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AN EVALUATION OF FOUR INSTREAM FLOW METHODOLOGIES

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EVALUATION OF FOUR INSTREAM FLOW METHODOLOGIES USED ON THE YAMPA AND WHITE RIVERS, COLORADO

by

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ABSTRACT

Four instream flow assessment methodologies were applied to selected reaches of the middle Yampa and White Rivers in Colorado. These were 1) The Tennant method, 2) R-2 Cross, 3) WSP, and 4) the incremental analysis method developed by the Cooperative Instream Flow Service Group (IFG) of the U. S. Fish and Wildlife Service in Fort Collins, Colorado.

The methodologies were applied in accordance with standard published procedures or criteria supplemented by various agencies. The flow recommendations were evaluated against actual field observations of physical and biotic conditions in both rivers and against weighted usable area predictions from the IFG incremental model.

Flow requests from the Tennant method (30 percent of mean annual flow) were acceptable for the White River but unnecessarily high for the Yampa River. R-2 Cross flow requests varied considerably depending upon cross sectional placement but the "best" request was considered adequate for both rivers. WSP requests approximated those of R-2 Cross and were also considered adequate.

The flow level derived from the first three methodologies (200 cubic feet per second (cfs) was analyzed in a two species contrast with the IFG methodology and found to provide critically low habitat for Colorado squawfish while offering near optimum conditions for channel catfish. Minimum flows in such rivers should be evaluated on a flow regime rather than a long-term minimum flow basis.

Cost and time evaluations were also conducted. The various field procedures required approximately equal cost and time inputs, but the IFG incremental analysis offered the greatest analytic advantages.

ACKNOWLEDGEMENTS

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INTRODUCTION

State and Federal agencies charged with determining amounts of water reservations for fish and wildlife have employed a variety of instream flow methodologies. Accounts of the field application of these methodologies are accumulating, and it is evident that refinements are necessary if the required efficiency and applicability is to be gained. Also, in some cases, a methodology which serves the purposes of a particular agency may not meet the needs of a similar agency concerned with flow preservations in a different hydrologic provence. Cost and time considerations may govern the selection of a third methodology.

In the Rocky Mountain states, most application and refinement of instream flow methodologies has centered around coldwater species and mountain streams, for obvious reasons of resource value. Recent studies demonstrating the acute habitat reductions of the arid rivers of the Upper Colorado River Basin, however, have focused attention upon measures necessary to prevent futher losses of both native fauna and the unique riverine character of the area.

The fate of the highly endemic fish fauna of the Upper Colorado River Basin is well documented (Holden and Stalnaker l975). At least four large river fish species are presently threatened. They are the humpback sucker *(Xyrauchen texanus)*, the bonytail chub *(Gila elegens)*, the humpback chub *(Gila cypha)* and the Colorado squawfish *(Ptychocheilus lucius)*. The latter two fish are designated as endangered species under federal law.

Concurrent with the decline of these fish populations are rising demands for the waters of their native rivers. Dewatering effects are probably secondary to dam construction and introduced species as factors in the decline of these fish, but limitation of habitat by water loss may have a far greater effect in the future.

Objectives of the project were: 1) To apply four currently used instream flow methodologies to selected reaches of the Yampa and White Rivers in Colorado; 2) To compare the resultant flow recommendations against actual observed instream conditions and to evaluate cost and time expenditure associated with each methodology; and 3) To make formal flow recommendations for the studied reaches.

Because of current fishery research being conducted on the Yampa and White Rivers in western Colorado by the authors (contractors to the Bureau of Land Management [BLM]), these rivers were selected as study sites. This fishery research will be referred to as the BLM study in this report. Both rivers are known to contain Colorado squawfish, and the Yampa River has yielded all four rare fish species in past studies (Holden and Stalnaker 1975, Hagen and Banks 1963).

The Yampa River arises above Toponas, Colorado, and flows approximately 275 km west to its confluence with the Green River in Dinosaur National Monument. Annual average flow has been about 1.2 million acre-feet (maf), or 1,479 hectare meters (hm). The Yampa River drains Colorado's two largest potential coal production areas, in the Williams Fork Mountains and the Danforth Hills.

The White River arises above Buford, Colorado, on the White River Plateau, and flows approximately 175 km west toward its confluence with the Green River south of Duchesne, Utah. Its average annual flow is about 500,000 af (616 hm). The White River drains two of Colorado's major oilshale deposit areas, the Piceance Plateau and Yellow Creek Basin.

DESCRIPTION OF METHODOLOGIES

The instream flow methodologies evaluated were of four major types: 1) Fixed percentage methodologies; 2) single cross section computer methodologies; 3) Multiple cross section computer methodologies; and 4) Multiple cross section computer methodologies with extensive output manipulation leading to incremental habitat analysis for each target species of fish. Methodologies which use computer programs to predict hydraulic conditions at unobserved flows are usually known by the name of the computer program. However, in this report the word methodology refers to the manner in which the computer output is used to obtain biologically meaningful flow assessments or to ensure predetermined criteria. Many such methodologies may exist for use with output from a single computer program.

FIXED PERCENTAGE METHODOLOGIES

Fixed percentage methodologies usually require the application of some fixed amount of flow reduction to historic flow data accumulated on the stream in question. Hoppe and Finnel (1973) determined that certain points on a flow duration curve were associated with favorable conditions in the stream, such as the Q^{17} (the flow exceeded during only 17 percent of the time period for which data were available) relationship with flushing flows which cleared the substrate of impacted fine sediment.

The fixed percentage methodology selected in this study was the Tennant method or Montana method, usually regarded as a field limited technique, was developed after a lengthy series of field observations noting reductions in such fluvial parameters as wetted perimeter, cross sectional area, and velocity, with reductions in flow. From these observations, approximations of maintenance flows were forecast as follows: 1) Minimum flow was to be about 10 percent of mean annual flow and corresponded to that flow below which only short-term survival of aquatic life might be expected; 2) Thirty percent of mean annual flow was recommended as a "base flow to sustain good survival conditions for most aquatic life forms..."; and 3) Sixty percent provided "excellent to outstanding habitat for most aquatic life forms." Tennant criteria have normally been applied to United States Geological Survey (USGS) mean annual flow figures without adjustments for losses due to consumptive use or impoundments upstream.

SINGLE CROSS SECTION COMPUTER METHODOLOGIES

Single cross section computer methodologies utilized cross sectonal dimensions and hydraulic parameters gathered at one stream cross section at one flow to predict hydraulic conditions at selected but unobserved flows. A U. S. Forest Service (USFS) program known as R-2 Cross (Anonymous 1974) was the most commonly used such program. Cross sectional dimensions were measured from a steel tape stretched across the stream channel. Program calculations allowed conversion of the sag tape data to straight reference line data. Hydraulic properties including discharge, velocity, wetted perimeter and cross sectional area were computed for alternate water levels. The criteria used in the methodology were supplemented by the agencies which used the program, but all users agreed that the single cross section placement should describe a "critical" area of the study section, usually a riffle. Some agencies used predetermined depth and velocity criteria to predict minimum flows, while others graphed these quantities against flow and noted inflection points.

MULTIPLE CROSS SECTION COMPUTER METHODOLOGIES

Multiple cross section computer methodologies utilized field data collected at more than one cross section of a stream reach. A computer program capable of analyzing all cross sections and predicting hydraulic properties at unobserved flows provided output which was used in selecting flows by criteria selected by the user of the methodology. The most commonly used multiple cross section computer program was called Water Surface Profile (WSP), a program developed by the Bureau of Reclamation (Burec) under the name "Pseudo". Several "water surface profile" programs exist, and it is important that references are made to the proper program.

The WSP ("Pseudo") program used in this evaluation was created by Burec for use in calculating water surface elevations below dams and sediment transport and hydraulic properties near bridges, wiers or orificies. Instructions for use of the program as an instream flow predictor were given by Dooley (1974), Spence (1975), and in less detail by Elser (1976) and Cochnauer (1976).

A second multiple cross section program, known here as AVDEPTH, was developed by Dr. Robert Milhous of the IFG and is known as "A-D" in this report. A-D utilizes observed or predicted discharge-depth relationships to empirically predict hydraulic porperties. Output from this program was used in most recommendations involving multiple cross sections because of limitations in the usability of WSP output.

Instream flow methodologies associated with WSP varied with the agency or individual using the program, but usually incorporated maintenance of certain velocity, area and wetted perimeter criteria. Graphs of velocity vs. discharge or wetted perimeter vs. discharge usually displayed an inflection point below which incremental discharge reductions resulted in increasing losses of the hydraulic property. Some users recommended those inflection points as critical flow levels below which further reductions should be made with great care.

Multiple cross section methodologies allowed for comparisons among cross sections by either an averaging of hydraulic property changes with flow or by the selection of the most critical cross section by its rate of degradation relative to other cross sections at the same station.

Both R-2 Cross and WSP used Manning's equation (Chow 1964) to predict hydraulic properties at unobserved discharges. The WSP program contained a subroutine which allowed the user to calculate the energy slope and predict water surface elevations at the cross sections. For detailed descriptions of the programs and calculations, the reader is referred to Anonymous (1974) for the R-2 Cross program and Spence (1975) or Dooley (1975) for the WSP program.

A multiple cross section computer program which allowed extensive output manipulation was developed by Robert Main of the IFG and will be known as "HABTAT" in this report. This program coupled WSP output with the "weighted usable area" system known as the IFG incremental flow methodology (USF&WS 1977). It was selected because of its sensitivity to individual species and their critical life history stages; and was considered, together with field observations made on the White and Yampa Rivers during the three year BLM study, to be a comparison standard by which the previously described methodologies could be evaluated.

Briefly, the methodology involved selection of suitable study areas and collection of multiple cross section data, such as that described for WSP. From these data, a matrix of depths, velocities and areas at a specified flow was constructed. Upon the assumption that depth and velocity were the most critical stream variables likely to change with flow alterations, the depth and velocity preferences of the fish species in question could be derived as probability curves (Bovee and Cochnauer 1977) and compared with percentages of stream area which still provided the depth-velocity requirements of the species in question. The procedure provided insight into the relative change of optimum habitat by the stream area (in square feet) offering preferred conditions to the target species at various flows. Obviously, the precise requirements of the endangered fish in question were not available, but approximations of their preferences were possible through field observations and descriptions in the literature.

While a discussion of the hydraulic predictions of the various programs seemed inevitable, effort was taken to avoid a "hydraulic comparison and verification study". The USGS has cautioned users of such hydraulic programs that all predictions will be improved by calibrations through several field observation steps. Recommendations made from unverified hydraulic model predictions in this study are fully open to change as more data accumulate.

BASIS FOR COMPARISONS AND EVALUATIONS

The purpose of the comparisons was to evaluate the biologic pertinence of several recommendation methodologies, not the predictive abilities of their hydraulic simulation models. Each methodology was applied to reaches of the Yampa and White Rivers as if a formal flow recommendation were to be made. Criteria used by agencies and individuals to determine required flows were then applied to computer output or historic flow data. The required flows thus determined were compared with observed stream conditions (if that flow was observed during the BLM study) and with weighted usable area predictions from the HABTAT program. Flow requests which were felt to be below observed flows which caused obvious temperature or crowding stress or disease, indicating obvious degradation of aquatic habitat, were noted. We also included an evaluation of the mechanics involved in using the systems from the standpoint of a biologist with little training in the surveying and computer techniques required to produce reliable data.

CONCLUSIONS

Application of several criteria to either computer output or historic USGS gage data produced remarkably similar minimum flow recommendations among three of the methodologies tested. For the White River the Tennant method request for 30 percent of mean annual flow (186.9 cfs) and the WSP and R-2 Cross requests (150 and 209 cfs respectively) were felt to be acceptable by their comparability with the median year low flow and by actual observations of the river at similar flows. For the Yampa River, R-2 Cross and WSP produced similar flow requests (about 170 cfs minimum) but the Tennant method 30 percent level was for 466 cfs which was considered unnecessarily high. The R-2 Cross and WSP recommended levels approximated the median year low flow (196 cfs) as did the Tennant method request for 10 percent of mean annual flow. This flow was considered acceptable by observation of the river at similar flows.

FIXED-PERCENTAGE METHODOLOGY

1. The Tennant method must be used with a thorough understanding of the flow regime of the river in question. Specific monthly mean flow printouts are very helpful in determining the validity of Tennant method recommendations, as are correlations with physical, chemical and biotic conditions at the prescribed flows when they are avail-

able from other sampling studies. If the 30 percent flow is less than the monthly flow not exceeded one in every two years, it may be too low to request as a flow which will become a permanent low flow after dams and diversions are in operation. If gage data are not available, the historic flow regime may be synthesized by use of techniques suggested by Orsborn (1974), but such methods are still formative and have not been verified in arid rivers such as those in this study.

2. Effort should be made to account for waters lost to consumptive use and not shown in gage data. Fixed percentage methodologies are more accurate when applied to mountain streams or protected rivers which exhibit essentially virgin flow. For such rivers as those in the Upper Colorado River Basin, application of the Tennant method is weakened by uncertainties in recreating a mean annual flow by additions of poorly known quantities lost to agricultural and municipal use and transmountain diversion.

If cost and time limit or prohibit field studies, flow recommendations by Tennant method procedures are acceptable only if proper consideration is given to the available hydrologic and biotic knowledge of the river.

SINGLE CROSS SECTION METHODOLOGIES

1. Placement of the cross section is critical to reproducibility of flow recommendations using any presently available single cross section methodology. At best, passage requirements may be assessed if the cross section is located across the shallowest riffle section, because in large, shallow-profiled rivers such as the Yampa and to some extent the White, such shallow areas are usually unsuitable for fish survival even at flows much higher than those considered minimum elsewhere in the same river.

2. Application of fixed criteria (such as percent wetted perimeter, minimum velocity, etc.) to single cross section computer output often results in flow recommendations which fail to incorporate the unique needs of certain species or their life history stages. Furthermore, as the depth-velocity substrate preferences of the target species in the Upper Colorado River Basin become known, fixed criteria may not be flexible enough to accommodate the new data.

3. Field procedures used in gathering single cross section data may have a significant effect upon the reliability of the hydraulic model. We suggest that, on rivers greater than 30 m in width, a surveying instrument be used instead of an Abney level or a clinometer to match elevations of the tape ends and to determine water surface slope. Also, alternate flows should be observed if at all possible, even if only one additional flow is available to establish a rating curve.

4. A modified version of the R-2 Cross program which requires fewer input steps and provides output more directly applicable to instream flow situations is available from the IFG in Fort Collins, Colorado.

MULTIPLE CROSS SECTION COMPUTER METHODOLOGIES

1. Multiple cross section methodologies provide a more flexible tool for use with species response criteria than do single cross section methodologies. Specifically, users may evaluate an entire reach of stream at several flows, noting hydraulic changes in pool riffle or run areas and compare these to requirements of individual species.

2. Output from the original WSP ("Pseudo") program was of limited utility to instream flow users. Certain parameters (wetted perimeter) were not calculated, while others were calculated but reflected only

average conditions at a cross section. Development of the A-D program and its coupling with WSP output provided output more usable in assessing the needs of species with known depth and velocity preferences. The width with a minimum specified depth table included in the A-D program output could be used to predict passage flows if depth and velocity preferences of certain species were known. A flow providing some width of water of at least minimum depth while providing the minimum velocity requirement would be regarded as minimum passage flow for that species. A flow which provided the greatest surface width of at least minimum depth while not producing excessive velocities would be considered optimum.

3. Percent wetted perimeter and lowest inflection points on the graphs of area, velocity or wetted perimeter vs. discharge probably have little relevance to the unique fauna of the Upper Colorado River Basin. Velocity inflection points typically occurred at flows much lower than those probably favored by the uniquely adapted fishes of the system. Primary inflections on the area and wetted perimeter graphs usually occurred at flows well below the proposed minimum flows. Secondary (higher) inflection points for these parameters, however, may be very helpful in determining the flows at or around which water ceases to cover the shallow "bench" or secondary channel areas as nursery areas. Typically, cross sectional area is lost rapidly as waters subside from a flat channel configuration area into a steeper sided area, which is the condition noted on both the Yampa and White Rivers.

4. On large rivers in the Upper Colorado River Basin, the following technical and analytic problems may arise: 1) Measurement of water surface elevations. Water surface slopes are usually about .001 on rivers similar to the White and Yampa Rivers. If studied reach lengths are too short and water surface elevations carelessly measured, errors may result which would prohibit calibration of the model. 2) Typically, long reach lengths are required on these rivers to adequately describe a given habitat unit. When such conditions exist, the following procedure is helpful in obtaining reliable surveying results efficiently: a) Close the level loop first, immediately after site selection and driving of headstakes. b) Determine water surface elevations at all cross sections. If manpower permits, determine discharge and verification velocities at this time or immediately afterward. c) Obtain cross sectional data as time permits. Cross sections with at least 15 coordinate pairs will provide better resolution if the data are to be used in more detailed methodologies such as the IFG incremental flow methodology. Also, on large, arid rivers, more detailed measurements often disclose the presence of small, flat or depressed areas which provide backwater nursery grounds for cyprinid and catostomid larvae and must be considered in rearing flow recommendations. d) Measure distances between cross sections at the water line, grass line and along the thalweg, if possible. Future refinements in existing programs may allow use of such dimensional data to construct plan-view topographic maps of the study reach. Again, verification of hydraulic models by observation of at least two disparate discharges is highly desirable.

