The total number of midchannel bars decreased slightly (from 15 to 13), but
Fig. 23. Surveys of cross-section 9 in August 1993 (thick line) and April 1994 (thin line). This shows the overwinter lateral erosion that occurred on the bank-attached bar within the 1.5-km reach.

comparison of the April 1994 and July 1994 videos showed that few of these bars were in locations where midchannel bars had existed prior to the flood. The bank-attached compound bars changed little in location or in length, but their shorelines became more complex upon emergence at low flow (Appendix D).

Modeled Bed Response to Flood Simulations

Comparison to Andrews and Nelson [1989]

2-Day Simulations

Simulations of bankfull discharge for 2 days produced 0.2 m scour in the thalweg and 0.1 m fill over the bar top (Figure 24), similar to that shown by Andrews and Nelson [1989]. Unlike Andrews and Nelson’s [1989] 2-day bankfull simulation, little change occurred in secondary channel elevation. Model cross sections (Figure 24) show the response of the bank-attached bar, secondary channel, and thalweg. These cross sections are upstream from those shown by Andrews and Nelson [1989] because the bar was located further upstream in 1994 than in 1986. The channel topography
Fig. 24. Modeled changes in topography for a period of 2 days at 475 m³/s (bankfull) discharge for the model cross sections of the bank-attached compound bar. Dashed lines indicate original topography, solid lines the topography after 2 simulation days. The changes in topography over the bank-attached bar were similar to those modeled by Andrews and Nelson (1989). Computational cross-section A is just above cross-section 10 (see Figure 18), B is midway between 9 and 10, C is just below cross-section 9, D is mid-way between cross-sections 8 and 9, and E is just below cross-section 8.
in 1986 was the result of very high flood peaks during the previous 4 years. In addition, the secondary channel was well defined for the length of the bar between 1992 and 1994 but more limited to an area near the channel constriction at cross-section 7 in 1986. The response of the secondary channel was possibly limited by the splined topography not adequately representing the bar and secondary channel topography. Increased topographic resolution might have resulted in more flow being routed into the secondary channel, and resulted in more a realistic secondary channel response.

**Flood Simulations**

Longitudinally, the areas of scour and aggradation predicted by the model were spatially restricted; these predictions are consistent with field data collected during this study. Although the bank-attached compound bar increased its elevation in all simulations, the point bar was scoured in all simulations. The secondary channel topography was relatively insensitive to discharge and changes in discharge in all runs. All runs produced localized areas of scour on river left just above and below the bend; the amount of scour was a function of simulation period. Simulations showed that scour of the upper surface of the bank-attached compound bar (93.0-94.5 m) occurred during steady flows of 400 m$^3$/s, and bar aggradation occurred only for the overbank (400-575 m$^3$/s) hydrograph. Thalweg scour of about 0.25 m was occurred during the steady (400 m$^3$/s) and bankfull (400-500 m$^3$/s) hydrograph simulations but a slightly greater amount of scour occurred during the longer overbank (400-575 m$^3$/s) simulation.

The change in average bed elevation over the longitudinal profile was very dependent on the flood hydrograph. Bed scour occurred throughout the reach for both the steady and bankfull runs, but the unsteady flow produced more thalweg scour than did the steady flows (Figures 25 and 26). The overbank hydrograph was the only run that increased the average bed elevation of the upstream cross sections, although this simulation greatly decreased the average bed elevation in the
Fig. 25. Effects of a simulated hydrograph on computational cross sections throughout the study reach. Modeled changes in cross-section topography for steady 400 m³/s discharge (dashed line) and a hydrograph from 400 to 500 to 400 m³/s (dashes with dots). The solid line denotes initial topography. While bar aggradation and thalweg scour occur in the upstream cross sections, unrealistic scour is produced on river left in downstream cross sections above and below the bend. Computational cross-section A is cross-section 12 (see Figure 18), B is near cross-section 10, C is just below cross-section 8, D is near cross-sections 4, and E the downstream end of the reach.
Fig. 26. Modeled effects of floods on the bank-attached bar. Modeled changes in computational cross-section topography (at 11 days for steady 400 m$^3$/s flows (solid line), a hydrograph that ramped from 400 to 500 to 400 m$^3$/s (dashed line), and at 17 days for a hydrograph of 400 to 575 to 400 m$^3$/s (dashes with dots). The latter simulation resulted in higher bars and in some cross sections, a more deeply scoured thalweg, but also produced unrealistic scour in some downstream cross sections. Computational cross-section A is cross-section 12 (see Figure 18), B is just above cross-section 11, C is near cross-section 10, D is just below cross-sections 9, and E is midway between cross-sections 8 and 9.
downstream cross sections (Figure 27). Very deep scour was simulated upstream and downstream from the inside of the bend. This unreasonably deep scour may be a modeling artifact resulting from the numerical method applied to the rapidly changing topography of the very steep banks at these locations.

Comparison to Field Work

The modeled flood simulations were of greater duration than the simulations of Andrews and Nelson [1989], although of shorter duration than the 1993 and 1994 floods (Figure 12) and greater in magnitude than the 1994 flood. The simulated hydrograph ramping rates were similar to those of the 1993 flood but comparable longer duration runs were not possible because of model instabilities. No direct comparison of these simulations to field data was possible because no floods occurred on high elevation bar topography during this study. The 1994 peak discharge of 330 m$^3$/s did not inundate the bar top, a condition necessary for successful simulations. However, it is possible to compare model results for bed evolution to the patterns of scour and fill observed in the field in 1993 and 1994.

The general patterns of scour and deposition simulated by the model were similar to those observed in the study reach. The model produced bar building on the bank-attached bar in response to flood events, with greater amounts of aggradation for higher floods of longer duration (Figure 27). The secondary channel was insensitive to flood hydrograph characteristics for the model runs (Figures 25 and 26), a result contrary to that of the field-measured cross sections. Field data showed that the secondary channel at cross-sections 8 and 9 scoured approximately 0.25 m (Appendix C) between May 14 and 28, 1994 at discharges much less than 400 m$^3$/s and the secondary channel aggraded about 0.5 m during the 1993 flood, thus demonstrating that the secondary channel did respond to flow regime attributes. Behavior of the downstream point bar was not adequately predicted by model simulations. Some scour occurred during the ascending limb of the 1994
Fig. 27. Longitudinal bed elevation for the three model runs. Average bed elevation is shown for the initial conditions, steady discharge, 500 m$^3$/s peak, and 575 m$^3$/s. The relationship of computational cross sections to field-measured cross sections is detailed in Figure 13. Only the greatest peak discharge was sufficient to accumulate sediment in the upper cross sections. Unrealistic scour at the bank edge in the downstream cross sections was more pronounced in simulated floods of greater magnitude and longer duration.

hydrograph on this bar, but the modeled scour greatly exceeded the measured scour. It was also expected that for higher discharges, such as the 1993 flood, fill would occur over the point bar.

