Reconnaissance – Level Application of Physical Habitat Simulation in the Evaluation of Physical Habitat Limits in the Animas Basin, Colorado

Open File Report 03-222

U.S. Department of the Interior
U.S. Geological Survey

USGS
science for a changing world

U.S. Department of the Interior
U.S. Geological Survey

Reconnaissance-Level Application of Physical Habitat Simulation in the Evaluation of Physical Habitat Limits in the Animas Basin, Colorado

By

Robert T. Milhous

U.S. Geological Survey
Fort Collins Science Center
2150 Centre Avenue, Bldg. C
Fort Collins, CO 80526-8118

Open-File Report 03-222

U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Avenue, Bldg. C, Fort Collins, CO 80526-8118

Suggested citation:

Milhous, R.T., 2003, Reconnaissance – Level application of physical habitat simulation in the evaluation of physical habitat limits in the Animas Basin, Colorado: U.S. Geological Survey, Fort Collins Science Center, Fort Collins, CO: Open File Report 03-222, 16 p.

Contents

Tables

Contents (concluded)

Figures

Reconnaissance – Level Application of Physical Habitat Simulation in the Evaluation of Physical Habitat Limits in the Animas Basin, Colorado

Introduction

The Animas River is in southwestern Colorado and flows mostly to the south to join the San Juan River at Farmington, New Mexico (Figure 1). The Upper Animas River watershed is in San Juan County, Colorado and is located in the San Juan Mountains. The lower river is in the Colorado Plateau country. The winters are cold with considerable snowfall and little snowmelt in the mountains in the upper part of the basin. The lower basin has less snow but the winters are still cold. The streamflows during the winter are low and reasonably stable.

The native trout in the Animas Basin is the cutthroat trout. Few native trout remain and the trout found in the upper watershed are brook trout with rainbow and brown trout in the lower river. There is considerable metal contamination in the upper basin near Silverton but a brook trout fishery does exist in the Animas River from just above Howardsville to where the Animas joins Cement Creek in Silverton.

There are two principle objectives of the habitat studies in the Animas Basin: (1) to improve understanding of the fate of sediment from mining operations from the view point of physical habitat impacts, and (2) to determine if reconnaissance level physical habitat studies can be useful in understanding the impacts of mining on the aquatic ecosystem.

Part of the project was to apply the Physical Habitat Simulation System (PHABSIM) to selected locations in the Upper Animas River Basin, Colorado in order to demonstrate the importance of physical habitat in evaluating the efficacy of mined land remediation activities. Physical habitat analysis included the use of sedimentation variables in physical habitat simulations. A map of the Upper Animas Basin is presented in Figure 2.

The project involves collecting data for the following locations: Animas River above Magee Creek; Animas River above Howardsville; Animas River below Howardsville; Animas River above Silverton at Hillsdale Cemetery; Animas River at Silverton; Cement Creek above Silverton; Cement Creek at Silverton; Mineral Creek at Powerline above Silverton; Mineral Creek at Campground; South Mineral Creek at Overflow Campground; Mineral Creek above Bear Creek; Mineral Creek at Silverton; Animas River below Silverton; and Animas River at Elk Park.

Bed material samples were collected at each site. These included samples of the armour, the substrate, and sand and fines deposited on the surface. At selected sites the stream morphology was measured. These measurements included one to three cross sections, stream discharge, and water surface elevations. The data are located in the files of the Fort Collins Science Center.