MULTIPLE CROSS SECTION WITH OUTPUT MANIPULATION

1. Use of multiple cross sectional data in the HABTAT program provided the most comprehensive analytic and predictive tool for use in flow recommendations on rivers such as the Yampa and White Rivers. Estimates of optimum flows for channel catfish corresponded well with observed abundances of these fish in both rivers. Comparisons of flow reduction effects upon channel catfish and Colorado squawfish (from hypothetical species response data for the latter) coincided

well with effects predicted using a compilation of our present knowledge of the biology of these two species. Estimates of optimum flows for larvae and juveniles of both species were especially similar to flows actually found to be favored by these life stages.

In this initial application of the HABTAT program capabilities to large arid rivers of the West, several unique problems arose. First, the fish communities of these rivers are more diverse than those of headwaters streams. The normal increase of diversity expected in the higher order reaches of a river system (Hynes 1970) has been augmented in these rivers by exotic species introductions and hybridization. Also, the populations of these rivers differ markedly from those of smaller streams in the interactive segregations necessary to balance the competitive stress induced by such introductions. The result is a complex management problem in which no single flow recommendation may address the needs of even a small portion of the fish community present. Even among the four threatened species of the river system, differences in life history and habitat preferences are great enough to confound single minimum flow recommendations.

This complexity of intraspecific interactions may also affect the actual depth-velocity-substrate preferences of all species in such a system, and electivity curves derived in the native range of an introduced fish species should be used with caution. Ideally, new probability curves should be derived for each species within the river system being studied.

The lowest flows in these rivers typically occur during the warmest period of the summer (because of irrigation demands), and these low flows are often constituted largely of irrigation return waters rich in both dissolved organic and inorganic substances. At certain observed low flow levels, these chemical properties, adversely affected by high water temperatures, may become more limiting than loss of suitable area. HABTAT program output should be used in association with reliable flow-temperature and temperature-dissolved oxygen models during the summer months. In the future, it may be necessary to note the effect of sedimentation following coal extraction and instream construction activities. Again, flows which provide sufficient suitable hatitat may not ensure proper conveyance of an unnaturally increased sediment load.

COST AND TIME EVALUATIONS

1. Because of the various applications and adaptations of each methodology by different users, direct cost comparisons were not possible. The level of efficiency attained by individual users probably varied enough to prevent accurate cost comparisons between two agencies using precisely the same methodology. The cost and time comparisons were thus made on a general basis, as they pertained to the procedures followed in this study.

2. The Tennant method offers high time-cost benefits, but is more reliable on large rivers with extensive hydrologic research which increases the time and expense.

3. Sag tape field measurements (r-2 Cross) are relatively quick (two sites per day are possible if long intersite travel is not required), but a three man crew is ideal (if not absolutely necessary), and equipment may be more expensive than that required to do multiple cross section procedures because of the need for a calibrated steel tape and tension handle, as well as surveying equipment. Single cross section measurement procedures done strictly with surveying equipment are quicker and less expensive.

4. As the use of surveying equipment is necessary to assure accuracy even of sag tape

procedures, we feel that at least three cross sections could be surveyed by an experienced crew in only slightly more time (about 4 hours for very long study sites) than the same crew could perform a single sag tape procedure. The increased analytic capability gained thereby (from use of the WSP, A-D or HABTAT programs) would more than outweigh the small additional time deficit. Also, the extreme dependence upon proper placement of a single cross section is somewhat relieved when a larger habitat unit is described by multiple cross sections. Equipment costs, allowing $750.00 to $1,000.00 for the surveying instrument, pole and tripod, may be as much as $300.00 less than those for sag tape procedures because no steel tape or tension handle are needed.

Cost and time of conversion of field data to finished computer output is higher for multiple cross section programs, primarily because of the necessity to calibrate observed and predicted water surface elevations of the cross sections by hand. If the WSP option for such calibrations is made reliable by reprogramming, cost and time of obtaining HABTAT output from raw field data would be minimally greater than that for R-2 Cross, WSP or A-D.

MATERIALS AND METHODS

SAMPLING SITES

Data for the comparison of methodologies were collected at two Yampa River and two White River sites. These sites corresponded with fish collection areas used in the BLM study and were chosen for comparability with biological observations and for their hydraulic character.

Station Y-3 (referenced from the BLM study stationing nomenclature) was located approximately 1 km north of Maybell, Colorado, on the Yampa River (Figures 1 and 2). Five cross sections were surveyed here extending over 200 longitudinal ft. (60 m) of stream.

Steep cliffs of unconsolidated sedimentary material bordered the north bank of the river. From the north river channel boundary to the cliffs were sage, grass and cottonwood. The area south of the river consisted of hay meadows and sage covered flatlands. No irrigation diversions existed within the area actually studied, but pump diversions were common in the Maybell-Sunbeam reach (approximately 12 river km).

Station Y-4 was located approximately 2.5 km downstream from Cross Mountain Gorge on the Yampa River (Figure 3). This station was referred to as Lilly Park which was actually downstream several kilometers. Researchers from Utah State University had sampled this reach extensively in their study of the Colorado squawfish. It was a regular sampling site of the BLM study.

Overbank vegetation of the area consisted primarily of sage with some willows and cottonwoods near the river. Steep cliffs of unconsolidated sedimentary material were found near the north river channel boundary.

The area studied at Station Y-4 was the downstream segment of a large meander and was the only such deep pool habitat found between the mouth of Cross Mountain Gorge and the Yampa's confluence with the Little Snake River.

WSP cross sections involving 740 ft. (226 m) of river were taken at Station Y-4. Single cross section data at this station were derived from surveyed WSP measurements because of the difficulty in utilizing the R-2 Cross sag tape technique over so wide a cross section.

Station W-A was located 2 km upstream from the White River's confluence with

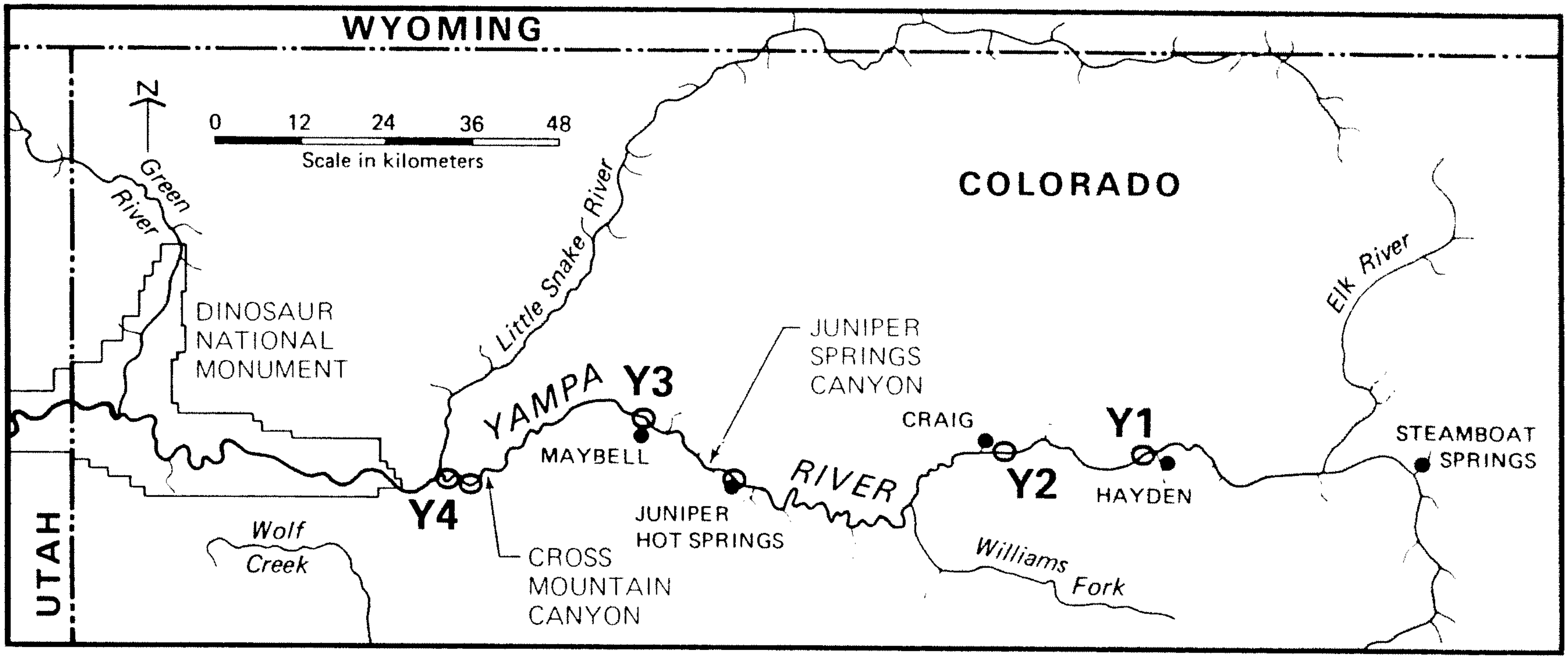


Figure 1. Location of Yampa River sampling sites.

Figure 2. Station Y-3, July, 1976

Figure 3. Station Y-4, July, 1976

Piceance Creek (Figures 4 and 5). The site was sampled regularly during the BLM study.

Overbank vegetation was dense willow and salt cedar, and no large trees were found near the river channel. The area studied was near the center of the valley and no meanders occurred within approximately I km. Irrigation pump diversions were common in the area, but no diversions or channeled return flows existed in the area actually studied.

WSP measurements of 409 ft (125 m) of river were taken on June 17, 1977. Single cross section data were again derived from surveyed WSP measurements.

Station W-B was located approximately 1 km downstream from the White River's confluence with Piceance Creek, near a temporary detour road. Overbank descriptions here were essentially the same as those at Station W-A. R-2 Cross (sag tape) and WSP measurements were taken over a 250 ft (76 m) reach on September 19, 1976. Verification measurements could not be taken because access was blocked upon completion of the White River Bridge.

FIELD MEASUREMENT PROCEDURES

R-2 CROSS

The sag tape procedure described in the original USFS instruction manual (Anonymous 1974) and used by the Colorado Division of Wildlife, was used at Station W-B. Single cross section data at Stations W-A, Y-3 and Y-4 were derived from survey data taken for WSP computations. The procedure was similar to that described by Rose and Johnson (1976) in which cross sectional data were gathered directly from transit readings and a zero datum line established at the grass line or river channel edge.

The original R-2 Cross program was obtained from the Colorado Division of Wildlife and modified for convenience by Dr. Robert Milhous of the U. S. Fish and Wildlife Service Cooperative Instream Flow Group in Fort Collins (IFG). Operation of the original program required three steps: 1) Conversion from sag tape to adjusted reference datum line-to-water distances; 2) Measurement of the level of the water surface elevation obtained from the Step "A" corrected cross section; and 3) Selection of alternative levels of flow for computations of hydraulic properties at those levels. The three input steps required by the original program were reduced to a single step, and output included a computer plot of the cross section and a table of surface widths above various prespecified depths.

WATER SURFACE PROFILE

Instructions for field data collection outlined by Spence (1975) were followed at all stations with the following exceptions: 1) Surveying at Stations Y-3 and W-A was accomplished without a change in instrument position. Sight distances to all headstakes were considered short enough to warrant this procedure. Elevations of all headstakes were triple checked, as was the backsight reading. 2) Many cross sections contained more than nine roughness segments, the greatest permissible number of segments outlined by Spence (1975) and in the coding manual. The present Bureau of Reclamation WSP program is dimensioned to accept as many as 100 roughness segments or one for each cross sectional coordinate pair. 3) Elevations of underwater points, in pools greater than 1.5 m in depth, were determined by subtraction of depth measurements from the water surface elevation measured at the corresponding cross section. Elevations read with a level or transit from a boat mounted rod were not reliable because of movement.

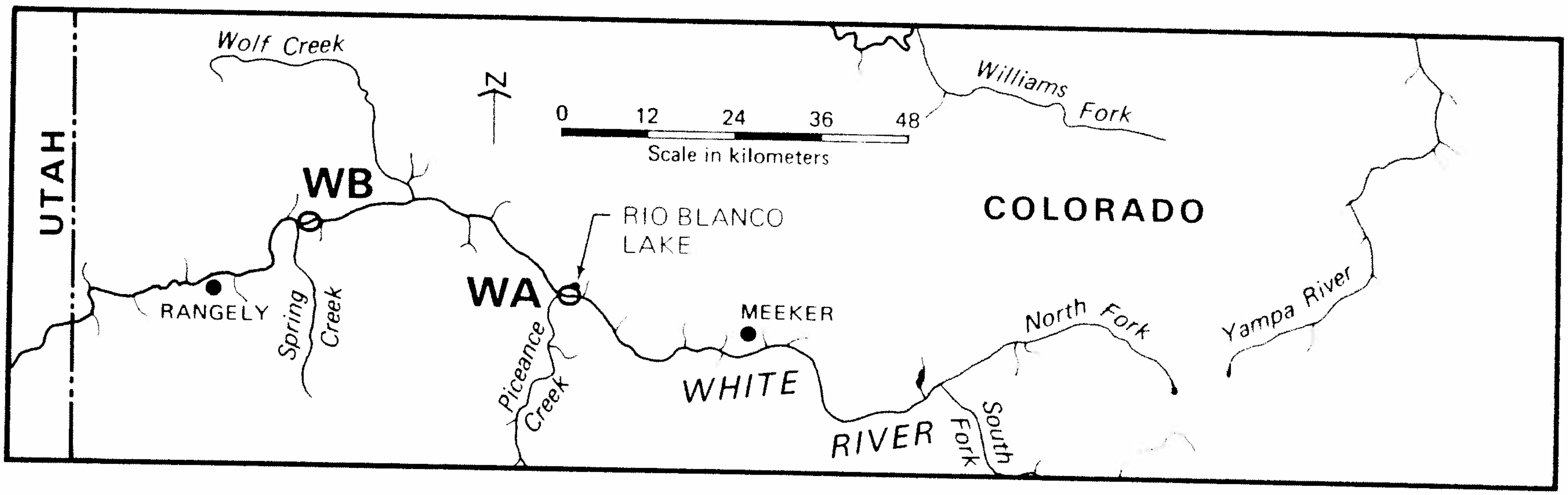


Figure 4. Location of White River sampling sites.

Figure 5. Station W-A, July, 1976

Distances were read from stadia hairs at Stations Y-4 and W-B at which the instrument was positioned at the head of each cross section. At Stations Y-3 and W-B, distances were read from a 60 m metal chain.

Placement of the initial downstream cross section site was governed by a flow control point, which in all cases was a riffle or channel constriction. The remaining cross sections were established either at 50 ft (15 m) intervals as suggested by Spence (1975), or across areas which best defined the topography of the area being studied.

Permanent benchmarks were emplaced by driving 9.5 mm reinforcement bars at least .5 m into an overbank area with nonrocky soil. The scarcity of large nearby trees or permanent structures at all four stations dictated this less desirable method.

Water velocities were determined with a Price Pygmy current meter in shallow areas and with the Model 2031 direct readout meter produced by General Oceanics, Inc. in areas more than 1.5 m deep. The latter technique involved mounting the meter on a 4 m rod which could be extended to a predetermined depth. Meter readings were observed for at least 20 seconds after reaching a stable range.

Substrate types were estimated using the modified Wentworth scale, which specified the following values:

Particle size (mm)	Description
16-64	Pebbles
2-16	Gravel
1	Very course sand
.5-1	Course sand
.25-.5	Medium sand
.125-.25	Fine sand
.0625-.125	Very fine sand
.004-.0625	Silt (mud)

The scale was used as a general guide and not applied strictly to areas of complex composition.

The WSP program was obtained in deck form from the sedimentation section of the Denver office of the Bureau of Reclamation, with instructions written at that office. Input was coded and punched by Mr. Prewitt.

From the list of four available programs, we selected the "n balance" option which supposedly matched observed and predicted water surface elevations within tolerances specified by the user. Calibration via adjustments in Manning's n values at each cross section was not possible to tolerances of less than .1 ft (30 mm), and use of the option was suspended.

Water surface elevations were observed at two discharges at Stations Y-3 and Y-4 and calibrations were made in the Manning's n values to provide some calibration of the model.

A-D PROGRAM

A computer program which utilized state-discharge relationships was developed by Dr. Robert Milhous and applied to WSP water surface elevation output or to data which included two or more observed water surface elevations and discharge measurements.