Relatively little thalweg scour was simulated in these model runs; these results were predicted by field and gage measurements. Field measurements in the study reach and at the discontinued USGS stream gage near Ouray (Figure 3) showed that much of the thalweg scour occurred during the ascending limb of the hydrograph in cross sections such those of the USGS gage and cross-sections 2 and 3. About 2 to 3 m of scour occurred in the thalweg at cross-sections 2 and 3 between the base flows of March 17, 1994 and much the higher discharge of 214 m$^3$/s on May 14, 1994 (Figure 28). The May 14, 1994 topography was measured on the ascending limb of the hydrograph. Much of the expected thalweg scour occurred prior to May 14, 1994 and, consequently,
Fig. 28. Cross-section surveys for cross-sections 2 (A) and 3 (B) during the ascending limb of the 1994 flood. The channel condition is shown for March 17 (thick line) prior to flood passage, April 30 (dash-dot line) at a peak in a spike on the ascending limb of the flood hydrograph, May 14 (dotted line) on the resumed ascending limb, and May 28 (thin line with +’s) near the maximum 1994 discharge (see Figure 10). The thalweg scoured more than 2 m in these cross sections.
only relatively small amounts of scour were expected in the thalweg for the modeled flood scenarios.

The use of the model of Andrews and Nelson [1989] for the Ouray 1.5-km reach was greatly expanded in this work. Simulations were of longer duration and allowed unsteady discharge. Although cross-section data resolution of this study was insufficient to address the response of individual nursery habitats to flood passage, increased topographic resolution for the channel and a new version of this model (J. Nelson, USGS, pers. comm., 1996) may improve the applicability of the model to changes in individual nursery habitats in response to flow regime in future studies. Although the secondary channel was not represented by model topography, simulation results were applicable to habitat availability in secondary channels. As discussed below, the elevation of the upstream portions of the bar affects the habitat availability curve for secondary channel, and the model simulated changes in the upstream bar elevation.

Year-to-Year Changes in Nursery Habitat Availability

Two very different data sets were used to assess changes in habitat availability in response to flood passage and as a function of discharge. Large-scale videography was used to determine the geomorphic setting of habitats in a 10-km reach and the year-to-year change in habitat availability at base flow. Smaller scale intensive geomorphic field studies provided an understanding of the physical framework that formed habitats, and hence the processes that form, maintain, and maximize habitat availability within the 10-km reach.

Use of Topographic Maps to Evaluate Discharge-Dependent Changes in Available Habitat

The Habitat Availability Curves (HAC’s) for the study bar were different each year of this study (Figure 29). The discharge-dependent habitat relation had more than one peak each year of this study, and each peak of each year’s HAC was the product of a bar feature (Figure 30). The
Fig. 29. Localized habitat availability curve for the study bar in 1993 and 1994. The 1993 curve is indicated by a dashed line, and the 1994 curve by a solid line. Base flows were about 50 m$^3$/s in 1993 and 1994, and the bankfull discharge was about 475 m$^3$/s. For these years, the greatest amounts of habitat were available at discharges greatly exceeding base flows. The geomorphic setting and area of habitats were determined from the GIS maps shown in Figure 15.

The discharge that maximized habitat availability for this bank-attached compound bar was greater in 1993 than was the discharge that maximized habitat availability in 1994. There was little available habitat at discharges greater than 290 m$^3$/s in 1993 and 240 m$^3$/s in 1994 (Figure 29), although the area of low-velocity habitat must increase dramatically once flows go over bank at a discharge of about 475 m$^3$/s. Although a data point does not exist for the peak in secondary channel habitat mode in 1994, it was inferred from the topographic maps as follows. At a stage of 93.75 m, a large area of habitat would exist at the upstream end of the secondary channel, a small area at the downstream end of the channel would be inundated, and an isolated pool habitat would exist between cross-sections 8 and 9. As discharge increases, the area of the isolated pool and the downstream inundated area would increase, although the upstream habitat would be overtopped by a stage of 94.0 m. The stage necessary for secondary channel throughflow in 1994 was less than 94.25 m, so that no secondary...
Fig. 30. Decomposition of the localized habitat availability curve by geomorphic classification. Area of available habitat is separated into geomorphic components, such as the habitats associated with the secondary channel, superimposed bars, and isolated pools. Dashed and solid lines indicate 1993 and 1994 habitats, respectively. The total available habitat in 1993 and 1994 are indicated by X’s and +’s, respectively. The lines do not always coincide with the markers but the addition of the curves for available habitat in each geomorphic setting for each year results in habitat availability curve shown in Figure 29.

Nursery habitats occurred over a large range of discharges, but in the lee of different bar features at different discharges. In 1993, all of the available habitat at discharges between 50 and
136 m³/s was associated with the secondary channel (Figure 30). The upper bar surface, for discharges between 175 and 250 m³/s, provided small amounts of habitat created downstream from an emergent portion of the bar. These upper-bar-surface habitats were observed during cross-section surveys and were further confirmed by silt deposits on the bar. The latter indicate low- or no-velocity areas. In 1994, habitats were associated with superimposed bars along the bar edge and the upstream end of the secondary channel at lower discharges (50-90 m³/s), the secondary channel at slightly higher discharges (100-136 m³/s), and the area downstream of the emergent portions of the bank-attached bar at higher (150-300 m³/s) discharges. As a consequence, the habitat availability curve had two peaks in 1993 and three peaks in 1994, and there was no habitat available at discharges greater than 240 m³/s in 1993 or 290 m³/s in 1994.

Changes in Habitat Availability in the 1.5-km and 10-km Reaches as Determined from Video Images

Validation of Remotely Sensed Data

Nursery habitats in the vicinity of Ouray NWR occupied only 1-2 percent of the inundated channel during low-flow periods. Consequently, I evaluated the adequacy of mapping these very small areas of habitat from the large-scale video prints. The area of individual habitats mapped in the field at the time the detailed topography survey was compared that the area of those habitats mapped on the GIS video maps from the 10-km reach (Figure 31). The relationship between area of habitat interpreted from the videos and from the field maps was linear ($r^2 = .89, df = 5, P = .001$), and the fitted line had a slope of 1.01. The area interpreted from the video prints tended to slightly underestimate the area interpreted from detailed topography of the study bar (Table 6). This analysis demonstrates that the digitizing of nursery habitat from interpreted, zoom-transferred video prints is an appropriate tool for assessing trends in total nursery habitat availability, although it does not assess the availability of high quality habitats.
Fig. 31. Comparison of interpreted video habitats and field-mapped habitats in 1994. The field-mapped water's edge and nursery habitats were added to the GIS of the 1994 detailed topographic map for comparison to the habitats interpreted on the July 1994 video prints. Areas of nursery habitat are hatched. Dark sand, white sand, and vegetation are indicated by dark stiples, dots and dashes, and dark stiples with “plants,” respectively.
TABLE 6. Comparison of Digitized Habitat Area from Video Prints and Low-Flow Field-Mapped Habitats of the Study Bar in 1993 and 1994. $r^2 = 0.89$. First Column Is Geomorphic Classification of Habitat as Described in Table 5

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Changes in the Geomorphic Setting of Nursery Habitats

Each geomorphic setting (e.g., Figure 15) had characteristic responses to flood passage. The habitats found at the downstream end of secondary channels ("bsd") were typically deep and a predominant type of habitat sampled by UDWR. Part of the predominance of this habitat type may be attributed to its depth; these habitats persist over a range of discharges, although they may be totally filled with sediment in some years. The habitats located at the upstream end of the secondary channel ("bsu") were typically shallow. Isolated pools tended to be transient, and their level fluctuated with changes in discharge. Horseshoe vortices ("hsv") observed in the field were often deep and, by their association with a stable feature, occurred in the same location from year to year. Bars and dunes superimposed on bank-attached bar edges ("bsb" and "bsd" habitats, respectively), and chute channel habitats ("bsc") were more transient and tended to be shallow. Midchannel bar habitats ("mcb") were the most transient habitats.