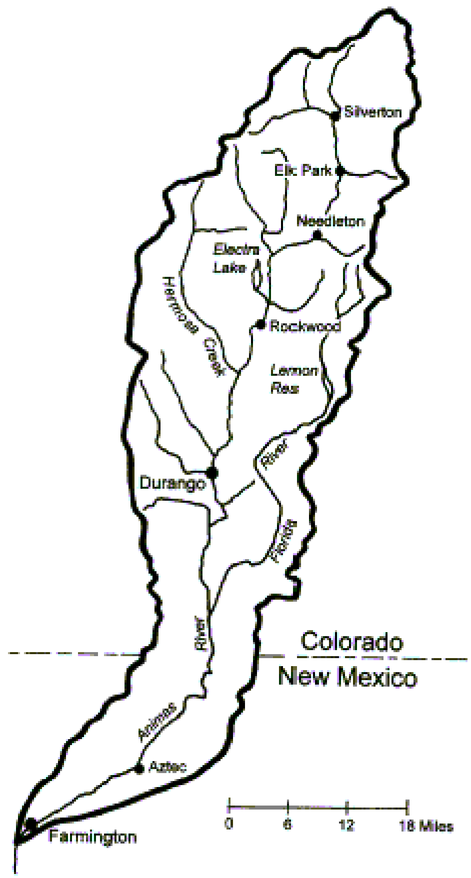

Figure 1. Map of the Animas River Basin in southwestern Colorado and northwestern New Mexico.

The major components from the Upper Animas River study element include the following:

- a study of the physical habitat which included considerations of physical habitat during the high flow period and during the winter,
- a study of the bed material,
- a study to link bed material (substrate) characteristics and physical habitat, and
- a study of the pore water characteristics.

Physical Aquatic Habitat

As used in this report, physical aquatic habitat is defined as the velocities, depths, and the nature of the bed-material (substrate) weighted by the needs of selected aquatic animals. The relation between the

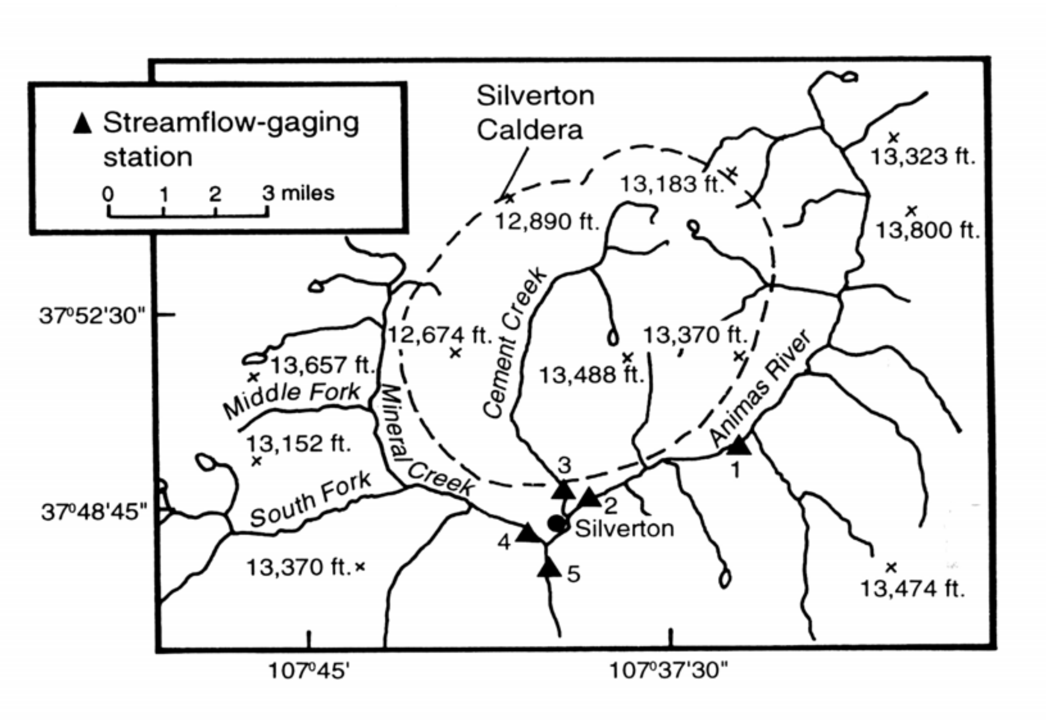

Figure 2. Location of the principle streams in the Upper Animas Basin. The numbers on the map refer to the gauging stations in the basin. The names of the stations are: (1) Animas River at Howardsville, (2) Animas River at Silverton, (3) Cement Creek at Silverton, (4) Mineral Creek at Silverton, and (5) Animas River below Silverton (modified from Wright, 1997).