From the log-log transformation of the rating curve, a linear rating graph was produced. By regression analysis of this linear relationship, water surface elevations at unobserved flows were predicted. A similar procedure was used to predict other hydraulic properties. This program utilized the water surface elevation predictions from WSP which were considered the most reliable element of that program's output. The A-D calculations did not utilize Manning's equation and were therefore considered more relaible than WSP predictions, especially of velocity, area, and wetted perimeter.

A-D program output included a table of surface widths above various prespecified depths and predictions of velocities, areas and wetted perimeters at various flows.

BIOLOGICAL FINDINGS

Preliminary conclusions of the BLM fisheries study (Prewitt and Carlson 1975, Prewitt *et al* 1977) which pertained to evaluations of instream flow recommendations for the Yampa and White Rivers were:

1. Certain fish species varied in abundance throughout the year in the Yampa River, suggesting migrations from lower reaches. The channel catfish *(Ictalurus punctatus)* and Colorado squawfish have been more abundant following runoff, although some recent prerunoff captures may indicate small resident (or nonmigratory) populations of both species. As both channel catfish and Colorado squawfish grow to large size (specimens of at least 3 kg have been taken in the Yampa River), passage flows should be determined by depths of at least 1.5 ft (.48 m). This is the minimum depth requested by Colorado Division of Wildlife personnel for large fish in large rivers.

2. All native cyprinid and catostomid species in both rivers spawned in the spring or early summer. Spawning areas and flow requirements were unknown for these fish at the time of this study.

3. Cyprinid and catostomid larvae to 70 mm in length utilized shallow backwater or standing water areas as nursery grounds in both rivers. Dense concentrations, especially of catostomid larvae, were evident when water levels were high enough to inundate the channel "bench" which extended from the midchannel depression to the lateral river channel margins.

Flows which provided shallow waters across this area would be desirable to provide areas for larval protection and good spawning success.

4. During the summers of 1976 and 1977, abnormally low flows were observed in the Yampa and White Rivers. In July, 1976, and again in August 1977, flows of less than 60 cfs (1.6 m^3 per second [cms]) in the White River and less than 50 cfs (1.4 cms) in the Yampa River were observed (Prewitt *et al* 1977). These flows were both less than the 1 in 20 year low monthly flows in both rivers (Appendices 2 and 4). The primary physico-chemical effects of such low flows were: 1) Abnormally high water temperatures resulting from stagnation; 2) Abnormally low dissolved oxygen concentrations resulting from depression of the saturation point by high temperatures; and 3) Very high dissolved solid concentrations, probably resulting from evaporation and increased proportional contribution of irrigation return waters. The observable biotic changes during low flows were: 1) Increased abundances of filamentous algae favored by the low, clear warm waters; 2) Stranding of larval and juvenile fishes in former backwater areas which were isolated when the stream level subsided; 3) Crowding of adult fishes in areas providing depth or cover or near the downstream flow control points of runs where velocities increased; 4) Alterations of normal species composition (for example, in the summer of 1977, following exceptionally low runoff flows and low stable flows, channel catfish and Colorado squawfish were found at Station W-A, far upstream from any previous squawfish capture and well above the areas where channel catfish normally reside). During the same summer, two squawfish were

captured above Maybell on the Yampa River, an area normally considered to be at the extreme upstream limit of this fish's range. Such captures may have been favored by low river conditions, but the intensity of sampling during previous years of the study should have produced some captures at these locations; and 5) Increased incidence of parisitism, bacterial ulcerations and other epidermal lesions in the adult fish sample. While massive fish kills were not evident, many dead or severly ill fishes were found near shore.

The native fishes of the Yampa and White Rivers are highly adapted to life in large, fluctuating rivers characterized by high velocities during the runoff periods. Changes in the annual hydrograph which have diminished instream flows may not only limit the habitat of native fishes but at the same time provide more favorable conditions for competitive nonnative fishes which are usually adapted to more moderate fluvial conditions. Indeed, three introduced species, the common carp *(Cyprinis carpio),* redside shiner *(Richardsonius balteatus)* and channel catfish have been shown by either intensive study elsewhere (unpublished velocity preference data, IFG) or by direct observation in the Yampa and White Rivers to prefer low to moderate velocities. Direct or indirect competition between these and native species has been suspected. Permanent reduction of the flow regime of either river, beyond certain levels, would probably increase the competitive advantage of the introduced fishes.

Approximations of the depth-velocity preferences of squawfish or humpback chubs were necessary for use in the HABTAT program. Since almost no frequency parameter data for squawfish or humpback chubs exist, only reconnaissance grade electivity curves could be produced from actual field observations and from descriptions in the literature.

Several researchers have attempted to characterize habitat preferences of squawfish in recent times. Vanicek (1967) captured squawfish in a "variety of pools, eddies and runs," with most adults found in pools and eddies and most young taken in still, shallow pools, near shore. No squawfish were found in fast water.

Vanicek and Kramer (1969) again reported adult squawfish captures in pools, eddies and runs with none found in fast water.

Jordan (1891) described portions of the Gunnison River as "2 to 4 feet deep" with swift current and gravel or sand substrate.

Chamberlain (1904) observed that squawfish ordinarily "lie in deep pools, especially just below riffles."

Koster (1960) captured two squawfish from a "pool" in the San Juan River near Rosa, New Mexico. The pool was 180 m long, 30 m wide and .9 to 1.2 m deep. Another squawfish was captured in a poorly defined riffle 45 m long, 23 m wide and .75 m deep with a strong current.

Sigler and Miller (1962) typified squawfish habitat as "in or near big rivers, where the current is typically strong, the water muddy, the bottom consisting of stones and sand, with water 3 or more feet deep." This paper and Miller (1964) reported that squawfish young prefer moderate current and shallow water.

Hagen and Banks (1962) captured adult squawfish in "all types of water" but found young only in quiet backwaters. An adult was captured in swift water on hook and line.

Smith (1960) found that the most productive site in his Green River study was a large pool with depths of at least 4.5 m with slow water velocities and a fine silt and organic matter substrate.

Taba *et al* (1965) found young squawfish to be "much in evidence in quiet backwaters."

Holden and Stalnaker (1975) collected adults in all habitat types but mainly in slow water. Again, young squawfish were most abundant in still, shallow water 60-90 cm deep.

Prewitt and Carlson (1975) reported a squawfish taken near Maybell and three squawfish from below Cross Mountain Gorge on the Yampa River. The pool from which the former fish was captured was recently dimensioned and found to be a maximum of 2 m deep where velocities ranged from 0.120 to 0.240 m per second (mps). Substrate was cobble and silt at the lower cross sections and predominately silt over boulders in the upper, slower segments. The flow was abnormally low, about 100 cfs (2.8 cms), because of drought conditions.

The Cross Mountain Gorge pool has not yet been dimensioned but was described as being quite deep and narrow, with low velocities after subsidence of runoff.

Prewitt *et al* (1977) reported the capture of two squawfish from the Yampa River; the first, in April, 1977, from a run area .8 m deep about 100 m upstream from the Maybell bridge and only 30 m below the habitat unit measured as Station Y-3. The velocity was not measured but could be predicted by the computer program as about 3.0 fps (.91 mps) across cobble substrate.

Two squawfish were captured by electrofishing in June from the White River 1.5 km above its confluence with Piceance Creek (Station W-A). Depths within 5 m of both capture sites exceeded 2.2 m and velocities were measured as .54 mps and still water for the respective fish.

A single squawfish was captured near Juniper Hot Springs on the Yampa River in July, 1977, from a run area in 1.1 m of water at a velocity ranging (in the column at the exact capture point) from 1.0 to 1.6 fps (.30 mps to .49 mps).

Sealing *et al* (1975) reported several captures of squawfish and humpback chubs from the Black Rocks area of Ruby Canyon on the Colorado River near the Utah border. This area was recently dimensioned, and depths of 9.75 m were measured. Velocities in the main channel area (said to be favored by humpback chubs by Kidd) were from 1.0 to 2.1 fps (.30 to .64 mps) at an abnormally low flow (1000 cfs [28 cms]). A single chub, apparently a *G. cypha X G. robusta* hybrid was taken on hook and line in the Black Rocks area in water 1.2 m deep at a column velocity ranging from 1.0 to 1.5 fps (.30 to 46 mps). The substrate was cobble, and numerous channel catfish and black bullheads were taken by angling in the same run area.

Obviously, summarization of specific or unique habitat preferences by either of these fish is difficult given only reports and descriptions. It seems, however, that some generalizations are forthcoming.

There is some agreement in the literature that larval and early juvenile squawfish prefer shallow water of low velocity. This also agrees with observations made on the White and Yampa Rivers of preferences of cyprinid and catostomid larvae. The hypothetical curves (Figures 6 and 7) simply describe conditions at which these larvae were found

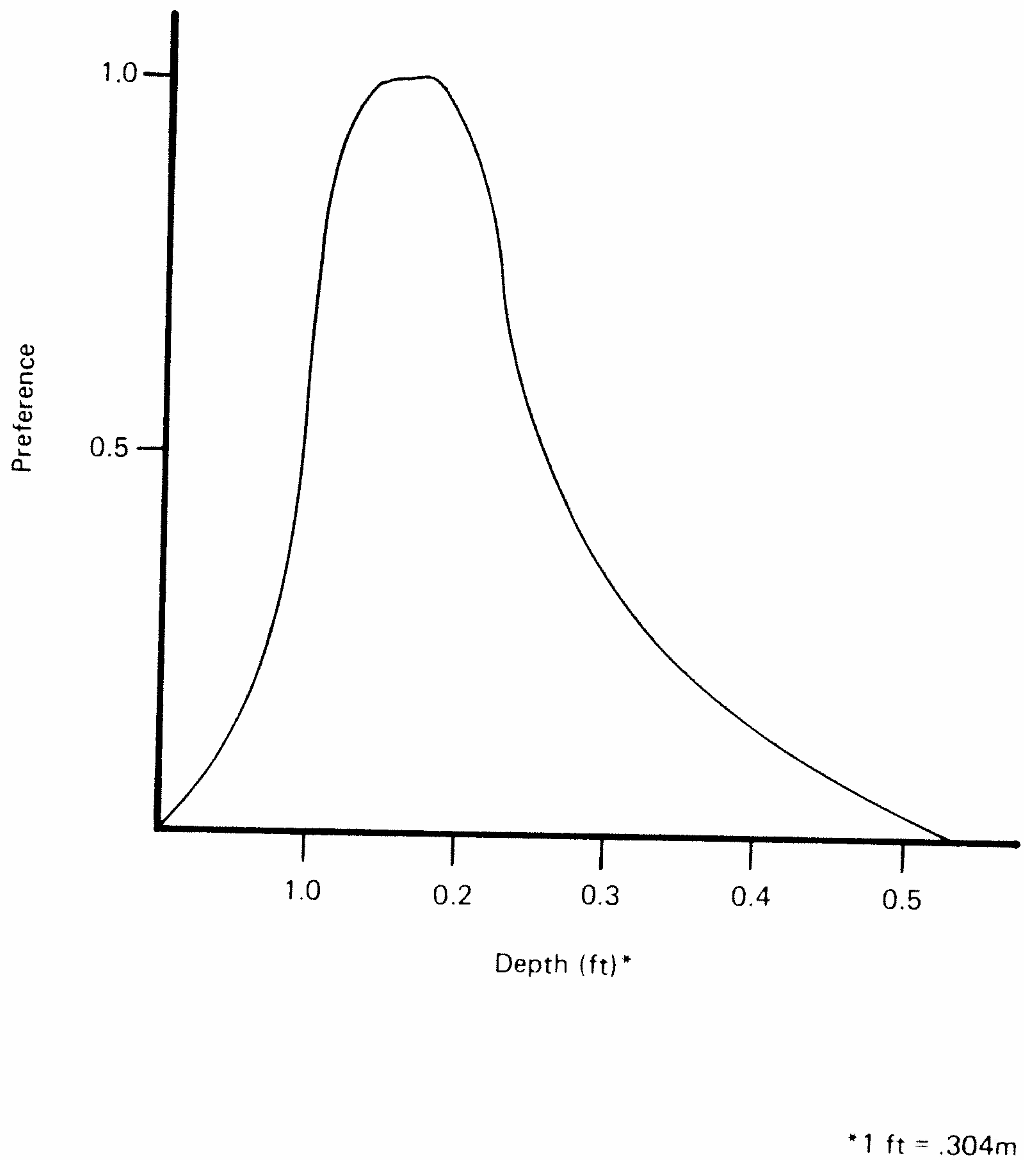
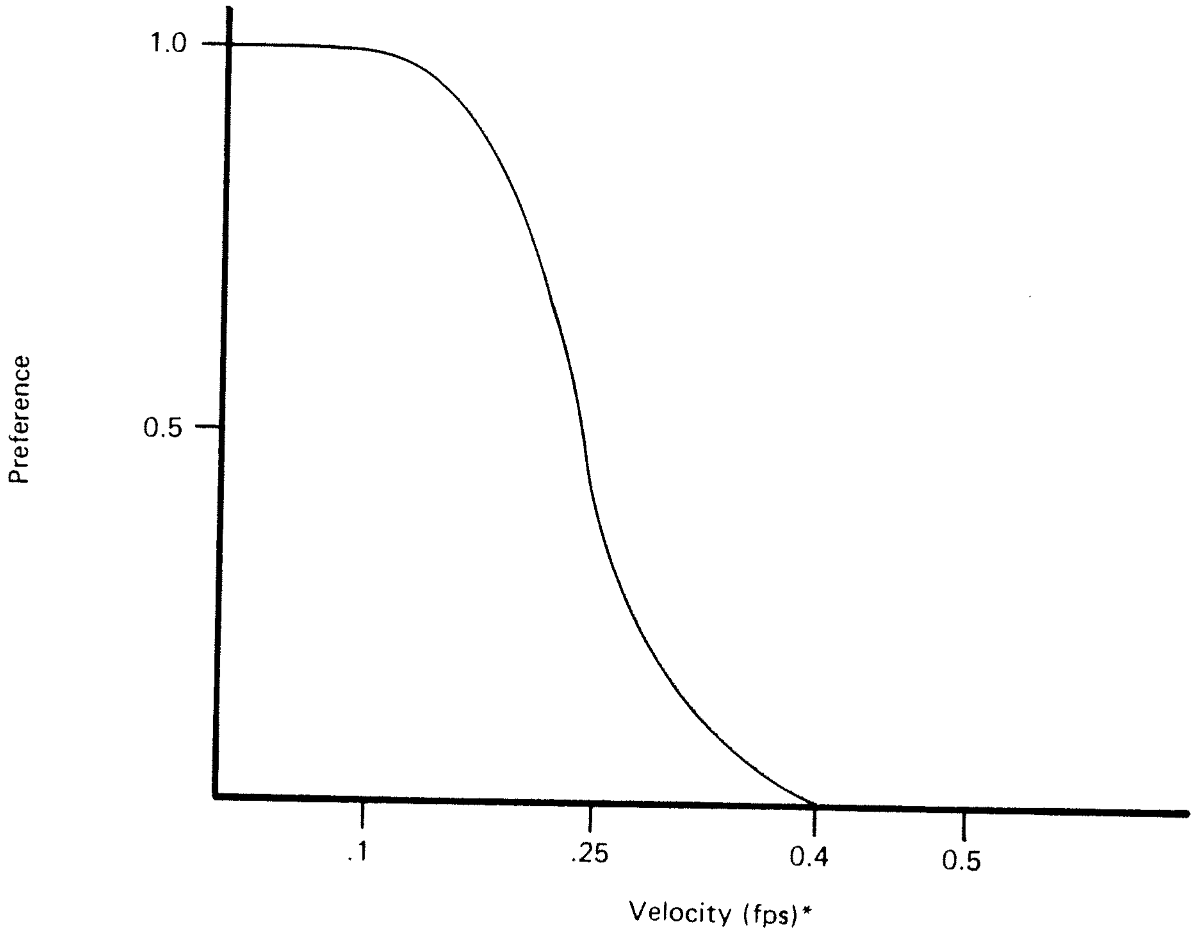


Figure 6. Hypothetical depth preference curve for larval Colorado squawfish.



*1 fps = .304mps

Figure 7. Hypothetical velocity preference curve for larval Colorado squawfish.

or have been most often described. The .4 ft. (.23 m) upper depth limit may be overly restrictive but no larvae less than approximately 50 mm in length have been captured in deeper water.

The velocity curve is for fish less than 100 mm long and represents a maximum of .5 fish length/second velocity.

Adult squawfish have been captured in such a variety of habitats that, from capture data alone, few conclusions may be drawn. It seems that most captures have been near or in pool areas, with few fish reported from actual shallow, high-velocity riffles. During the BLM study, 2 km river segments were electrofished at Stations Y-3 and Y-4 and no squawfish were turned in very shallow areas not located near major pools.

Since most adult squawfish captures were made in areas which also contained channel catfish, and since both species appear to prefer rather deep water, modified probability curves for adult channel catfish are used here to approximate squawfish preference. The basic channel catfish depth preference curve was used (Figure 8) but the velocity axis was extended to beyond 4 fps (1.52 mps) and the probability peak moved to about 1.5 fps (.48 mps) in accordance with recent measurements at capture sites (Figure 9). This adjustment was also deemed neces sary in view of the reports of several squawfish captures from waters of at least moderate velocity and the absence of channel catfish from such areas in both the Yampa and White Rivers.