Within the 1.5-km and 10-km study reaches, the geomorphic settings of available nursery habitats changed yearly during this study, and these patterns of changing habitat availability in the
1.5-km study reach were similar to those of the 10-km reach. In 1992, habitats were formed by chute channels on emergent portions of dissected bank-attached compound bars (Figure 19). A greater area of total and deep habitat was available at discharges much less than the target base flows in 1992. Within the 10-km reach, habitat areas of 29,970 and 16,960 m², total and deep habitat, respectively, were available at a discharge of 35 m³/s, but the area of total available habitat was reduced to 21,700 m² and the area of deep habitat to 13,220 m² at a discharge of 46 m³/s. In 1993, the bank-attached compound bars of the 10-km reach were single, nondissected units. The downstream ends of the secondary channels and some stranded dunes on the edge of the bars were the location of nursery habitats (e.g., Figure 15B). Field observations in August 1993 showed that individual stranded dune habitats (bsd) were too small (often <10 m²) to be adequately interpreted on the Reclamation video prints, although areas associated with a field-observed series of stranded dunes were delineated in the GIS. In addition, the individual “bsd” habitats were too small to meet the Interagency Standardized Monitoring Program’s minimum requirements for suitable backwater habitat [Valdez and Cowdell, 1994]. In 1994, the low-elevation bars superimposed along the edge of the bank-attached bar and the upstream end of the secondary channel were the location of nursery habitat (Figure 15B).

In the study reach, habitat location and setting did not persist through the spring flood. Similarly, in the 10-km reach, particular habitats often did not persist from year to year, and the contribution of different geomorphic settings to habitat availability changed yearly (Tables 7 and 8). Not all geomorphic categories were equally represented in terms of total number and area contributed for nursery habitat. The most consistent and largest contributors to the overall number and area of available nursery habitat were the secondary channels’ downstream end, upstream end, and chute channels (Tables 7, 8, and B-1). The habitats found at the downstream end of the secondary channel and in chute channels were most commonly the deep habitats (Tables B-2 and B-3).
To compare actual yearly change in habitat availability, the effect of discharge on habitat availability should be minimized. The July 1992, August 1993, and July 1994 video prints were made at similar discharges of about 45 m$^3$/s, and are used in the discussion below to compare changes in availability of nursery habitat in the 10-km reach. The September 1992 video prints, made at a discharge of about 35 m$^3$/s, demonstrate the effect of discharge on nursery habitat availability. The 1993 flood increased the number of deep habitats and the total number of habitats available, although a greater number of habitats and deep habitats had been available during the September 1992 low (35 m$^3$/s) flows. The 1993 flood also increased the area of available deep habitat within the 10-km reach from 13,210 to 17,460 m$^2$. The 1994 flood greatly increased the number and area of all habitats, but greatly decreased the number and area of deep habitats, from 8 to 1 and from 17,460 to 3,080 m$^2$, respectively. As discussed above, the newly formed, shallow habitats in the study reach were associated with bar edge deposits with low-topographic relief, and hence these habitats persisted for only a narrow range of discharges. Similar bar edge habitats were found throughout the 10-km reach.

Significant changes in habitat availability occurred during the winter low flows and between field seasons. The average discharge during the winter was higher than the summer low flows, and habitats that were available the previous summer were typically reduced in size or eliminated by stream processes during the winter. The digitized videos from September 1993 and April 1994 (Appendix D) show these winter channel changes. The total number and area of habitats were reduced by winter channel changes (Tables 7 and 8). Habitats that occurred at the downstream ends of secondary channels were degraded by erosion or filling reducing the total number and area of habitats. Valdez and Cowdell [1994] observed an ice dam at RM 255.8 that eliminated a large, deep habitat by diverting the river over a bar and through that habitat. The downstream end of the study bar experienced erosion that progressively shortened the tail of the bar and, consequently, reduced
TABLE 7. Counts of Represented Geomorphic Classification of Nursery Habitat for Each Sampling Date and from the Digitized 1963 Photos. The Number of Deep Habitats Is in Parentheses, but No Depth Data Were Available for the 1963 or the March 1992 Dates. Descriptions of the Geomorphic Classification Codes Are in Table 5

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TABLE 8. Total Area (m²) of Nursery Habitat by Geomorphic Classification from the GIS for Each Video Overflight and the Digitized 1963 Photos

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the area of the deep habitat at the downstream end of the bar. The area, interpreted from the video GIS, was reduced from 869 to 345 m$^2$ between September 1993 and April 1994. The total area of available habitat was reduced from 21,083 to 14,309 m$^2$ during the winter. By April 1994, the number of deep habitats was reduced from 13 to 4, the reduction a consequence of some habitats filling with sediment and other habitats becoming throughflow.

**Comparison to Habitat Availability Prior to Flow Regulation**

The discharge at the time of the 1963 photos was between 9.6 and 27.8 m$^3$/s, but was not unusually low for base flow prior to river regulation. The mean of the annual minimum discharges prior to dam regulation was 15 m$^3$/s. The total area of habitat available at this discharge in 1963 was very similar to the area of available habitat found during the 2-year period of this study. Approximately one third of the 1963 habitat area was found in isolated pools. The rest were distributed in the geomorphic units that are still predominant (Tables 7 and 8). Consequently, the overall contribution of different geomorphic features to habitat availability has changed little since dam regulation.

**Shoreline Complexity and Habitat Availability**

Shoreline complexity has been correlated with habitat complexity in large rivers [Gosse, 1963 cited in Sedell et al., 1989]. Habitat complexity, the degree of heterogeneity of a habitat, is a different quantity than habitat availability, the total area of available habitat, although greater areas of available habitat should occur in more heterogeneous rivers.

**Complexity, Habitat, and the Detailed Topographic Maps**

The peak of Gosse’s complexity index coincided with maximum habitat availability in 1993, (Figure 32), but did not in 1994. High ratios of shoreline length to reach length occurred in both
Fig. 32. Relationship between area of available habitat and Gosse's complexity index (Gosse's C.I.). The discharges associated with the greatest complexity indices and greatest area of available habitat did not coincide in both years. Shoreline lengths, and hence complexity index, were greater for the higher discharges (and the corresponding stage) where no habitat was available.