streamflow and physical habitat area as used herein was developed using the PHABSIM described in Milhous and others (1989). The equation relating the physical habitat area (HA) in a stream to the streamflows is:

$$HA = \int f(v, d, ci)\, da$$

where HA is the physical habitat area, v is the velocity, d the depth, and ci an index to the physical characteristics of the stream channel. The integration is over the area of a reach of stream. In most applications of PHABSIM the function f( ) is divided into independent functions of velocity, depth, and channel index. The function used in the equation above is then:

$$f(v, d, ci) = h(v)*g(d)*j(ci)$$

where h(v), g(d), and j(ci) are independent functions between velocity, depth, and the channel characteristics, respectively. The physical habitat areas calculated are the habitats available for a life stage and species of aquatic animal weighted by how well the area meets the needs of the species. Examples of life stages are spawning, fry, juveniles, and adults. Factors other than physical habitat may limit aquatic animal populations, therefore, physical habitat alone may not always be a good predictor of population size or strength.

The species criteria used in the analysis were developed during previous studies (Culp and Homa, 1991), except for the adult trout criteria, which is a composite of the criteria for brook and brown trout. However, the acceptable velocities are about 0.5 fps larger than the original criteria because of the characteristics of the model (HABVD) in PHABSIM used in the analysis. The criteria for adult trout in the Animas River Basin are given in Figure 3. Similar criteria for the benthic biomass are available. Benthic biomass area relates to the ability of the habitat conditions to produce benthic invertebrates.

The relations between the discharge and the physical habitat available for adult trout and total benthic biomass are given in Figure 4 along with the water year 1996 daily streamflows measured at the stream gaging station on the Animas River at Howardsville.

The average annual discharge for water year 1996 was close to the median discharge at the Howardsville gage. The average discharge for 1996 was 103 cfs; the median for the period of record (1936-1996) was 102 cfs. In the Upper Animas Basin, the winter discharges are low compared to other seasons because the air temperatures are cold and the precipitation is snow.

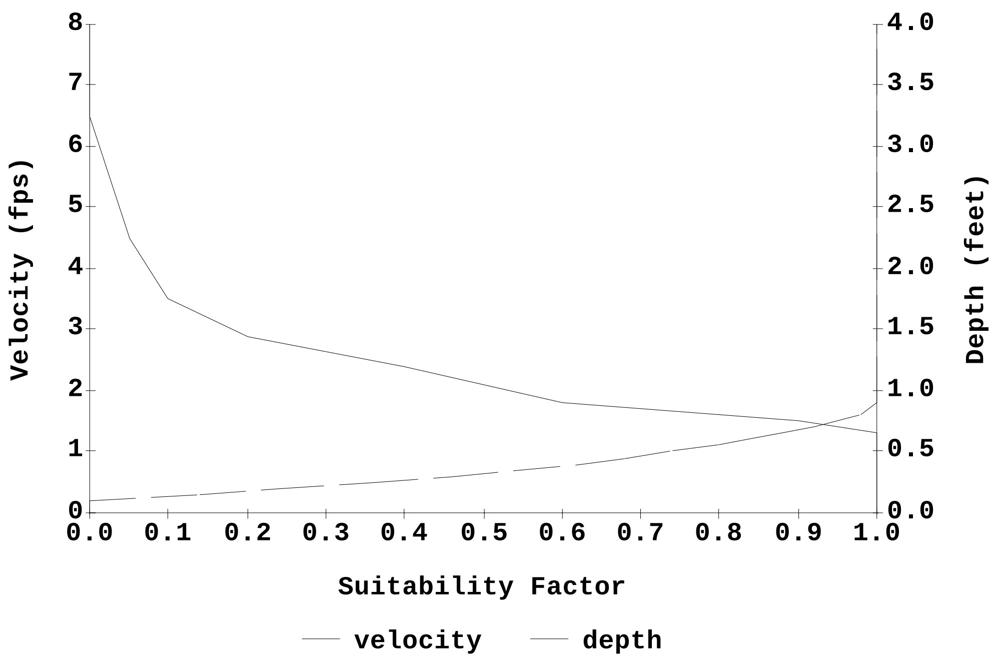

Figure 3. Habitat criteria for adult trout in the Animas River, Colorado.