RESULTS AND DISCUSSION

Results of the computer procedures performed in the calibration of the WSP model at the three stations are presented in Appendices 5 through 7. Calibrations to within .05 ft (15.2 mm) were deemed necessary by the hydrologist in consideration of the minimal water surface slopes encountered at all three stations.

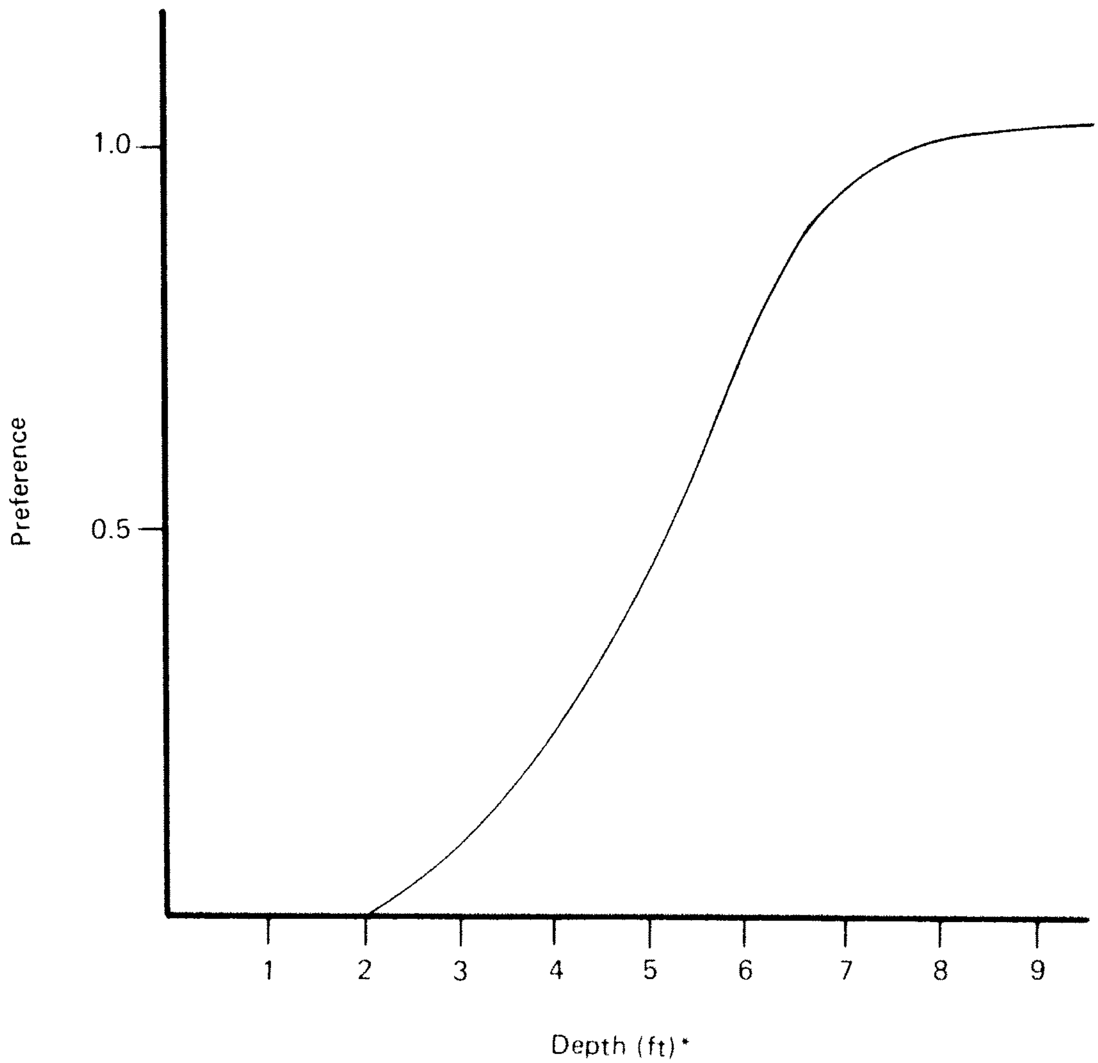
As WSP output included neither reliable wetted perimeter predictions nor depths, A-D output for Stations Y-3 and Y-4 was substituted. A summary of WSP output is found in Appendices 9 through 11. Water surface elevation predictions from WSP for Station W-A were used directly in the A-D program, in lieu of a second observed flow-stage relationship. Only limited verifications of velocities were performed (Table 1). In general, velocities at higher flows were overestimated while those at lower flows were quite accurate.

A calcomp plotter routine was developed for the production of cross sectional plots from WSP card decks. Examination of these plots is necessary for both selection of downstream flow control cross sections (if the placement of the actual control was not certain in the field) and for segmentation of the stream channel for use in the HABTAT program. The output from the A-D program included a large plot (on standard computer paper) which was more satisfactory for the latter purpose.

MULTIPLE CROSS SECTION METHODOLOGIES - WSP

Interpretation of WSP data and evolution of flow recommendations have followed many courses in many states. In Montana, Workman (1976) used graphic accelerations of loss of velocity, wetted perimeter and conveyance area with decreasing discharge to evaluate flow needs in a trout stream.

Warmwater applications of WSP in Montana by Elser (1976) and Bovee (1974), and in Idaho (White 1975) have incorporated requirements of certain target species at several life history stages into flow recommendations which met the demands of the more critical stages.



*1 ft = .304m

Figure 8. Depth preference curve for adult channel catfish, derived from frequency analysis by K.D. Bovee of IFG, 1977

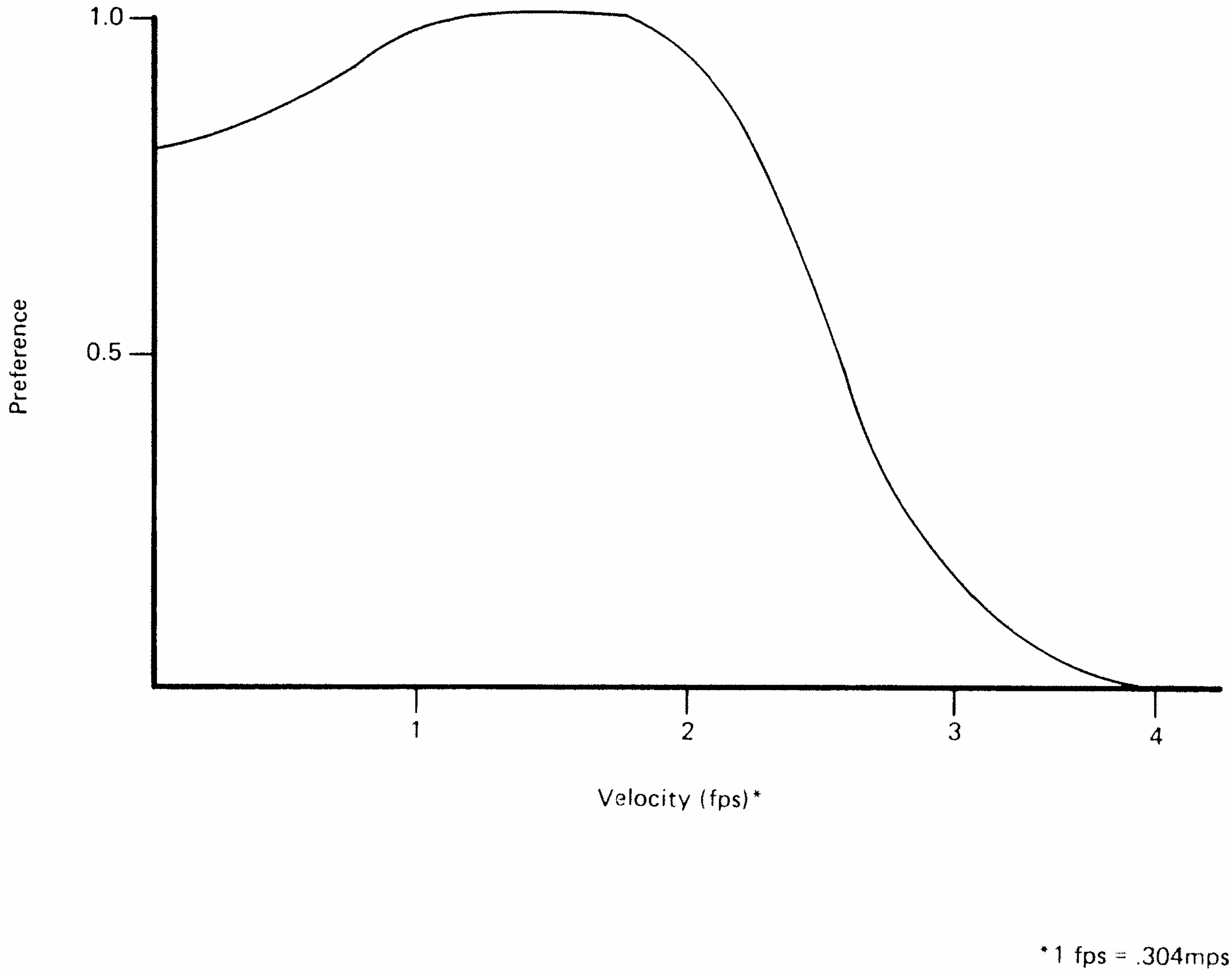


Figure 9. Hypothetical velocity preference curve for adult Colorado Squawfish.

TABLE 1. Observed and predicted velocities at Stations Y-3 and Y-4 from WSP and S-D computer output (in fps*).

		PROGRAM		
	FLOW	WSP	OBSERVED VELOCITY	S-D
Station Y-3 (50)	170	1.35	1.34	1.35
	950	3.25	2.23	2.13
Station Y-4 (0)	170	1.99	1.41	1.23
	950	3.41	2.57	2.57

* 1 fps = .304 mps

Generally, the life history stages considered were spawning, rearing and migration. Spawning flows were listed as those which adequately covered substrate areas suitable for spawning during spawning season but detailed criteria were lacking or applicable only to salmonid species. Passage flows were related to cross sections spanning riffle areas which might become impassibly shallow at low flows. Rearing flows were determined by wetted perimeter under the assumption of Collings (1974) that rearing was related to food production which was related to wetted perimeter. Either the wetted perimeter vs. discharge inflection point or an arbitrary percentage (usually 50 percent of bankfull or optimum) were used as flow recommendation standard (Al Elser and Larry Peterman, personal communication with Robert Milhous).

The A-D output was analyzed by plotting percent (of optimum) conveyance area against flow and wetted perimeter and examining the graph for an inflection point. The "optimum" value arbitrarily selected for Stations Y-3 and Y-4 were 1,500 or 2,000 cfs because these flows were above the inflection points of the discharge area and wetted perimeter graphs and because of the nature of the Yampa River flow regime. The bankfull flow of the Yampa River near Maybell exceeds 10,000 cfs and represents conditions which are probably less than optimum for most of the fish species present. A flow of 1,000 cfs, while not known to be optimum, represents moderate velocity values and sufficient depths for all fish species present.

Utilization of WSP output to formulate passage flows was quite difficult; direct computer output contained only surface width and conveyance area, from which an estimate of average depth could be derived by division. Accurate depths at increments of width or surface widths with depths exceeding a minimum standard were obtainable only by measurement of hand drawn cross sections or by use of a separate computer program.

A-D program predictions of velocity and area were quite similar to those of WSP (Appendices 9 through 11) and the surface width with depth greater than a minimum standard option was available. Based upon A-D output of area, velocity and wetted perimeter inflection points (Figures 10 through 17) and upon the range of flows offering 50 percent wetted perimeter, the following flow recommendations were made.

Station	Velocity Inflection		Recommendation using Area Inflection*		W. P. Inflection*
	cfs	cms	cfs	cms	
Y-3	170	4.76	200 (500)	5.6 (14)	170-200 (500)
Y-4	170	4.76	170-200(500)		170-200 (500)
W-A	50	1.4	125	3.5	200

* Secondary inflection in parenthesis.

Although use of inflection points and fixed criteria as required flow criteria produces reasonably uniform recommendations using several computer programs, it does not address the requirements of individual species of fish and fails to provide for critical life history stages whose flow needs might be much higher than the flow required for adult survival.

It was possible to determine the amount and distribution of selected depths across the stream width from the modified R-2 Cross and the standard A-D program, but no criteria as to their habitat importance had been established at the time of this report. However, they were useful as an accurate means of assessing passage flows over critically shallow riffle areas and as a method of selecting the more critical cross sections among multiple cross sections.

As Colorado squawfish and humpback suckers travel extensively in these rivers, passage flows across riffle areas are probably

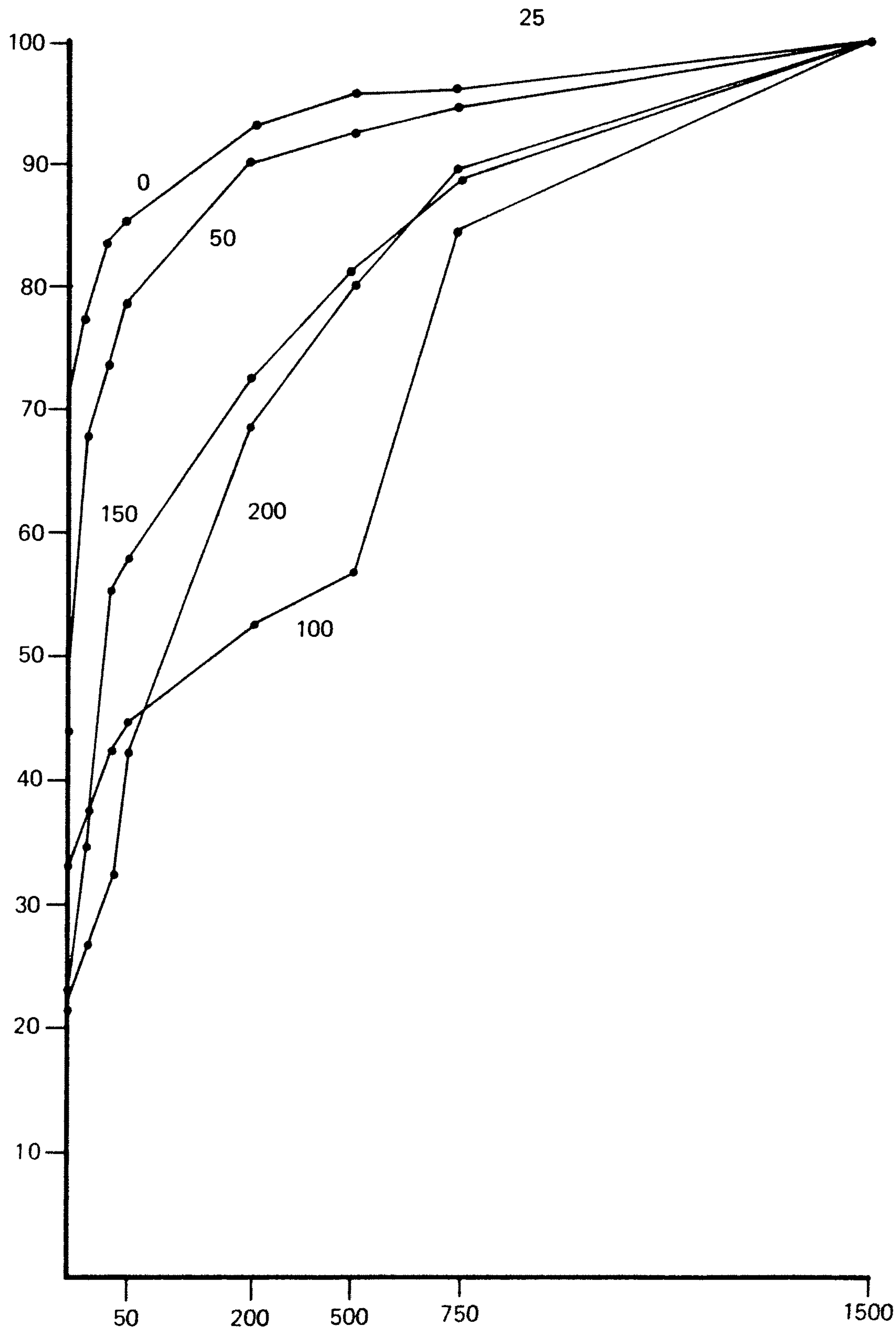


Figure 10. Percent of 1500 cfs (42 cms) wetted perimeter at Station Y-3 (cross-sections 0-200) as predicted by A-D computer program at eight flows