1993 and 1994 at discharges where there was actually little habitat available, such as between 175 and 250 m³/s (Figure 30). Consequently, for the bank-attached bar within the 1.5-km study reach, Gosse's complexity index was not a reliable indicator of discharge-dependent habitat availability for the period of this study.

Complexity, Habitat, and the Video Maps

The Wetzel complexity index for the 10-km reach in 1993 and 1994 peaked at an elevation greater than the base flow at which the video was flown (Table 9). The raw data used to calculate the values in Table 9 is in Tables B-4 and B-5. The detailed topographic maps (Figure 15) demonstrate that these higher elevations, particularly those above the dark sand level, about 94.0 m in the study reach, had greater values of Gosse's complexity index, but a smaller area of available habitat (Figure
TABLE 9. Wetzel’s Complexity Index for Each Topographic Level of the 10-km Reach. Columns Are the Overflight Dates Detailed in Table 3 or the 1963 Photos. The Range of Discharges Given for Each Level Indicates the Approximate Discharges That Inundated That Level During 1993 and 1994.

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<td>7.61</td>
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</tr>
<tr>
<td>wt</td>
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<td></td>
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</tr>
<tr>
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<td></td>
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<td>6.42</td>
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</tr>
<tr>
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<td></td>
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<td>4.10</td>
<td>4.17</td>
<td>4.07</td>
<td>4.06</td>
<td>4.11</td>
</tr>
</tbody>
</table>

30). Throughflow in the secondary and chute channels greatly increased shoreline length, but the throughflow overtopped habitat-forming feature reducing the area of available habitat.

The Gosse and Wetzel complexity indices were not reliable indicators of base-flow habitat availability. The area of available habitat, as interpreted from video prints and digitized on the GIS map for each video sampling date, and the corresponding Wetzel index are shown in Figure 33. The correlation for Gosse’s index to habitat availability at base flow was not significant. The correlation for Wetzel’s complexity index and habitat is best for shallow habitats ($r^2 = 0.61$, df = 4, significant with $P = 0.069$), significant for total habitat ($r^2 = 0.54$, df = 5, $P = 0.077$), but is not significant for deep habitats ($r^2 = 0.20$, df = 4, $P = 0.33$) (Figure 34). The low correlation between the complexity index and deep nursery habitat and better correlation with shallow habitats may be explained as follows. First, the scale of the area and perimeter of habitats, 100’s of meters, is very small compared to that of the overall scale of the channel, 10’s of kilometers. Consequently, resolving a “signal,” such as the area of available habitat, based on other parameters in this noisy geomorphic system was difficult at best. Second, the greatest amount of habitat was found in three geomorphic settings: (1) the up- and downstream ends of secondary channels, (2) chute channels, and (3) the lee of superposed bars. Of all of these, only the chute channels and superimposed bars greatly increased
Fig. 33. Area of available nursery habitats (total, deep, shallow, and unknown), and corresponding Wetzel complexity index, 1992-1994, inclusive. The area of available habitat is a function of channel condition and discharge, and while the total area of habitat and the area of shallow habitats were significantly correlated to a shoreline complexity index, the area of deep habitats was not. In addition, the relative overall contribution of deep and shallow habitats to total area of nursery habitat was not consistent from year to year.

The population of midchannel bars and measures of shoreline complexity varied from year to year. Consequently, whatever relationship could be discerned between shoreline complexity and area of available habitat for a single year would vary greatly in subsequent years. Shoreline complexity was an inappropriate surrogate for deep habitats availability, but was correlated to total nursery habitat availability.
Fig. 34. Correlation of total area of available nursery habitat to shoreline complexity. The total area of nursery habitat (filled X's) and area of shallow habitat (X's) were significantly correlated to shoreline complexity ($r^2 = 0.54$, and $r^2 = 0.61$, respectively) but the area of deep habitat (+'s) was not desirable nursery habitats. A conceptual model is developed below to target optimal habitat formation and to provide estimates of the year-to-year changes in the base flows required to maximize habitat availability.

Development of a Conceptual Habitat Availability Model

Nursery habitat availability was not maximized by the base flows in 1992, 1993, or 1994. Colorado squawfish populations are probably limited by other factors, such as nutrient availability, temperature, and the presence of sympatric and predatory species, in addition to habitat availability. Knowledge of the river processes that form habitats allows not only the design of flood flows to target those flows that form the habitats available at base flow, but also the design of those flows that form the most desirable nursery habitats. A conceptual model is developed below to target optimal habitat formation and to provide estimates of the year-to-year changes in the base flows.
required to maximize habitat availability.

It was possible to consider the geomorphic features associated with individual modes of the HAC for the study bar, and to determine those modes that were associated with optimal habitats. Biological research has shown that deep backwater habitats, in the absence of predators, are optimal for young-of-year Colorado squawfish (T. A. Crowl, Dept. of Fisheries and Wildlife, Utah State University, pers. comm., 1996) and this study has shown that deep habitats occurred most often in secondary channels. Consequently, the conceptual model presented below targets secondary channels and the maximization of deep backwater habitats, although the concept may be applied to other geomorphic features as well.

For optimal backwater habitat to be available, it is necessary for the geomorphic feature associated with that habitat to be inundated but not have through-flowing current. Exposed bars must block throughflow, but the secondary channel must be inundated. If the controlling geomorphic feature is overtopped, water flows through the channel and the low-velocity areas are eliminated; no habitat is then available in that geomorphic setting. If the elevation of the secondary channel bed is higher than the stage at low flow, the potential habitat is dry.

These ideas are demonstrated by the changing relation of the study bar's secondary channel habitat to base-flow discharge. In 1992, the secondary channel had throughflow at discharges less than 45 m$^3$/s, the target summer discharge for Flaming Gorge Dam operations. Throughflow occurred between the vegetated island and the downstream end of the bar (Figure 19), so no habitats associated with the secondary channel were available at the mandated base flow. In 1994, the secondary channel bed was higher than the typical low-flow stage and, as a consequence, no secondary channel habitats occurred at low flow. The elevation of the secondary channel bed in 1993 was deep enough to be inundated at typical base flows but the upstream parts of the bar were high enough to block throughflow from upstream. Consequently, some secondary channel habitat was
available at typical base flows in 1993.

Three conditions must be met to maximize the area of available optimal habitat at low flow. First, a portion of the geomorphic feature, such as the secondary channel bed, must be high enough to block throughflow. Second, the backwater must have an opening that allows some inflow from the channel. Third, the discharge, and hence stage, must be sufficient to fill, but not overtop, the area provided by the geomorphic feature, thus maximizing the area of habitat provided by that feature. In 1993, the discharge at which the maximum area of secondary channel habitat occurred was much greater than was the base-flow release from Flaming Gorge Dam (Figure 30). Consequently, while some optimal habitat was available in 1993 within the study reach, the area of optimal habitat was not maximized. In 1992, the secondary channel became active at about 35 m$^3$/s, and thus the maximum area of available habitat associated with the secondary channel occurred at a discharge less than 35 m$^3$/s. Base flows in 1992 exceeded 35 m$^3$/s; consequently, no secondary channel habitat was available at low flow in 1992, although a large area habitat would have been available in this location at a lower discharge.

The shape of the habitat availability curve for each geomorphic feature of the study bar (Figure 30) was inferred from field data and the detailed topographic map. In both 1993 and 1994, the area of available secondary channel habitat increased with increasing discharge. Then, when the channel had active flow, the area of available habitat decreased rapidly to zero. Consequently, the habitat availability curve for the secondary channel was skewed left in 1993 and 1994 (Figure 30).

The width of the secondary channel habitat availability curve was indicative of the difference in elevation between the upstream portions of the bar that prevent throughflow and the elevation of the secondary channel bed that determined the lowest base flow that inundated parts of the secondary channel. When there was less difference in elevation between the up- and downstream ends of the secondary channel, such as occurred in 1994, the curve was narrower, and the long tail was truncated.
on the left side of the curve. The larger flood in 1993 aggraded the upstream end of the secondary channel and scoured the secondary channel bed more deeply. The increased range of elevation for the secondary channel increased the width of the curve, and hence the range of discharge for which habitat was available.

A conceptual model of habitat availability for a single geomorphic setting was developed by making some simplifying assumptions. A normalized value for habitat area was assumed so that the maximum area of available habitat in any year was 1. Hence, only the variations in the width of the curve and the discharge associated with maximum area of available habitat were considered. In 1994, the discharge associated with throughflow in the secondary channel was slightly less than in 1993 (Figure 30), and the width of the curve was greatly reduced. The reduction of the secondary channel HAC curve width was the result of aggradation at the downstream end of the secondary channel such that the total longitudinal relief of the secondary channel bed was reduced by about 1 m, narrowing the range of discharges for which water occupied, but did not flow through, the secondary channel.

This conceptual model was used to consider the temporal changes to the habitat availability curve. The peak of the habitat availability curve for secondary channels is shifted right, to greater discharges, in response to the passage of a large flood, and then progressively moves left, to lower discharges (Figure 35) in subsequent years of lower flood peaks. The width of the curve, and hence the range of discharge for which secondary channel habitat exists, is dependent on flood dynamics. During this study, the larger flood peak increased the range of elevations of the bed of the secondary channel and, hence, the width of the curve. The low flood peak decreased the range of elevations by scouring the higher elevations and filling the lower elevations of the channel bed, thus narrowing the width of the curve and shifting the peak to a lower elevation and reducing the discharge that maximized habitat availability. A series of low-peak floods should continue this process until,
Fig. 35. Conceptual model of secondary channel habitat curve. The shape of the curve and the discharge associated with the maximum area of available habitat changes in response to flood passage. Large floods rebuild topography, shifting the peak for available habitat to the right as the overall elevations of the secondary channel is increased. The peak of habitat availability shifts to the left in subsequent low flood peak years as the upper end of the secondary channel erodes. The width of the curve narrows as the total relief within the secondary channel is reduced.

similar to the conditions observed in 1992 after 6 years of drought, the discharge that maximizes secondary habitat availability is less than the currently mandated base flow. Using more detailed topographic information and a new version of the flow and sediment transport model used in this study, it may be possible to resolve the details of bar and secondary channel response critical to habitat formation (J. Nelson, USGS, pers. comm., 1996).

The Effects of Floods on Colorado Squawfish Nursery Habitat in the 10-km Reach

The magnitude of flood peaks of the Green River may be separated into three categories: (1) very low flood peaks that do not inundate the bar tops but rearrange sediment along the bar margins, (2) low flood peaks that inundate the bars but do not overtop the banks, and (3) large floods that overtop the banks. Although the channel responds rapidly to changes in discharge, the imprint of the antecedent conditions on the low-flow channel form survives flood passage, especially the passage of
low-magnitude floods. For example, the relative elevation of the bar tops and the distribution of
sediment within the channel were changed little by the passage of the 1994 flood. The effect of
floods of different magnitudes and different antecedent conditions on nursery habitat availability
were measured and modeled during this study (Table 10).

The large flood of 1993 caused significant aggradation of bar tops and, while reducing the
area of shallow habitat, did not adversely affect the availability of deep habitats (Table 11). The
much lower 1994 flood greatly rearranged sediments along the bar margins, increased the availability
of shallow habitat, but greatly reduced the availability of deep habitat. Model runs on the high-
elevation 1994 topography suggested that less-than-bankfull flood peaks rearrange sediments, while
greater-than-bankfull floods continue bar building. I hypothesize that the latter would maintain the
increased availability of deep habitats. Aggradation and scour in this sediment-abundant system
should be a function of flow depth rather than absolute discharge. The change in habitat availability
in response to the passage of less-than-bankfull floods on low-elevation bars is unknown, but it is
reasonable to hypothesize that very low and less-than-bankfull floods on low-elevation bars behave
similarly to less-than-bankfull floods and greater-than-bankfull floods on high elevation bars,
respectively (Table 11). These hypotheses should be tested by additional research.

TABLE 10. Flood Magnitude and Antecedent Conditions for the 1993 and 1994 Floods, and the
Model Runs of This Study

<table>
<thead>
<tr>
<th>Antecedent conditions</th>
<th>Flood magnitude, increasing from left to right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-elevation bar tops</td>
</tr>
<tr>
<td>Antecedent conditions</td>
<td>Less than bar top flood</td>
</tr>
<tr>
<td></td>
<td>Greater than bankfull</td>
</tr>
</tbody>
</table>
Table 11. The Effects of Floods on Colorado Squawfish Nursery Habitat Availability on the 10-km Reach. The Effect of Very High Floods on High-elevation Antecedent Topography Was Determined from Model Run 3 Which Showed Continued Bar Top Aggradation, and 1986 Topography Surveyed by Andrews and Nelson [1989] Which Showed a Very Simplified Channel Form in the 1.5-km Reach after 4 Years of Floods with Peaks Greater than 590 m$^3$/s

<table>
<thead>
<tr>
<th>Antecedent conditions</th>
<th>Less than bar top flood</th>
<th>Less than bankfull</th>
<th>Greater than bankfull</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-elevation bar tops</td>
<td>Increase shallow habitat availability.</td>
<td>Rearrangement of habitats.</td>
<td>Increase availability of deep habitats.</td>
</tr>
<tr>
<td></td>
<td>Decrease deep habitat availability.</td>
<td>Net change in habitat availability unknown</td>
<td>Decrease availability of shallow habitats.</td>
</tr>
<tr>
<td>High-elevation bar tops</td>
<td>?</td>
<td>?</td>
<td>Maintain the increased availability of deep habitats.</td>
</tr>
<tr>
<td></td>
<td>Maintain or decrease availability of shallow habitats.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hypotheses are generalized for all flood magnitudes and antecedent conditions, but consider the channel only as it currently exists and ignores possible long-term changes such as channel narrowing. Further work is necessary to determine the effect of floods on habitats in a channel that is much wider or narrower than currently exists.
DISCUSSION AND CONCLUSIONS

The results of this multiscale study provide a geomorphic framework for understanding year-to-year changes in habitat availability for juvenile Colorado squawfish. Aquatic habitats in high-gradient headwater streams are associated with channel roughness elements such as boulders, rocks, and large woody debris. In this low-gradient alluvial river, the habitats are associated with bedform roughness elements of multiple scales; these elements were primarily dunes and bars that responded dynamically to flood passage and changes in flow regime. Habitats occur in similar and predictable geomorphic settings throughout the reach in each year, although the predominate geomorphic settings of habitats in any year are dependent on flood magnitude and antecedent conditions.