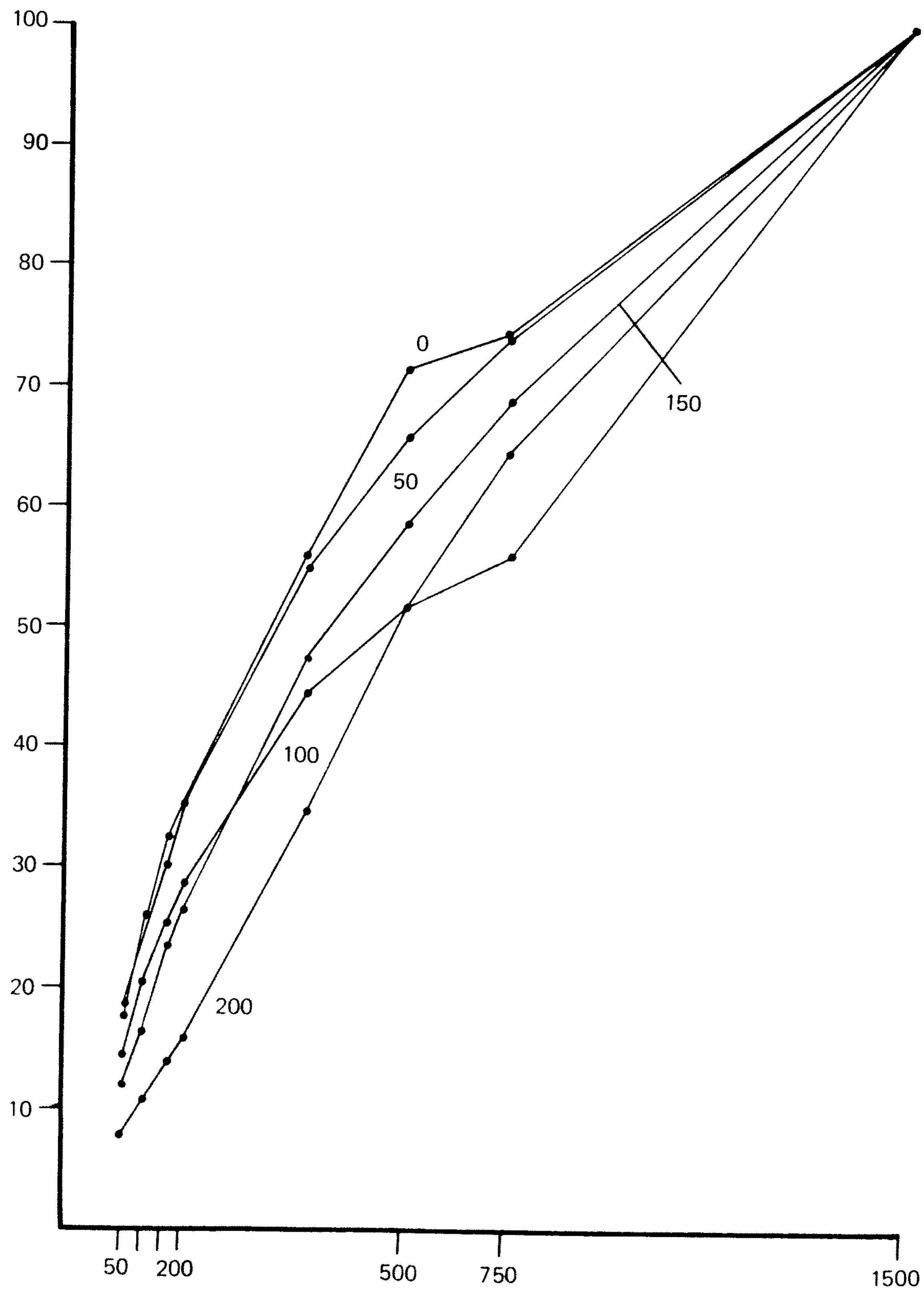


Figure 11. Percent of 1500 cfs (42 cms) cross-sectional area at Station Y-3 (cross-sections 0-100) as predicted by A-D computer program at nine flows

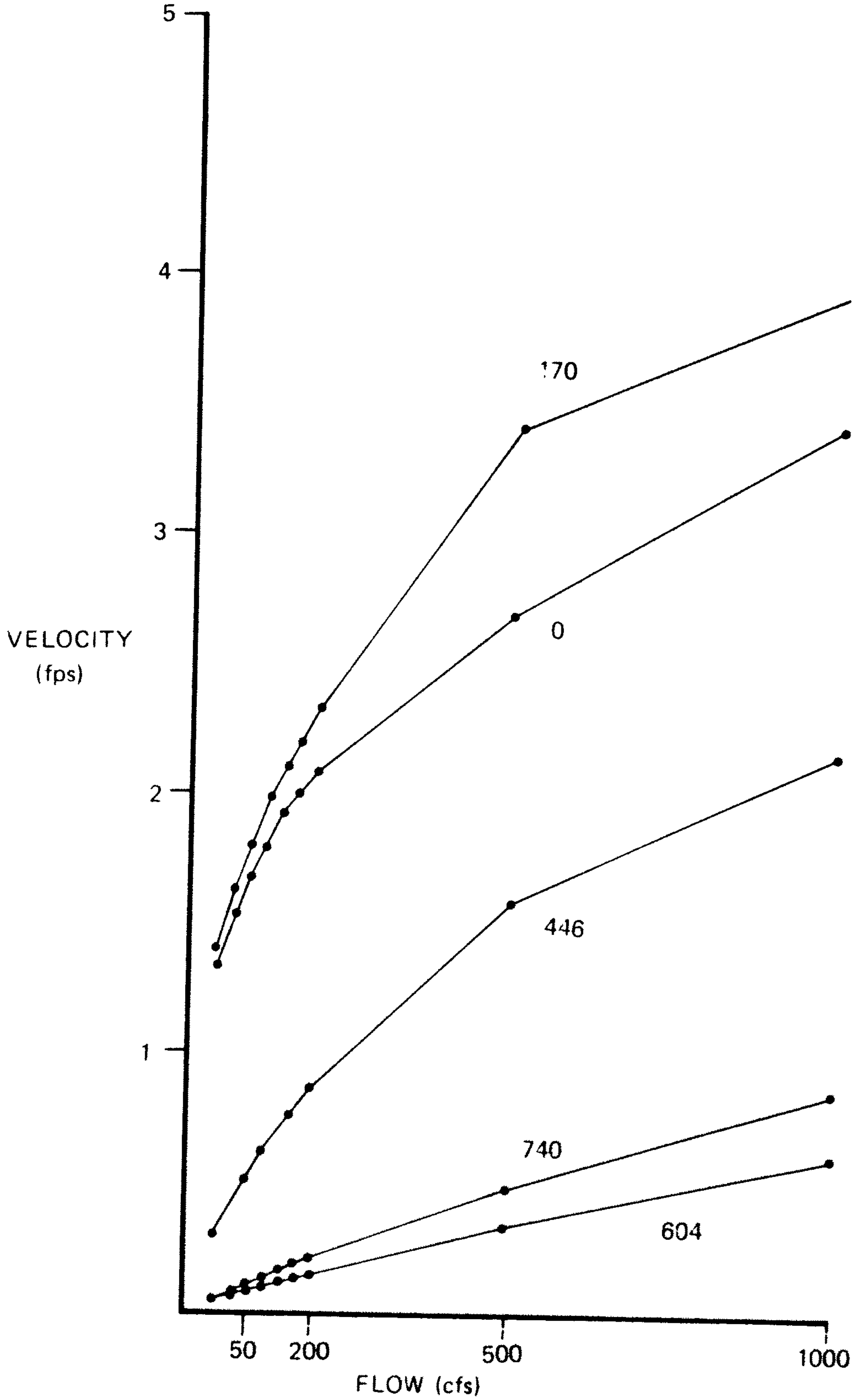


Figure 12. Velocity-discharge relationship at Station Y-4 (cross-sections 0-740) as predicted by A-D computer program at nine flows

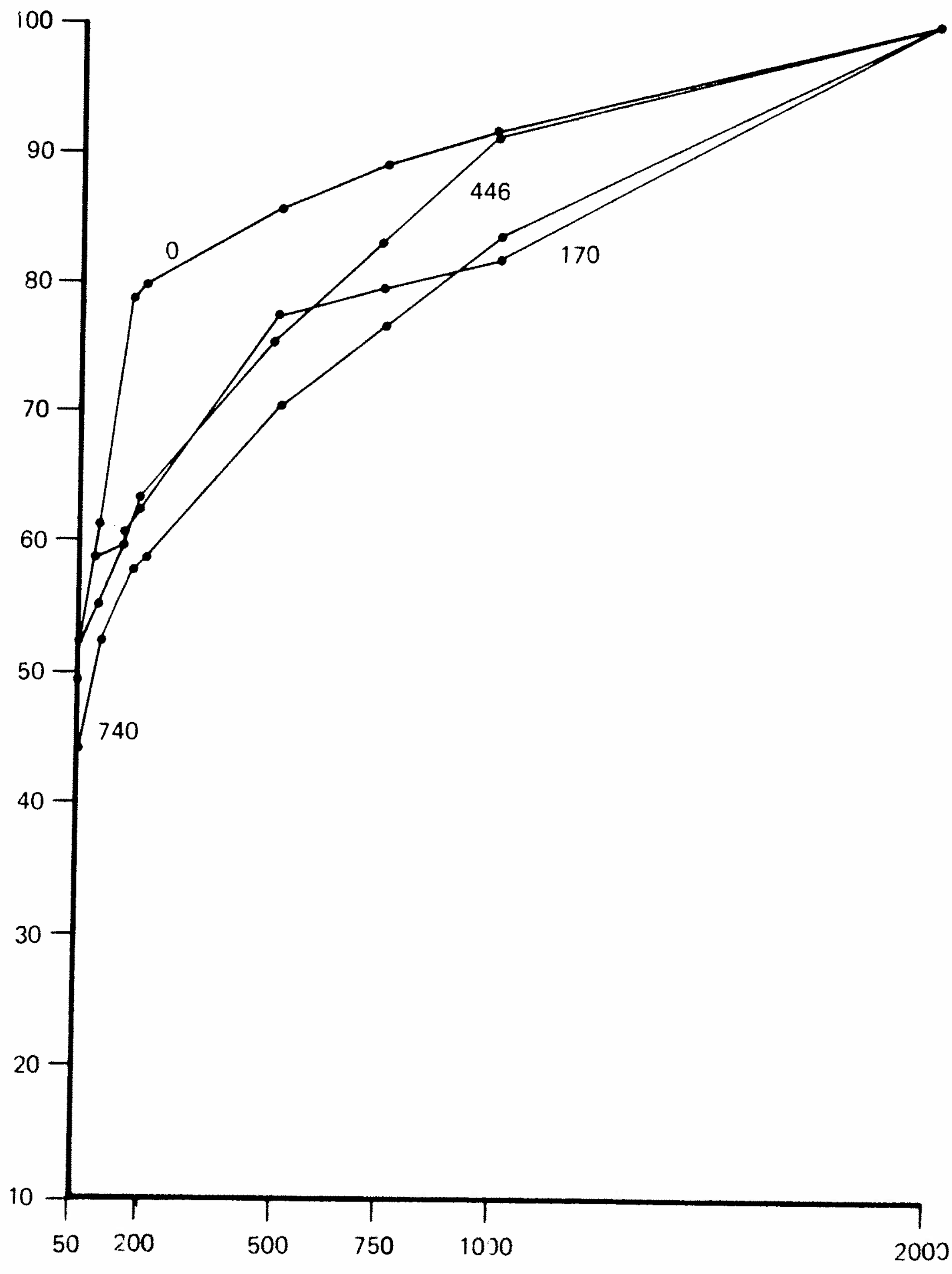


Figure 13. Percent of 2000 cfs (56 cms) wetted perimeter at Station Y-4 (cross-sections 0-740) as predicted by A-D computer program

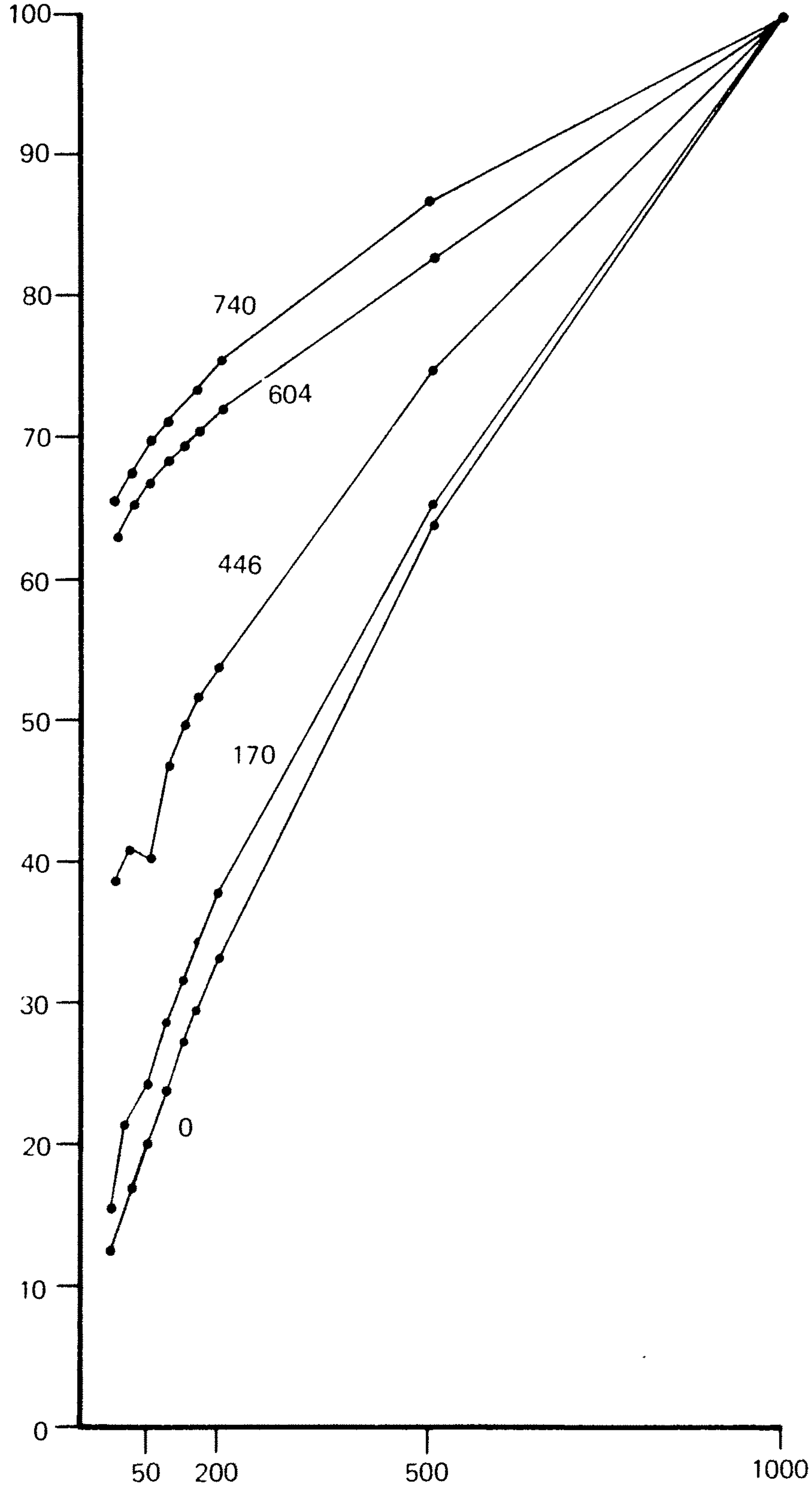


Figure 14. Percent of 2000 cfs (56 cms) cross-sectional area at Station Y-4 (cross-sections 0-740) as Predicted by A-D computer Program

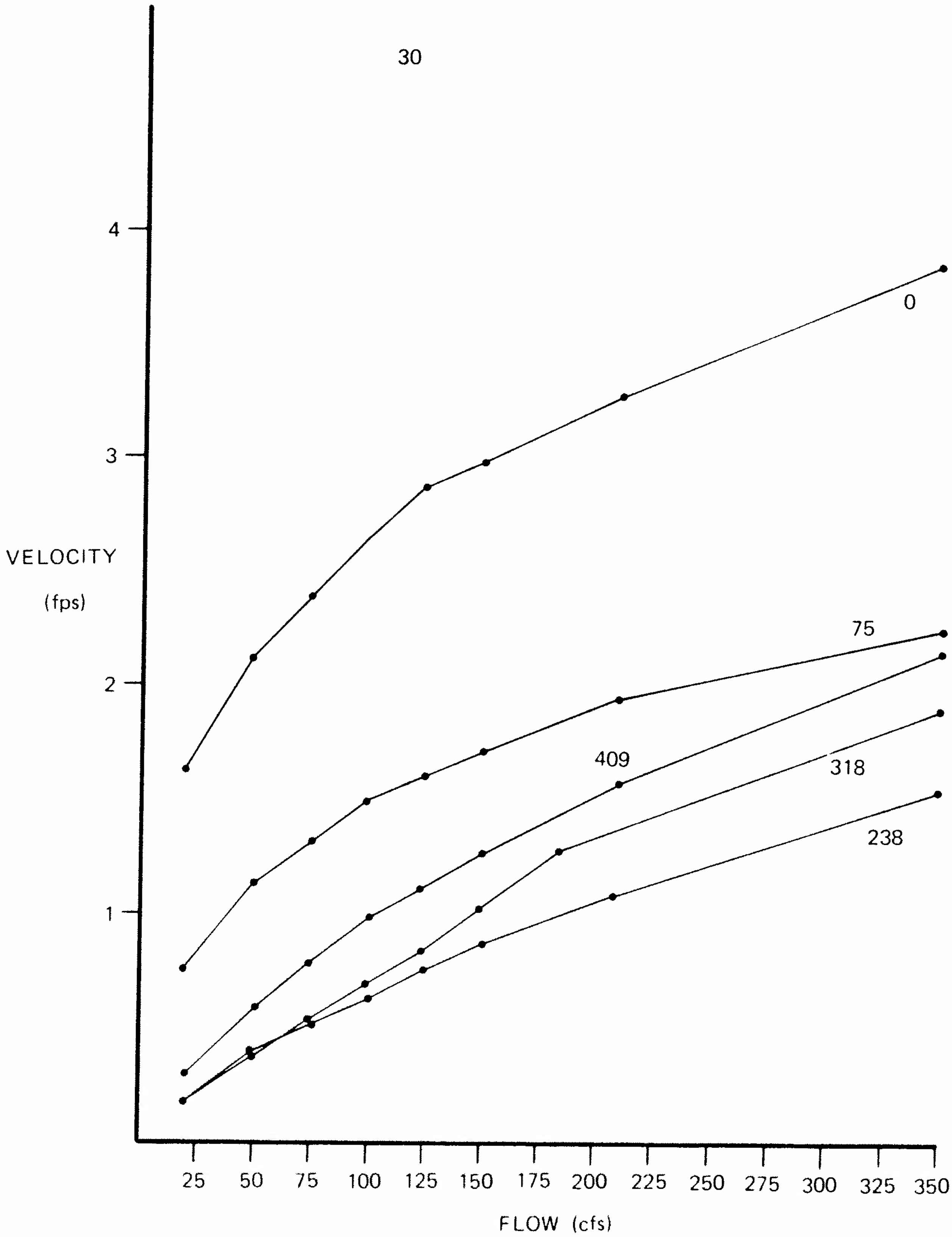


Figure 15. Velocity-discharge relationship at Station W-A (cross-sections 0-409) as predicted by A-D computer program

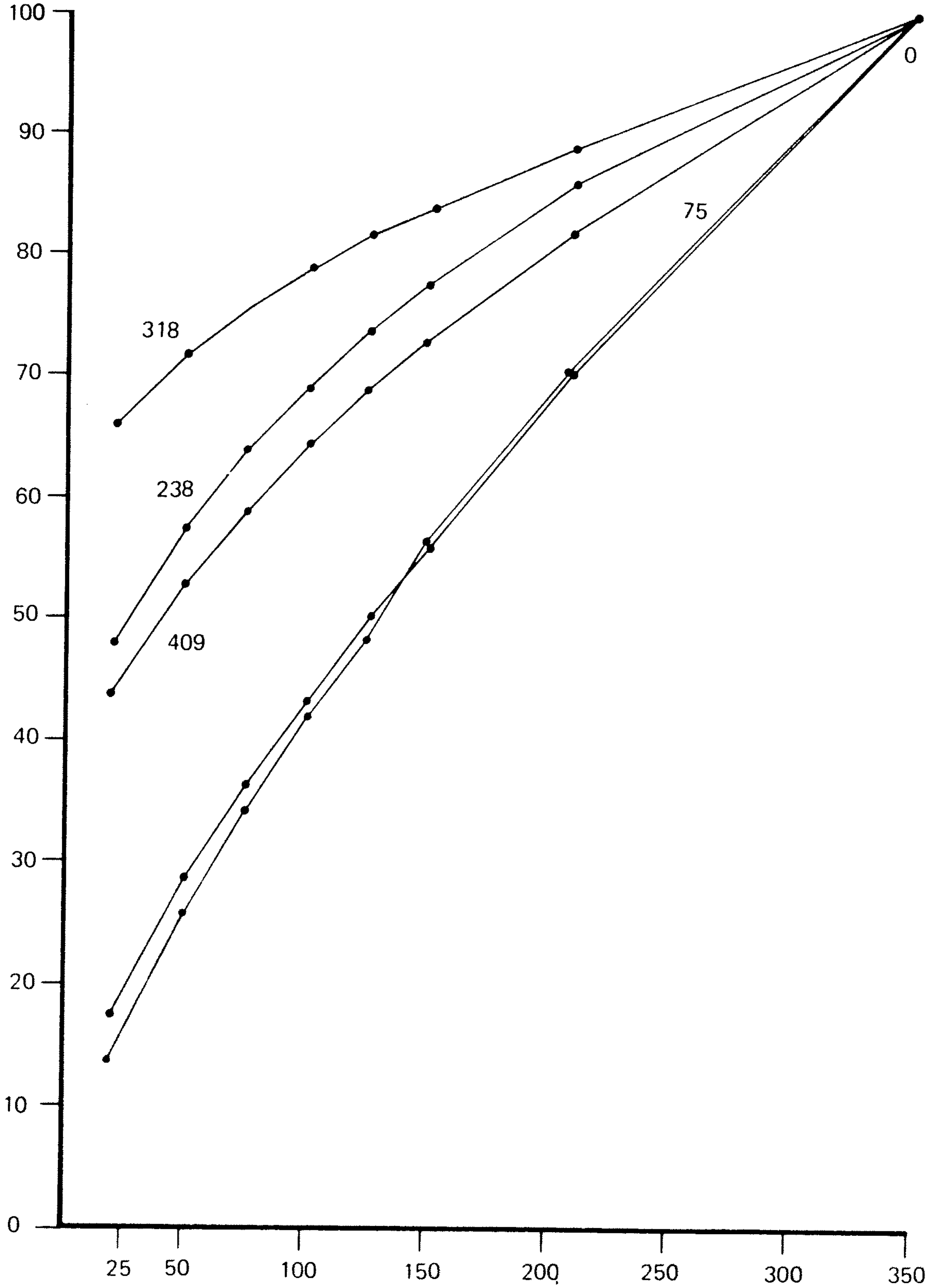


Figure 16. Percent of 350 cfs (9.8 cms) wetted perimeter at Station W-A (cross-sections 0-409) as predicted by A-D computer program.

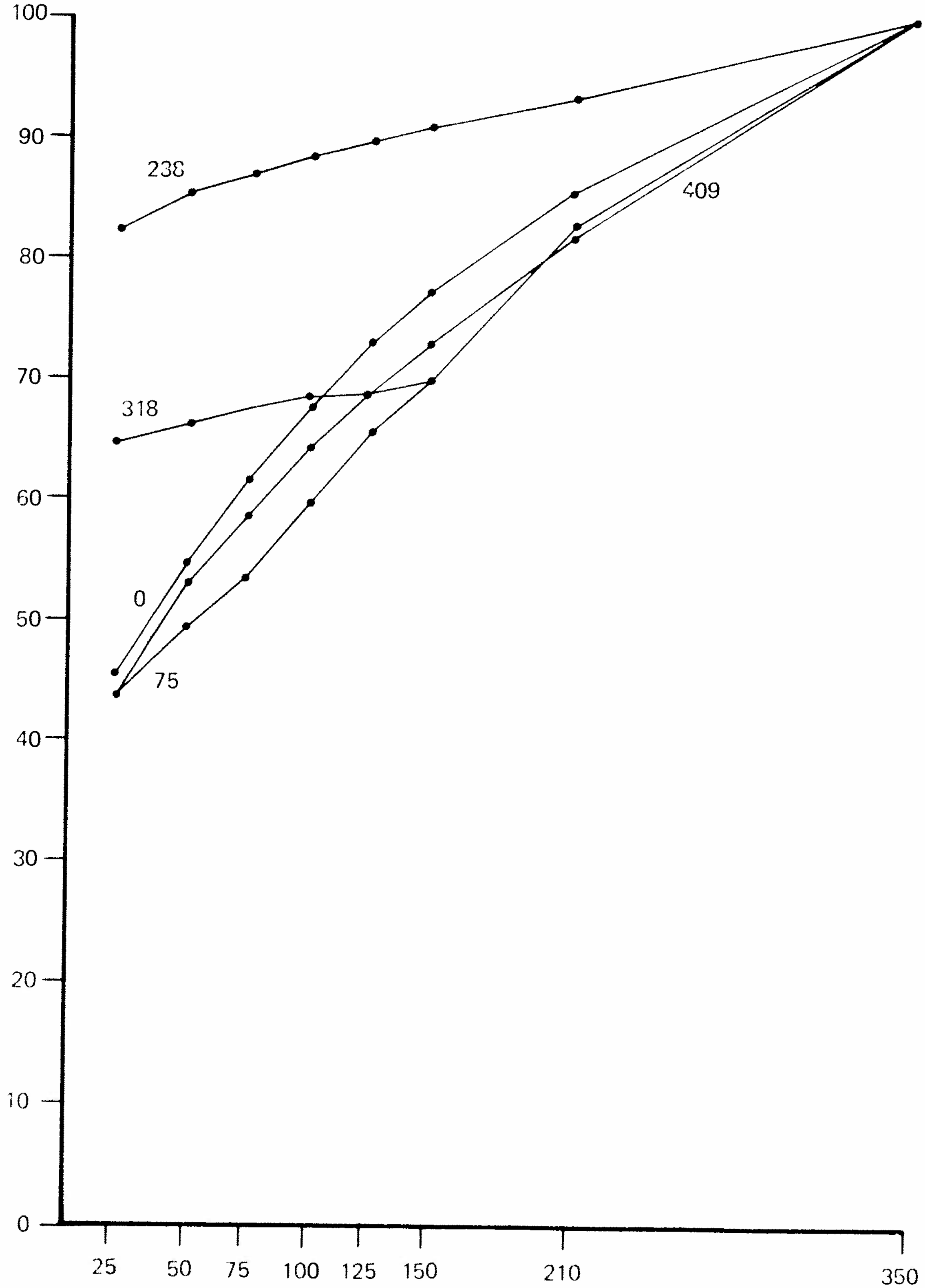


Figure 17. Percent of 350 cfs (9.8 cms) wetted perimeter at Station W-A (cross-sections 0-409) as predicted by A-D computer program

as important as maintenance flows in pool and run areas, which are often adequately deep for most native fish species even at very low flows (Tables 4 and 6).

Using a 1.5 ft. (.46 m) minimum passage depth requirement previously suggested, a flow between 200 cfs (5.6 cms) and 500 cfs (14 cms) provided minimal passage area at Station Y-3, while a flow of 200 cfs (5.6 cms) would be required at Station Y-4 (Tables 2 and 3). A flow of at least 200 cfs would be required at Station W-A to provide passage for the same fish (Tables 5 and 6). In each of these cases, transect average velocity at the suggested discharge was less than 3.0 fps, well within the suspected tolerance range of native fish species. For species such as channel catfish which prefer moderate velocities during migration, a flow of 750 cfs would provide both passage depth (from Figure 8) and subcritical velocities.

As the migratory activity of Yampa and White River fishes apparently peaks just before or just after runoff periods, passage flows are usually maintained naturally. If impoundments were constructed on either river, however, their water storage period may coincide with runoff, greatly reducing downstream flows during this period. Single or multiple cross sectional output in the form presented here would be of great utility in suggesting releases to provide minimum passage requirements from cross sectional data already gathered.

SINGLE CROSS SECTION COMPUTER METHODOLOGIES

Criteria for required flow recommendations from R-2 Cross output varied with the state and federal agencies implementing a particular methodology. For example, the Colorado Division of Wildlife (DOW) developed a system whereby a flow meeting criteria for parameters (average depth, average velocity and percent wetted perimeter) was selected as a minimum or required flow (Eddie Kochman, personal communication 1977). For large rivers (wetted perimeter greater than 100 ft 30.4 m), a flow providing at least 60 percent of an optimum wetted perimeter was specified. Average velocities were specified as 1-1.5 fps (.304-.456 mps), and average depths varied with the body depths of the largest game fish present. Optimum flows were specified as the lowest discharges above which little velocity area, or wetted perimeter, was gained with additional discharge (Rose and Johnson 1976). Optimal flows selected in this study at the three comparison sites met this criterion. DOW definitions were derived from the language of Senate Bill 97, which reads as follows:

Optimum Instream Flow:

> *That flow based on biological and hydrological parameters which when either annually maintained at a constant discharge in cubic feet per second, or in segmented monthly increments, will enable optimum development of aquatic habitat, related fish production and recreational use.*

Required Instream Flow: *

> *That flow based on biological and hydrological parameters which when either annually maintained at a constant discharge in cubic feet per second, or segmented into monthly increments, will enable maintenance of the existing condition of aquatic habitat, related rate of fish production and corresponding recreational use, or in cases of degraded conditions,*

* Represents objective of DOW flow recommendation unless otherwise stated.

TABLE 2. Surface widths, depths and velocities at eight discharges, Station Y-3, as predicted by stage-discharge methodology.

SURFACE WIDTH WITH DEPTH OF AT LEAST						
.25 FT	.50 FT	1.00 FT	1.50 FT	2.00 FT	FLOW	VELOCITY
176.94	134.21	0.00	0.00	0.00	50.00	.42
196.58	173.20	60.32	0.00	0.00	100.00	.61
221.83	198.45	129.11	0.00	0.00	200.00	.88
252.80	241.42	197.51	126.56	0.00	500.00	1.43
267.03	258.27	232.11	185.35	93.44	750.00	1.67
268.39	261.46	238.43	191.90	111.28	1000.00	2.13
279.61	274.78	265.10	242.33	199.38	2000.00	3.17
214.34	190.96	108.73	0.00	0.00	168.00	.81

1 cfs = .028 cms
1 ft = .304 m

TABLE 3. Surface widths, depths and velocities at eight discharges, Station Y-4, Cross-Section 0, as predicted by stage-discharge program.

SURFACE WIDTH WITH DEPTH OF AT LEAST						
.25 FT	.50 FT	1.00 FT	1.50 FT	2.00 FT	FLOW	VELOCITY
71.57	51.05	13.71	0.00	0.00	50.00	.96
95.66	74.79	33.12	0.00	0.00	100.00	1.23
139.60	119.63	79.89	37.09	0.00	200.00	1.28
158.31	155.15	148.60	109.24	67.46	500.00	1.71
164.63	161.47	155.15	148.60	109.24	750.00	2.00
169.68	166.52	160.21	153.89	141.20	1000.00	2.26
184.96	181.80	175.49	169.17	162.86	2000.00	3.03
130.01	110.04	68.28	28.27	0.00	170.00	1.23

1 cfs = .028 cms
1 ft = .304 m

TABLE 4. Surface widths, depths and velocities at eight discharges, Station Y-4, Cross-Section 604, as predicted by stage-discharge computer program.

SURFACE WIDTH WITH DEPTH OF AT LEAST						
.25 FT	.50 FT	1.00 FT	1.50 FT	2.00 FT	FLOW	VELOCITY
204.46	200.82	193.55	186.28	179.01	50.00	.05
109.16	205.20	197.91	190.64	183.37	100.00	.09
212.65	208.69	201.11	193.84	186.57	160.00	.12
213.77	209.80	202.13	194.86	187.59	170.00	.14
215.51	211.54	203.73	196.46	189.19	200.00	.16
228.13	223.76	215.83	207.90	200.39	500.00	.35
242.99	238.51	229.56	221.06	213.13	1000.00	.61
254.26	249.79	240.84	231.89	223.13	1500.00	.84

1 cfs = .028 cms
1 ft = .304 m

TABLE 5. Surface widths, depths and velocities at eight discharges, Station W-A, as predicted by stage-discharge program (cross-section 0).

SURFACE WIDTH WITH DEPTH OF AT LEAST						
.25 FT	.50 FT	1.00 FT	1.50 FT	2.00 FT	FLOW	VELOCITY
25.11	8.04	0.00	0.00	0.00	20.00	1.63
34.23	26.27	0.00	0.00	0.00	50.00	2.16
38.08	33.10	7.14	0.00	0.00	75.00	2.43
42.29	35.52	17.42	0.00	0.00	100.00	2.64
45.94	38.92	25.34	0.00	0.00	125.00	2.81
49.30	42.29	28.99	2.68	0.00	150.00	2.94
55.47	48.46	35.03	15.26	0.00	209.00	3.26
66.31	59.40	45.37	33.26	7.59	350.00	3.86

1 cfs = .028 cms
1 ft = .304 m

TABLE 6. Surface widths, depths and velocities at eight discharges, Station W-A, cross-section 238, as predicted by stage-discharge computer program.