My study shows why the approach of establishing a single discharge that is intended to maximize habitat availability every year is inappropriate. Year-to-year bar topography, and hence habitat availability, changes annually. The discharge that maximizes habitat availability also changes each year, and the habitat availability curve in any year has multiple modes. The multipeak curves observed during this study probably explain the poor correlation of habitat availability to discharge found by Pucherelli et al. [1990] in the Ouray reach.

This study evaluated the adequacy of remotely sensed complexity indices to adequately predict habitat availability. Although it is more inexpensive to calculate complexity indices from remotely sensed data, this study demonstrates the need for an annual field assessment of channel topography to determine the discharges that maximize habitat availability.

This study used an unvalidated assumption common to IFIM: that a positive, linear relationship exists between habitat availability and fish biomass. Sympatric and predatory species have an overwhelming presence in this system, and there are indications that habitat selection may be driven by predatory pressures (T.A. Crowl, USU Dept. of Fisheries and Wildlife, pers. comm., 1996). In addition, the overall area of available habitat does not appear to have greatly decreased.
since dam closure, but the population of endemic fishes has plummeted. Consequently, Colorado squawfish populations are probably not habitat limited, although population may be limited by the area of habitat that, given the presence of predatory species, is optimal for recruitment. Hence, it is necessary for biologists to determine those types of habitats that promote successful recruitment of Colorado squawfish in the Green River as it exists today rather than its pristine state, and those high flows that are detrimental to the exotic species of the Green River.

I have placed individual habitats sampled within the larger context of geomorphic setting, and mapped the relative contribution of different types of habitats spatially and temporally. To meet the need of improving existing habitat and creating preferred habitats, we have used information from ecologists and biologists to note what are some preferred habitats. By knowing the geomorphic setting of existing preferred habitat, and the discharges that form desirable habitats, we can recommend flows to improve the quality and quantity of available habitat.

Basis for New Flow Recommendations

A new flow recommendation that improves habitat availability for Colorado squawfish must include both antecedent-condition and flood magnitude components. The flood cycle over a period of years should include both infrequent large floods that rebuild channel topography and frequent lower magnitude floods. The practice of extending the duration of low-peak floods should be reevaluated. The extended peak of the low 1994 flood greatly reduced the total area of high-quality habitat available at base flow and created many large lower quality habitats. Within the study reach, the newly created habitats were associated with low topographic-relief geomorphic features that were available for a much smaller range of discharges than the 1993 habitats and were subject to overtopping by the greater magnitude winter flows. In addition, juvenile squawfish that have successfully overwintered are relatively small, about 4-5 cm [Tyus and Haines, 1991], and probably
still need refuge from the main channel flood flows, or, at the least, a minimization of periods for which no refuge from high velocities exists. If the prolonged peak’s stage is greater than the bar tops but less than bankfull, then neither the habitats associated with the bars nor with the floodplain are available, a condition typically of very short duration for the Green River prior to dam closure. The target summer flow should be dependent on channel morphology and recommendations will need to be evaluated annually. Furthermore, winter flows and their impact on overwinter habitat availability and degradation must also be evaluated.

Flow Recommendations

Large floods are necessary to maintain channel width [Yu and Wolman, 1987], scour encroaching vegetation, and, as shown is this study, rebuild bar topography and channel relief. Ecologically, as a river becomes simplified and channelized, there are fewer bars and secondary channels and hence fewer locations for low-velocity habitat. To improve availability of high-quality habitat, we focus on the secondary and chute channels because they provide the greatest area, number, and quality of habitat.

The 4.5-year recurrence flood of 1993, while rebuilding dissected bars, was not sufficient to remove encroaching vegetation. The floods of 1983-1986 accomplished the latter. If channel width is to be maintained, floods that accomplish more geomorphic work than the 1993 flood will be necessary (i.e. of greater peak and/or longer duration).

The unregulated Yampa River provides much of the peak flow at Jensen. Flaming Gorge Dam has been used to augment the peak of the Yampa River, although peak dam releases have been reduced to minimize downstream flooding. The magnitude of large, infrequent floods must be sufficient to maintain channel form, (e.g., greater in magnitude than the 1993 flood), and the practice of augmenting the Yampa River peak should be continued.
High flows may not be necessary every year. Moderate peaks in the years following large floods rearrange the deposits that are midchannel bars at base flows and increase the complexity of portions of the bank-attached compound bars. Although habitat availability may be increased by moderate floods, these floods do not necessarily create high-quality habitats at current summer target flows. The lower flood peaks from the Yampa River, produced by years of low snow pack within the Yampa basin, should be augmented, but the duration should be limited for those flood discharges less than bankfull, but greater than bar top, stage.

Summer and winter base flows should be reviewed. Operations under the Final Biological Opinion for Flaming Gorge Dam mandate summer flows that are much closer to historic levels. My research showed that in some years, the maximum area of available nursery habitat may occur at discharges much lower or much higher than the recommended base flow; as such, the target summer discharge should vary annually and reflect changes in channel topography. Formative flows can be used to target geomorphic categories of habitat so that optimal habitats are available at base flows. Winter discharges, increased by Flaming Gorge Dam releases, overtop many low elevation deposits above nursery habitats. Impact to recruitment from overwinter habitat loss should be evaluated in future studies.

Although the Green River, as it exists today, has not dramatically changed in its area of available habitat since dam closure, many other pressures exist for endemic fishes. Being a long-lived species, successful recruitment does not need to occur each year, but some years must have strong age classes. Management practices that promote the formation and availability of optimal habitats for Colorado squawfish and suppress exotic species populations should be pursued: This is the only viable instream flow philosophy for species recovery [Tyus, 1992].
REFERENCES


Engelund, F., and E. Hansen, *a Monograph on Sediment Transport in Alluvial Streams*. Teknisk Verlag, Technical University of Denmark, Copenhagen, Denmark, 1967.


APPENDIX A. SEDIMENT TRANSPORT CALCULATIONS
Critical Depth for Sediment Transport to Occur

To calculate the critical discharge necessary to move the sand of the Ouray NWR reach, the critical shear stress, \( \tau_c \), necessary to move sand was calculated. The average boundary shear stress, \( \tau_b \), was calculated for the reach, then minimum flow depth necessary to move the sand was determined.