SURFACE WIDTH WITH DEPTH OF AT LEAST						
.25 FT	.50 FT	1.00 FT	1.50 FT	2.00 FT	FLOW	VELOCITY
62.13	59.80	46.82	36.86	25.81	20.00	.18
64.19	62.67	51.82	44.47	33.32	50.00	.38
65.47	63.95	60.29	47.56	37.96	75.00	.52
66.50	64.98	61.94	50.06	41.72	100.00	.64
67.41	65.89	62.85	52.27	44.91	125.00	.75
68.20	66.68	63.64	59.80	46.82	150.00	.86
69.78	68.26	65.22	62.19	50.65	209.00	1.08
73.81	70.93	67.90	64.86	61.75	350.00	1.55

1 cfs = .028 cms
1 ft = .304 m

enhance such habitat thereby enabling a reasonable rate of fish production and corresponding recreational use to occur.

Degrading Instream Flow:

That flow based on biological and hydrological parameters which when either maintained at a constant discharge in cubic feet per second, or segmented into monthly increments, will degrade existing or reasonable established conditions of aquatic habitat, including rate of fish production and corresponding recreational use.

No criteria were listed for the characterization of optimum flows. The laws also state that "the word minimum is not a correct connotation of the objective of a DOW flow recommendation and has only encouraged misunderstanding."

Recommendations of single cross section procedures in the studied rivers were for required flows which met any two of the following three criteria (from DOW instructions):

Average Depth (ft)	Average Velocity (fps)	Percent Wetted Perimeter
.6 - 1.0	1 - 1.5	60

Flows at the study sites which fulfill these criteria are as follows:

Station	April-September Flow (cfs)	October-May Flow* (cfs)
Y-3 (50)	250-300(7-8.4 cms)	272(7.61 cms)
Y-4 (0)	210(5.88 cms)	272(7.61 cms)
W-A (0)	50(1.4 cms)	328(9.18 cms)

* Same as April-September flow or at minimum monthly natural flow during this period, from USGS gage records (Appendices 1 through 4).

These recommendations are derived from A-D program output at the cross section displaying the most typical riffle characteristic (Figures 10 through 17). A similar set of recommendations derived from the nearest upstream cross section were as follows:

Station	April-September Flow (cfs)	October-May Flow (cfs)
Y-3 (100)	200(5.6 cms)	272(7.61 cms)
Y-4 (170)	150(4.2 cms)	272(7.61 cms)
W-A (75)	50(1.4 cms)	328(9.18 cms)

Results of the sag tape R-2 Cross procedure at Station W-B yielded the following recommendations derived from results presented in Table 7.

April-September Flow (cfs)	October-May Flow (cfs)
229 (6.41 cms)	257 (7.20 cms)

Obviously, flow recommendations from single cross section methodologies varied greatly with the choice of the cross section location and the methodology used, as well as the determinative criteria selected. In the case of the White River, a recommendation of 50 cfs (1.4 cms) would probably be dangerously low. A minimum of 109 cfs (3.05 cms) was measured in 1934 near Rangely, but the mean monthly minimum has been 409 cfs (11.26 cms) measured for July since 1924 (Appendix 1). Water temperatures exceeding 27 C were recorded in the White River near Rangely and 1 km above Piceance Creek on July 23, 1977 at a flow of approximately 100 cfs (2.8 cms) (Prewitt *et al* 1977). Dissolved solids were abnormally concentrated at that flow and dissolved oxygen levels were the lowest measured at those sites during that study (6.25 and 6.75 ppm). Electrofishing produced fish only in restricted deep areas where great concentrations of suckers, carp and mountain whitefish were found in close association.

Table 7. Percent wetted perimeter, average depths and velocities at Station W-B as predicted for eight flows by R-2 Cross program.

% Wetted Perimeter	Depth	V	Q
100.00	1.11	4.82	791
92.85	1.09	4.82	756
89.18	.81	3.96	443
85.00	.67	3.42	304
80.49	.58	3.17	229
59.69	.50	2.86	131
55.70	.44	2.61	98.3
32.39	.35	2.27	40

1 cfs = .028 cms
1 ft = .304 m

The erroneous recommendation was caused by improper selection of a "critical area." The single cross section spanned an area of abnormally high velocity which itself would probably not be selected by any of the White River fish species. Velocity criteria were met here at all flows and therefore only one of the remaining two criteria had to be met. Percent wetted perimeter was high at all flows probably because of the selection of 350 cfs (9.8 cms) as an "optimum." Such biased results are possible even if study locations and criteria are conscientiously selected.

Summer recommendations of 200 and 150 cfs (5.6 and 4.2 cms) for Yampa Stations Y-3 and Y-4 respectively, are acceptable and fall roughly between the minimum and average natural flows for the April-September period as measured at the Maybell gage since 1917 (Appendix 3). Both recommendations approximate the median year monthly low flow (196 cfs 5.5 cms) for September (Appendix 4). Extreme low flows of 20 (.56), 26 (.73) and 28 (.78) cfs (cms) were recorded in July, August and September of 1923. Flows estimated to be less than 50 cfs (1.4 cms) were observed at Maybell in July, 1977 by USGS personnel and the river character was said to be degraded; many reaches consisted of isolated pools and intrasubstrate flow. A discharge of 168 cfs (4.7 cms) was observed at both Y-3 and Y-4 in September of 1976 (Prewitt *et al* 1977). Water temperatures did not exceed 24 C with an air temperature of 38 C. Dissolved oxygen was at saturation, possibly as a consequence of the abundant growth of filamentous green algae favored by the low, clear water conditions.

TENNANT METHOD FLOW RECOMMENDATIONS

Station	
Y-3 and Y-4	10 percent* = 155.5 cfs (4.35 cms)
	30 percent = 466.0 cfs (13.1 cms)
	60 percent - 933.0 cfs (26.1 cms)
W-A	0 percent + 62.3 cfs (1.74 cms)
	30 percent = 186.9 cfs (5.23 cms)
	60 percent = 373.8 cfs (10.47 cms)

* of mean annual flow

Care must be taken to note the effects of consumptive water use upon the undiminished flow. Both the White and Yampa Rivers are depleted during certain summers as a consequence of both municipal and agricultural water demand. Steele (1976) estimated that the municipal consumptive water use from the Yampa River above Maybell was about 6 percent in 1970 and could rise to as much as 24 percent by 1985, depending upon the rate and manner of coal extraction in the area. Adjustments of mean annual flow by additions of as much as 50 percent may be necessary in order to return such flows to a virgin quantity.

Survival flows recommended by the Tenant method for Stations Y-3 and Y-4 are not below observed flows which were deemed adequate for good survival of fish populations in both rivers. The 10 percent survival flow was probably higher than the real survival flow at both Y-3 and Y-4. The 60 percent flow, at about 1,000 cfs would be adequate to maintain levels above the "bench" which, when covered with shallow water, served as a major nursery area for catostomid and cyprinid fish larvae at both Stations Y-3 and Y-4.

The survival flow recommended for the White River, at 62 cfs (1.74 cms) would probably represent a degrading flow, especially for coolwater species such as mountain whitefish and mottled sculpin. Only at or above the 40 percent flow level (at flows exceeding 250 cfs [7] cms), would summer conditions be considered minimal by application of temperature criteria for summer months to the least temperature tolerant species (mountain whitefish).

Two major influences upon the effectiveness of Tennant method flow recommendations for the White River are: 1) The stability of the flow regime about the mean annual flow during most years, and 2) The effect upon mean annual flow figures of consumptive water uses which were well established prior to installation of the gages.

Since 1924, White River fishes have experienced few extended periods of abnormal flow depletion. Such depletions appear to have a comparatively large effect upon the flow-temperature (and therefore upon the flow-dissolved oxygen) relationship. The 10 percent survival flow recommendation is necessarily made without this knowledge and fails to adjust for the peculiarity that 63 cfs is less than one-third the monthly 1-in-20 year low flow expected during the summer months on the White River (Appendix 2). Inclusion of a "virgin flow" estimation would raise the survival flow request somewhat but reconstructions of undiminished flow are difficult at best.

The Tennant method recommendation for 10 percent of mean annual flow was well below the observed temperature and dissolved oxygen stress point for the White River, but above that point for the Yampa River. Establishment of that flow level as a permanent, annual phenomenon during the summer months, would undoubtedly compromise the fish fauna of the White River. A request for the 10 percent mean annual flow in the Yampa River, however, while not considered a threat to the fish populations, might meet severe opposition from water users noting that this flow was well above certain monthly minima occurring in dry years when irrigation demand was highest.

Use of the 30 percent level recommendation as an optimum would provide acceptable lotic conditions in the White River but could not be provided by natural flows during the summer months in the Yampa River.

HABTAT

HABTAT results are shown for stations Y-4 and W-A for channel catfish and Colorado squawfish. The squawfish probability curves were those derived from actual measurements and descriptions from the literature and presented in the Materials and Methods section.

HABTAT results for Station Y-3 are not presented because of difficulties in segmentation of the broad, shallow cross sections at that station. As only nine segments were allowable in the HABTAT program, segmentation could not be selected which would provide sufficient sensitivity of output at the lower flows. The program is being revised with respect to such limitations, however.

Channel catfish adults, probably because of depth preference and velocity sensitivity, were restricted to limited areas at Station W-A and there was a reduction of usable area at higher discharges (Figure 18). It is probable that adult usable area continued to decline even at flows above 350 cfs because of the velocity restriction. Higher flows produced more shallow water across the flat secondary channel while velocities became restricted in areas of suitable depth.

Juvenile channel catfish, suspected to prefer shallow water of slightly higher velocity than adults, were favored by higher flows which created shallow waters over the secondary channel, at about 200 cfs (5.6 cms) (Table 8).

The same phenomena were apparent at Station Y-4, with a distinct optimum in adult habitat occurring at 200 cfs (5.6 cms) (Table 9). Again, juveniles found more suitable area when flows covered the secondary channel, in this case at about 1,000 cfs (28 cms).

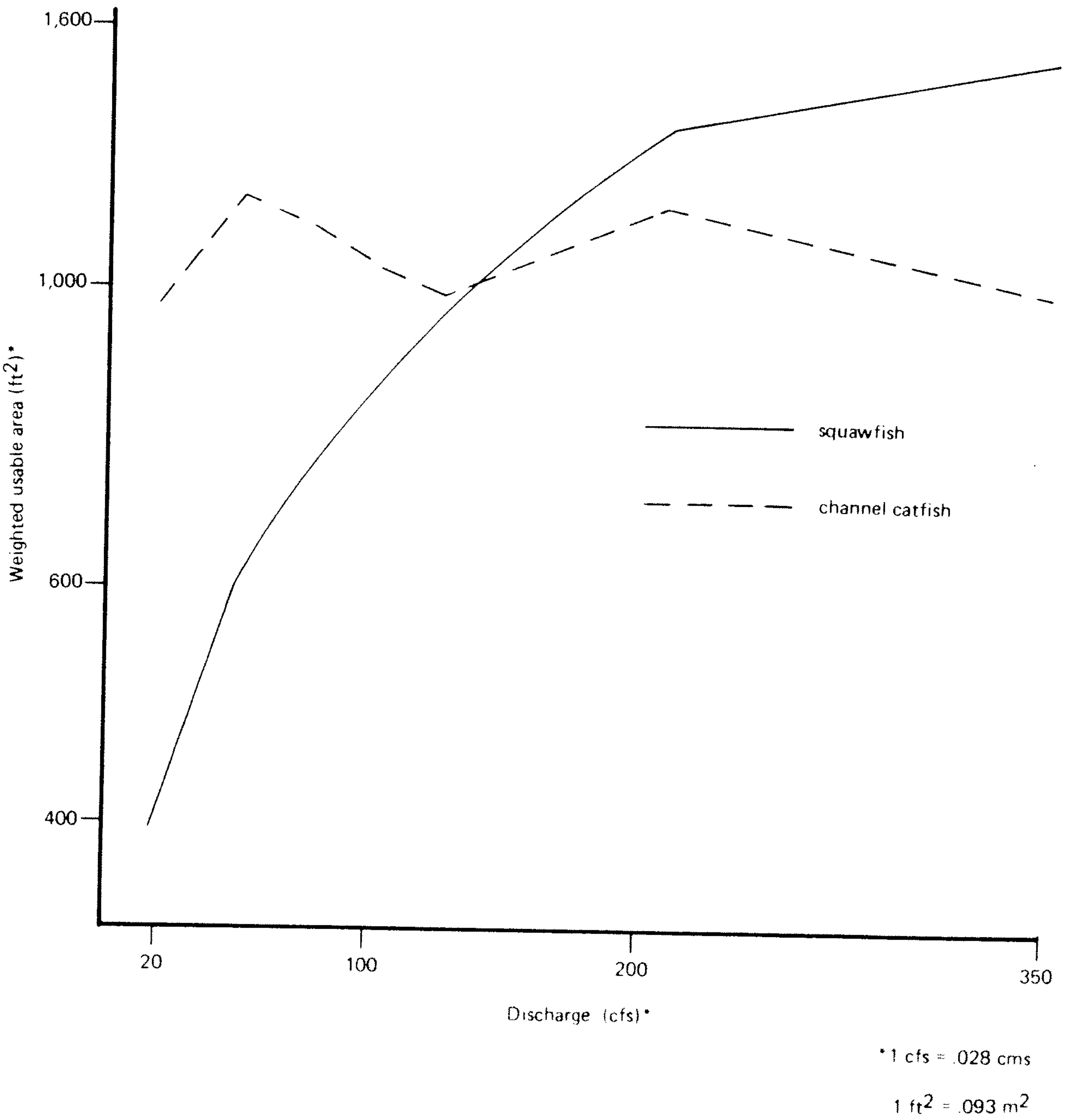


Figure 18. Weighted usable areas (in ft^2)* for adult channel catfish and adult Colorado squawfish at Station W-A as predicted by Habtat program

Table 8. Flow vs. available habitat (in square feet) for channel catfish at Station W-A, as predicted by U. S. Fish and Wildlife "Habitat" program.

Flow (cfs)	Fry	Juveniles	Adult	Spawning
20.00	1574.90	361.34	973.77	1236.19
50.00	6724.42	437.64	1172.04	1092.62
75.00	7448.00	476.71	1111.55	906.01
100.00	8895.86	543.47	1024.23	814.15
125.00	13079.32	650.83	996.95	750.10
150.00	21835.44	974.65	1016.98	716.69
209.00	72165.29	2712.32	1150.09	745.82
350.00	168755.13	6810.69	1003.64	599.72

1 cfs = .028 cms

Table 9. Flow vs. available habitat (in square feet) for channel catfish at Station Y-4, as predicted by U. S. Fish and Wildlife "Habitat" program.

Flow (cfs)	Fry	Juveniles	Adult	Spawning
50.00	3387.80	2221.65	24064.17	25366.10
75.00	8945.82	2284.36	25208.42	26156.63
100.00	16240.72	2323.16	26169.87	26802.71
125.00	17801.41	2416.83	26844.34	27342.16
150.00	18868.13	2491.48	27321.60	27788.88
170.00	19927.52	2519.28	27655.37	28135.79
200.00	21163.78	2569.42	28026.25	28224.12
500.00	8696.80	7903.23	26588.71	21707.50
1000.00	9228.85	17243.92	21140.60	13897.57
1500.00	11402.19	15350.44	19502.74	11374.76

1 cfs = .028 cms

Habitat for adult squawfish began a rapid decline with flows below 200 cfs (5.6 cms) at Station W-B and at both the 75 cfs (2.1 cms) and 500 cfs (14 cms) levels at Station Y-4 (Figures 18 and 19). The minor differences in the velocity tolerances between these two species produced the disparate proportions of usable area at the higher flows.

Adult squawfish habitat at Station Y-4 continued to improve with flows up to 1,500 cfs. No major inflections were apparent in flow vs. habitat curve but some changes occurred at 500 and 75 cfs. It is likely that, in terms of actual usable area for adult Colorado squawfish, the Station Y-4 inflection is much higher than 1,500 cfs, at a flow providing high velocities even in pool areas. In consideration of competition with channel catfish and the fact that flows may diminish in the future, Station Y-4 would appear to be at the lower limits of flows tolerable by squawfish. Indeed, the "minimum" flow recommendations produced by the previous methodologies appear to be near optimum for adult channel catfish, while they represent a rather small portion of the flows probably favored by squawfish.

Weighted usable areas for larval squawfish varied similarly with increasing flows in both rivers (Table 10). While good larval habitat existed at flows already considered marginal for adult squawfish, a distinct decline began in both rivers as flows approached the filling limit of the primary channel. At these flows, velocities generally exceeded the larval squawfish tolerances. As water surface elevations rose above the elevation of primary channel, areas of shallow, slow water were increased and available habitat rose. At flows of at least 350 and about 1250 cfs (respectively at Stations W-A and Y-4), conditions could be considered favorable for both larval and adult squawfish.