**Calculation of critical shear stress:**

Shield’s equation:

\[
\tau_c = \theta_c g (\rho_s - \rho) \quad \text{and,} \quad \text{d(ave) = 0.3 mm = 3x10^{-4} m for medium sand}
\]

\[
\text{d(ave) = 1.0 mm = 1 x10^{-3} m for coarse sand}
\]

\[
\theta_c = 0.04
\]

\[
(\rho_s - \rho) = 1600 \text{ kg/m}^3
\]

\[
g = 9.8 \text{ m/s}
\]

Therefore,

\[
\tau_c = 0.18816 \text{ N/m}^2 \text{ for medium sand}
\]

\[
\tau_c = 0.6272 \text{ N/m}^2 \text{ for coarse sand}
\]

**Boundary shear stress:**

\[
\tau_b = \gamma RS
\]

\[
S = 0.0002 \text{ at Ouray}
\]

\[
\gamma = 1000 \text{ kg/m}^3 \times 9.8 \text{ m/s}
\]

Now setting \( \tau_c = \tau_b \) and solving for \( R \), we find \( R = 0.1 \text{ m for medium sand, 0.32 m for coarse sand} \).

The average flow depth for all observed discharges was greater than the minimum flow depths necessary to move sand at Ouray NWR.

**FORTRAN Program to Calculate Bed Elevation**

The limits for channel, thalweg, and bar are delimited and labeled on each plotted cross section (Appendix C). Data for individual cross sections from multiple surveys were used as input. The program prompts for input cross section data and delimiting files and output file name. Expected data format is detailed within the program.

**PROGRAM AVEDEPTH**

C This program calculates the average depth of a given cross section.
C Input is a single cross section surveyed a number of times. Thalweg,
C bar and channel limits have been defined in a secondary file, infile2. Infile
C contains the cross sections in the form: number of points in the
C cross section, then pairs of distance from RL and
C the elevation associated with that distance.
C parameter(ns=5,nn=87)
C ns = number of surveys, if changed, also need to change nums in subroutine
dimension zin(ns,nn),inum(ns),maxdepth(ns),avethal(ns),avebar(ns)
dimension dist(nn,nn),thalarea(ns),bararea(ns),chanarea(ns)
dimension avebed(ns)
real maxdepth
character*20 infile, outfile, infile2
write(6, *) 'Enter the name of the cross section survey file:
read(5,3) infile
write(6,*) 'Enter name of thalweg/bar definition file:
read(5,3) infile2
write(6,*) 'Enter the name of the output file:
read(5,3) outfile
open(8, file=infile)
open(10, file=infile2)
open(9, file=outfile)
3 format(a20)
C Read inputfiles: first is cross section, second defines lateral location of bar/thalweg.
read(8, *) inurn
do 80 k=1,ns
80 continue
do 25 k=1,ns
in=inurn(k)
do 21 l=1,in
read(8,*) dist(k,i), zin(k,i)
21 continue
25 continue
read(10,*) sthal, ethal, sbar, ebar, rl, rr
C find main channel, calc area, width (and hence avedepth) of bar and thalweg
C
wthal=ethal-sthal
wbar=ebar-sbar
wchannel=rr-rl
call calcdepth(ns, inum, dist, zin, sthal, ethal,thalarea, maxdepth)
call calcdepth(ns, inum, dist, zin, sbar, ebar,bararea, maxdepth)
call calcdepth(ns, inum, dist, zin, rl, rr, chanarea, maxdepth)
C C CALCULATE AVERAGE DEPTHS C
do 40 k=1,ns
avethal(k)=96-thalarea(k)/wthal
avebar(k)=96-bararea(k)/wbar
avebed(k)=96-chanarea(k)/wchannel
40 continue
write(9,*)' wthal, wbar, wchannel = ', wthal, wbar, wchannel
write(9,*)'Number Thalweg Bar Channel ''
do 60 I=1,ns
write(9,*)i, avethal(i), avebar(i), avebed(i)
60 continue
close 8)
close 9)
close 10)
The subroutine `calcdepth` is used to calculate the depth of a channel in a computer program. The subroutine takes several parameters, including the number of sections (`ns`), the number of iterations (`inum`), the distances (`dist`), the start and end points (`start`, `end`), and the area and depth (`area`, `mxdepth`).

The subroutine begins by initializing some variables to zero, including `mxdepth`, `area`, `iflags`, and `iflage`. It then iterates over each section, calculating the area using a formula that takes into account the distance between points and the depth at those points. If the section is within the desired section, the area is calculated and added to the total area. If the section is just past the end of the section, the area is calculated and added to the total area at the end of the section.

The subroutine also includes checks for when the section is just past the start or end of the desired section, and writes error messages if the calculated depth exceeds a certain limit.

The code snippet provided includes comments that explain the purpose of each block of code, making it easier to understand the logic and flow of the subroutine.
endif

C now calculate cross section area for thalweg
C

if (((dist(k,1).gt.start).and.(dist(k,1).lt.end)) then
  if (zin(k,1).gt.96) then
    write(6,*)'PANIC TIME...zin for thalweg > 96'
  endif

  area(k)=area(k)+(96-zin(k,1))*(dist(k,1)-dist(k,1-1))
  area(k)=area(k)+0.5*(zin(k,1)-zin(k,1-1))*(dist(k,1)-dist(k,1-1))
endif

C write(6,*)'the area of the section is:' ,area(k)
C find maximum depth
30 if (mxdepth(k).GT.zin(k,1)) then
    mxdepth(k)=zin(k,1)
endif
31 continue
31 continue
  return
end

Sediment Size

Fig. A-1. Sediment sieve data from June 22, 1993. Both the D_{84} and D_{50} indicate that medium-sized sand was in transport over the bank-attached bar on this date. A grain-size of 0.3 mm was used as input to the flow and sediment transport model of Andrews and Nelson [1989]. The bold line is the aggregate curve for all sediment samples.
APPENDIX B. GIS STATISTICS AND ADDITION HABITAT DATA
GIS Statistics and Addition Habitat Data

TABLE B-1. Average Size (m²) of Habitat for Each Geomorphic Setting from the GIS for Each Video Overflight and the Digitized 1963 Photos

<table>
<thead>
<tr>
<th>Date</th>
<th>bsd</th>
<th>bsu</th>
<th>bsb</th>
<th>bds</th>
<th>bsc</th>
<th>ip</th>
<th>mcb</th>
<th>hsv</th>
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</thead>
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<tr>
<td>1963</td>
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<td>634</td>
<td>0</td>
<td>0</td>
<td>208</td>
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<td>1017</td>
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<td>241</td>
<td>197</td>
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TABLE B-2. Average Size (m²) of Deep Habitats for Each Geomorphic Setting from the GIS for Each Video Overflight and the Digitized 1963 Photos