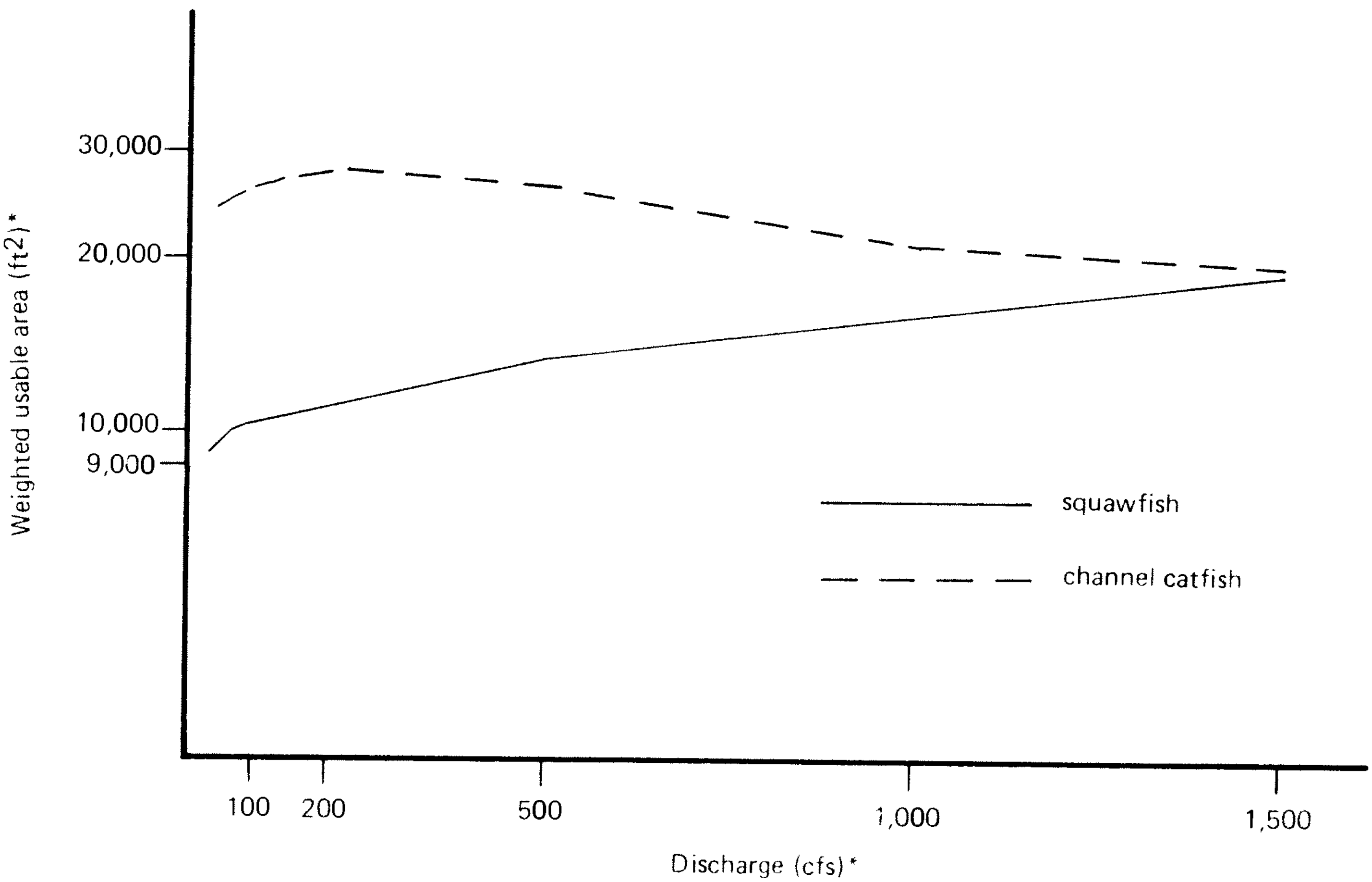
Analysis of the HABTAT output for Station Y-4 and its comparison with flow recommendations made by other methodologies (Table 11) produced the following conclusions.

The 170-200 cfs minimum recommended by use of Tenant, R-2 Cross and WSP methodologies is acceptable on the basis of observed physico-chemical and biotic conditions at those flows. However, in terms of the two species contrast mentioned previously, such flows would offer a distinct advantage to channel catfish in a competitive situation.

In the White River, although the most acceptable recommendation (from R-2 Cross and A-D) was for a required flow of about 200 cfs, results of the two species contrast from the HABTAT program indicated again that such a flow was optimum for channel catfish while being the lower inflection point for squawfish.

Use of the weighted usable area approach, then, has provided a distinct advantage in the detailed evaluation of flow reduction effects upon the dynamics of a two species interaction in these rivers. While the recommendations of 200 cfs as desired minima in both rivers might offer long-term assurance of the survival of most fish species present, they might establish more firmly the trends which have participated in the present demise of the few remaining native fish species.

* * * * *



*1 cfs = .028 cms

1 ft^2 = .093 m^2

Figure 19. Weighted usable areas (in ft^2)* for adult channel catfish and adult Colorado squawfish at Station Y-4 as predicted by Habtat program

Table 10. Flow vs. weighted usable area (WUA; in ft^2) for larval squawfish at Stations Y-4 and W-A as predicted by Habitat computer program.

Station Y-4		Station W-A	
Flow	WUA	Flow	WUA
50.00	925.64	20.00	45393.34
75.00	1058.83	50.00	63281.82
100.00	1279.13	75.00	34299.19
125.00	1458.22	100.00	10985.18
150.00	1544.03	125.00	3581.20
170.00	1488.82	150.00	686.73
200.00	1169.83	209.00	272.30
500.00	512.03	350.00	2664.55
1000.00	126.28		
1500.00	1818.22		

1 cfs = .028 cms
1 ft^2 = .09 m^2

Table 11. Summary of flow recommendations derived from four instream flow methodologies and their related criteria for Stations Y-3, Y-4, W-A and W-B, April - October. Flows in cfs with cms in parentheses.

METHODOLOGY AND CRITERIA	STATION Y-3	Y-4	W-A	W-B
Multiple Cross-Section				
Wetted perimeter inflection	170 (4.76)	170 (4.76)	200 (5.60)	
Area inflection	200 (5.60)	200 (5.60)	125 (3.50)	
Velocity inflection	170^2 (4.76)	170^2 (4.76)	50^1 (1.40)	
1.5 ft passage requirement				
(squawfish)	200 (5.60)	200 (5.60)	200 (5.60)	
(channel catfish)	200 (5.60)	200 (5.60)	75^{1}* (2.10)	
Single Cross-Section (surveyed)				
Depth, velocity and wetted perimeter	CS+50: 250-300 (7.00-8.40) CS+100: 200 (5.60)	CS+0: 210 (5.88) CS+170: 150 (4.20)	CS+0: 50^1 (1.40) CS+75: 50^1 (1.40)	
R-2 Cross				
Depth, velocity and wetted perimeter				229^2 (6.41)
Tennant				
10% mean annual flow	155^2 (4.34)	155^2 (4.34)	62^1 (1.74)	
30% mean annual flow	466 (13.05)	466 (13.05)	187^2 (5.24)	
60% mean annual flow	933 (26.12)	933 (26.12)	374 (10.47)	
Habitat				
Optimum area				
(squawfish)		>1500 (42.00)	>350 (9.80)	
(channel catfish)		200 (5.60)	200 (5.60)	
Minimum area[2]				
(squawfish)	200-500 (5.60-14.00)	200 (5.60)		
(channel catfish)		<50 (1.40)		

1. Flow deemed less than survival flow by biological observations.
2. Flow recommendation selected as best for a given methodology by consideration of biologic and historic hydrologic factors.
* Only passage levels less than 1.0 ft offered at this flow.
\+ CS = Cross section

1 cfs = .028 cms

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APPENDICES

Appendix 1. Average, maximum and minimum monthly flows and annual mean flow of the White River below Meeker, Colorado. Derived from USGS gage data collected since 1962.

	MONTH					
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Average	436.000	397.000	358.000	328.000	335.000	373.000
Q/Qann	5.829	5.135	4.784	4.380	4.076	4.991
Cov Var	.183	.134	.153	.115	.106	.123
Skew	-.285	-.626	.229	-.667	1.036	.422
Maximum	561.000	472.000	476.000	371.000	424.000	452.000
Minimum	277.000	305.000	266.000	257.000	286.000	308.000

	MONTH					
	Apr.	May	June	July	Aug.	Sept.
Average	552.000	1538.000	1826.000	665.000	408.000	398.000
Q/Qann	7.145	20.551	23.613	8.888	5.458	5.152
Cov Var	.359	.251	.383	.485	.208	.221
Skew	2.014	.467	-.795	1.060	-.432	.520
Maximum	1115.000	2159.000	2720.000	1471.000	558.000	587.000
Minimum	400.000	1076.000	463.000	216.000	238.000	249.000

	Annual Mean
Average	635.000
Q/Quan	100.000
Cov Var	.168
Skew	-.362
Maximum	791.000
Minimum	454.000

1 cfs = .028 cms

Appendix 2. Monthly flow-duration table for White River below Meeker, Colorado. Derived from USGS gage data collected since 1967.

	YEARS FLOW IS NOT EXCEEDED					
Month	9 in 10	2 in 3	1 in 2	1 in 5	1 in 10	1 in 20
October	550	466	429	364	335	312
November	471	418	394	350	329	312
December	432	378	354	311	290	274
January	380	343	326	294	279	267
February	380	348	333	305	292	281
March	434	391	371	335	317	304
April	774	600	527	410	359	322
May	2049	1661	1494	1214	1090	997
June	3283	2071	1642	1042	822	675
July	1136	739	595	389	312	259
August	534	440	399	330	298	275
September	517	428	389	323	293	271
Annual	785	675	626	540	500	469

1 cfs = .028 cms

Appendix 3. Average, maximum and minimum monthly flows and annual mean flow of the Yampa River near Maybell, Colorado. Derived from USGS gage data collected since 1917.

	MONTH					
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
Average	344.000	345.000	298.000	272.000	320.000	671.000
Q/Qann	1.872	1.819	1.624	1.483	1.591	3.655
Cov Var	.526	.345	.350	.311	.337	.514
Skew	1.321	1.044	.817	1.084	1.598	1.520
Maximum	1001.000	691.000	624.000	610.000	743.000	1900.000
Minimum	117.000	191.000	137.000	115.000	160.000	221.000

	MONTH					
	Apr.	May	June	July	Aug.	Sept.
Average	2621.000	6275.000	5537.000	1360.000	380.000	241.000
Q/Qann	13.819	34.191	29.197	7.409	2.409	1.271
Cov Var	.449	.324	.426	.751	.558	.659
Skew	.720	.459	.763	2.019	.969	1.932
Maximum	6496.000	11270.000	12810.000	5819.000	1052.000	972.000
Minimum	735.000	2450.000	548.000	20.000	26.000	28.000

	Annual Mean
Average	1558.000
Q/Quan	100.000
Cov Var	.301
Skew	.650
Maximum	2947.000
Minimum	517.000

1 cfs = .028 cms

Appendix 4. Monthly flow-duration table for Yampa River near Maybell, Colorado. Derived from USGS gage data collected since 1917.

	YEARS FLOW IS NOT EXCEEDED					
Month	9 in 10	2 in 3	1 in 2	1 in 5	1 in 10	1 in 20
October	577	376	303	199	160	133
November	495	376	327	249	216	192
December	437	326	281	211	181	160
January	385	296	260	201	176	158
February	452	348	305	236	206	185
March	1088	733	601	407	332	281
April	4320	2892	2364	1591	1293	1090
May	9124	6866	5952	4496	3882	3440
June	9603	6206	4983	3238	2586	2147
July	3115	1486	1024	493	337	246
August	733	422	320	185	140	110
September	471	263	196	110	82	64
Annual	2223	1702	1488	1143	996	889

1 cfs = .028 cms

Appendix 5. Observed and predicted water surface elevations (WSE) after calibration of WSP for Station Y-3; flow = 168 cfs.*

Cross-Section	Observed WSE	Predicted WSE	Error
0 + 50	91.59	91.59	.00
1 + 00	91.60	91.63	.03
1 + 50	91.64	91.65	.01
2 + 00	91.65	91.66	.01

Appendix 6. Observed and predicted water surface elevations (WSE) of WSP for Station Y-4; flow = 168 cfs.*

Cross-Section	Observed WSE	Predicted WSE	Error
0 + 00	92.26	92.26	0
1 + 70	92.66	92.59	.07 in (21.2 mm)
4 + 46	92.71	92.69	.02 in (6.1 mm)
6 + 04	92.72	92.70	.02 in (6.1 mm)
7 + 40	92.73	92.70	.03 in (9.1 mm)

* 1 cfs = .028 cms

Appendix 7. Observed and predicted water surface elevations (WSE) after calibration of WSP for Station W-A; flow = 209 cfs.*

Cross-Section	Observed WSE	Predicted WSE	Error
0 + 00	95.08	95.08	0
0 + 75	95.27	95.29	.02
2 + 38	95.34	95.38	.04
3 + 18	95.35	95.39	.045
4 + 09	95.38	95.39	.01

Appendix 8. Observed and predicted velocities (V) in fps at Station W-A; flow = 209 cfs.*

Cross-Section	Observed V	Predicted V	Error
0 + 00	3.46	3.26	.20
0 + 75	1.83	1.93	.10
2 + 38	1.35	1.39	.04
4 + 09	1.56	1.81	.25

* 1 cfs = .028 cms

Appendix 9. Velocity (V) in fps* and percent conveyance area (%A) at nine flows in cfs* as predicted by WSP program for Station Y-3, cross-sections 0-200.

	CROSS-SECTION									
	0		50		100		150		200	
Flow	%A	V	%A	V	%A	V	%A	V	%A	V
50	15.99	.54	10.74	1.03	17.68	.78	13.65	1.01	9.50	1.54
75	21.09	.62	16.78	1.19	21.55	.95	15.88	1.30	12.17	1.79
100	25.66	.68	17.67	1.26	25.97	1.06	18.66	1.49	15.43	1.91
125	29.88	.73	21.48	1.30	29.01	1.19	21.73	1.58	18.10	2.02
150	33.92	.77	25.28	1.33	31.77	1.30	25.07	1.66	20.18	2.19
168	36.73	.80	27.74	1.35	33.98	1.38	27.02	1.72	21.66	2.29
200	40.77	.86	31.77	1.40	37.02	1.51	30.64	1.82	24.33	2.45
300	51.85	1.03	43.18	1.54	45.86	1.87	40.67	2.11	34.72	2.63
1000	100.00	2.90	100.00	2.23	100.00	3.46	100.00	3.24	100.00	3.96

* 1 cfs = .028 cms
* 1 fps = .304 mps

Appendix 10. Velocity (V) in fps* and percent conveyance area (%A) at nine flows in cfs* as predicted by WSP program for Station Y-4, cross-sections 0-740.

	CROSS-SECTION									
	0		170		446		604		740	
Flow	%A	V	%A	V	%A	V	%A	V	%A	V
50	12.5	1.32	15.56	1.40	37.24	.31	67.93	.05	65.32	.07
75	16.27	1.52	20.44	1.62	40.98	.43	70.08	.07	67.72	.10
100	20.00	1.68	24.44	1.79	44.03	.53	71.86	.09	69.61	.12
125	23.73	1.80	28.44	1.95	46.84	.62	73.33	.10	71.16	.15
150	27.12	1.91	31.56	2.09	49.41	.71	74.68	.12	72.70	.18
170	29.49	1.99	34.22	2.19	51.29	.78	75.72	.14	73.73	.20
200	33.22	2.07	37.78	2.33	53.86	.87	77.13	.16	75.28	.23
500	63.72	2.69	64.89	3.41	74.47	1.58	87.74	.35	86.87	.49
1000	100.00	3.41	100.00	4.44	100.00	2.41	100.00	.63	100.00	.86

* 1 cfs = .028 cms

* 1 fps = .304 mps

Appendix 11. Velocity (V) in fps* and percent conveyance area (%A) at nine flows in fps* as predicted by WSP program for Station W-A, cross-sections 0-409.

	CROSS-SECTION									
	0		75		238		318		409	
Flow	%A	V	%A	V	%A	V	%A	V	%A	V
20	13.3	.62	17.5	.74	47.8	.25	66.48	.16	43.21	.10
50	24.4	2.18	28.57	1.13	57.6	.51	73.08	.38	52.47	.60
75	33.3	2.44	36.4	1.34	63.8	.68	76.37	.54	58.64	.86
100	41.1	2.64	42.86	1.50	68.8	.84	79.67	.69	63.58	1.07
125	48.89	2.80	60.0	1.62	73.2	.98	82.42	.83	68.52	1.25
150	55.56	2.94	55.8	1.73	77.7	1.11	85.16	.97	72.84	1.42
175	63.3	3.07	62.3	1.82	80.8	1.23	87.36	1.10	76.54	1.59
209	71.1	3.26	70.13	1.93	85.3	1.39	90.11	1.27	82.10	1.81
350	100.00	3.95	100.00	2.31	100.00	2.02	100.00	1.91	100.00	2.51

* 1 cfs = .028 cms
* 1 fps = .304 mps

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