<table>
<thead>
<tr>
<th>Date</th>
<th>bsd</th>
<th>bsu</th>
<th>bsb</th>
<th>bds</th>
<th>bsc</th>
<th>ip</th>
<th>mcb</th>
<th>hsv</th>
<th>oth</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
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<td>--</td>
<td>--</td>
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<td>--</td>
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</tr>
<tr>
<td>18-Mar-92</td>
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<td>295</td>
<td>--</td>
<td>--</td>
<td>--</td>
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</tr>
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<td>--</td>
<td>--</td>
<td>903</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>1892</td>
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<td>29-Jul-94</td>
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<td>--</td>
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<td>--</td>
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<td>--</td>
<td>--</td>
<td>355 858</td>
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</table>
TABLE B-3. Average Size (m$^2$) of Shallow Habitats for Each Geomorphic Setting from the GIS for Each Video Overflight and the Digitized 1963 Photos

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<tr>
<th>Date</th>
<th>bsd</th>
<th>bsu</th>
<th>bsb</th>
<th>bds</th>
<th>bsc</th>
<th>ip</th>
<th>mcg</th>
<th>hsv</th>
<th>oth</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>1963</td>
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<td>--</td>
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<td>--</td>
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<td>18-Mar-92</td>
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<td>--</td>
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<td>--</td>
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<td>2155</td>
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<td>--</td>
<td>--</td>
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<td>--</td>
<td>--</td>
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<td>--</td>
<td>200</td>
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<td>--</td>
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<td>537</td>
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<td>197</td>
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<td>355</td>
<td>3752</td>
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</table>

TABLE B-4. GIS Statistics for the Area for a Given Pseudo-Topographic Level and Below. Area Is in m$^2$. Each Column Is for an Overflight Date Detailed in Table 3 or the 1963 Photos

<table>
<thead>
<tr>
<th>Topo level</th>
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<th>July 92</th>
<th>Sept. 92</th>
<th>April 93</th>
<th>Aug. 93</th>
<th>April 94</th>
<th>July 94</th>
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<tbody>
<tr>
<td>water</td>
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<td>675399</td>
<td>1480315</td>
<td>1212578</td>
<td>1088171</td>
<td>1163692</td>
<td>1173208</td>
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<td>1138657</td>
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<tr>
<td>wt</td>
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<td>718149</td>
<td>1480315</td>
<td>1225532</td>
<td>1088846</td>
<td>1167413</td>
<td>1174953</td>
<td>1195305</td>
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<tr>
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<td>1780937</td>
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<tr>
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<td>2214441</td>
<td>2215819</td>
<td>2192119</td>
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</table>

TABLE B-5. GIS Statistics for the Perimeter of Each Pseudo-Topographic Level and Below. Perimeter Is in Meters. Each Column Is for an Overflight Date Detailed in Table 3 or the 1963 Photos

<table>
<thead>
<tr>
<th>Topo level</th>
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<th>1963</th>
<th>May 92</th>
<th>July 92</th>
<th>Sept. 92</th>
<th>April 93</th>
<th>Aug. 93</th>
<th>April 94</th>
<th>July 94</th>
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<td>32769</td>
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<td>30759</td>
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<tr>
<td>wt</td>
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<td>32614</td>
<td>33316</td>
<td>32894</td>
<td>29706</td>
<td>29524</td>
<td>29342</td>
<td>34759</td>
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<tr>
<td>ds</td>
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<td>33986</td>
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<td>36958</td>
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<td>37521</td>
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<tr>
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<td>28673</td>
<td>31209</td>
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<tr>
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<td>21775</td>
<td>21490</td>
<td>21446</td>
<td>21581</td>
<td>21567</td>
</tr>
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</table>
Measurements of the area and perimeter of the polygons lumped as vegetation (and below) vary by 1.5 and 1.9 percent, respectively, for the 7 video sampling dates. Since the vegetation polygon is assumed not to have changed during the study period, the difference in measurements reflects the cumulative errors of various transfer methods. The area and perimeter measurements of other map units changed greatly from time to time, and are assumed to represent real topographic change.
APPENDIX C. CROSS-SECTION DATA
Figure C-1. Cross-section 1 (top) and 2 (bottom) survey data from 1993.
Figure C-2. Cross-section 3 (top) and 4 (bottom) survey data from 1993.
Figure C-3. Cross-section 5 (top) and 6 (bottom) survey data from 1993.
Figure C-4. Cross-section 7 (top) and 8 (bottom) survey data from 1993.
Figure C-5. Cross-section 9 (top) and 10 (bottom) survey data from 1993.
Figure C-6. Cross-section 1 survey data from 1994.
Figure C-7. Cross-section 2 survey data from 1994.
Figure C-8. Cross-section 3 survey data from 1994.
Figure C-9. Cross-section 4 survey data from 1994.
Figure C-10. Cross-section 5 survey data from 1994.
Figure C-11. Cross-section 6 survey data from 1994.
Figure C-12. Cross-section 7 survey data from 1994.
Figure C-13. Cross-section 8 survey data from 1994.
Figure C-14. Cross-section 9 survey data from 1994.
Figure C-15. Cross-section 10 survey data from 1994.
Figure C-16. Cross-section 11 survey data from 1994.
Figure C-17. Cross-section 12 survey data from 1994.
APPENDIX D. DIGITIZED VIDEO MAPS
## Table D-1. Date and Discharge for Reclamation Video Overflights

<table>
<thead>
<tr>
<th>Figure</th>
<th>Date</th>
<th>Days since Jan. 1, 1992</th>
<th>Discharge (m³/s)</th>
</tr>
</thead>
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<td>68.5</td>
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<tr>
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<td>July 29, 1992</td>
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<td>45.9</td>
</tr>
<tr>
<td>D-3</td>
<td>September 23, 1992</td>
<td>266</td>
<td>35.4</td>
</tr>
<tr>
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<td>August 10, 1993</td>
<td>587</td>
<td>45.6</td>
</tr>
<tr>
<td>D-5</td>
<td>September 27, 1993</td>
<td>635</td>
<td>51.0</td>
</tr>
<tr>
<td>D-6</td>
<td>April 5, 1994</td>
<td>825</td>
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<td>D-8</td>
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</table>
Figure D-1. Video data from March 18, 1992
Figure D-1. Continued
Figure D-1. Continued.
Figure D-2. Video data from July 29, 1992
Figure D-2. Continued
Figure D-2. Continued.
Figure D-3. Video data from September 23, 1992.
Figure D-3. Continued.
Figure D-3. Continued.
Figure D-4. Video data from August 10, 1993.
Figure D-4. Continued.
Figure D-4. Continued.
Figure D-5. Video data from September 27, 1993.
Figure D-5. Continued.
Figure D-5. Continued.
Figure D-6. Video data from April 5, 1994.
Figure D-6. Continued.
Figure D-6. Continued.
Figure D-7. Video data from July 29, 1994.
Figure D-7. Continued.
Figure D-7. Continued.
Figure D-8. Photography from 1963
Figure D-8. Continued.
Figure D-8. Continued.