The adult trout habitat criteria for winter are not the same as the criteria for the rest of the year. Velocities limit the habitat during the winter because low velocities are required for good habitat. When the velocities are low enough for reasonable habitat, the depths are too small (as the depths increase the velocities increase). (Velocities also limit the availability of trout habitat in the spring.) The result is that little winter trout physical habitat exists in the river. The winter habitat is compared to the habitat during the rest of the year in Table 1.

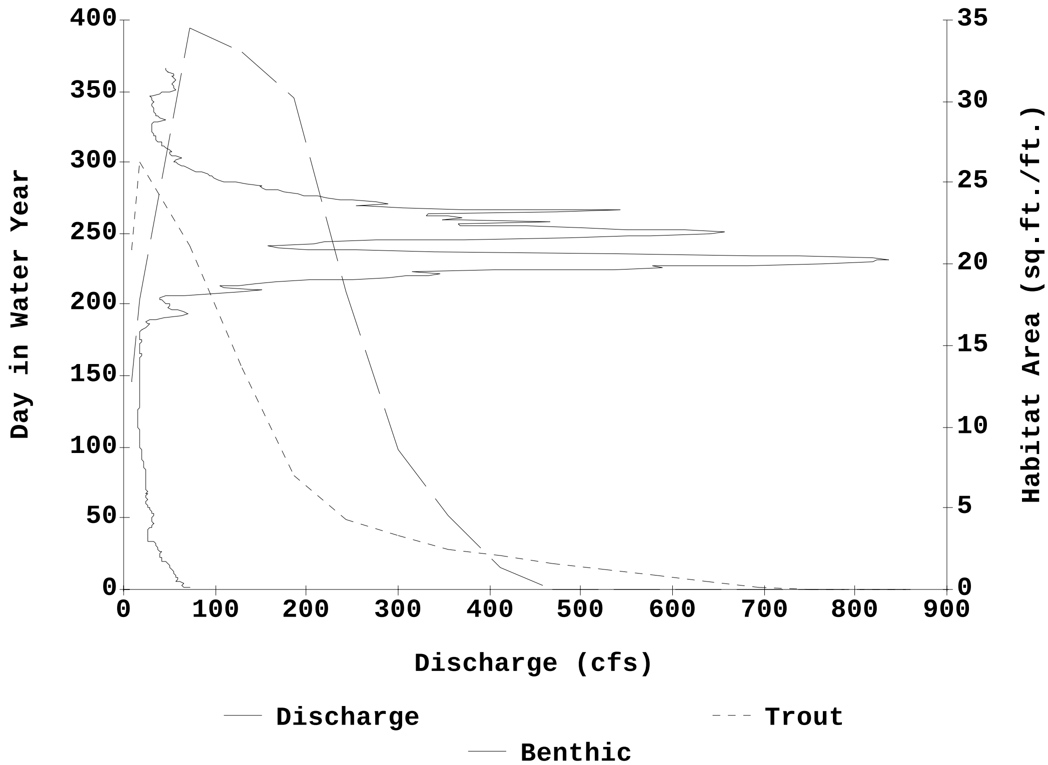

Figure 4. The 1996 daily streamflows, the relation between habitat and discharge for trout in the Animas River, and for total benthic invertebrate biomass.

Table 1. Physical habitat as related to discharge for the lower discharges of the Animas River at Howardsville, Colorado.

Discharge (cfs)	Surface area	Adult trout (square feet/foot of stream)	Winter trout (square feet/foot of stream)	Benthic biomass
8.3	25.0	20.9	0.94	12.8
16.6	28.2	26.3	1.07	17.9
73.1	36.4	21.1	0.35	34.5
129.6	40.1	13.7	0.00	33.1

Figure 4 indicates high discharges limit habitat and Table 1 indicates winter habitat also is limited. Each of these conditions is considered in the following paragraphs.

High Streamflow Conditions

High velocities limit the quality of the physical habitat during spring runoff (Figure 4). An index describing the stress on the trout population during the spring runoff period has been used to investigate the variation in stress from year to year. The conceptual basis of the stress index is that high velocities reduce the quality of the physical habitat and the more days the velocities exceed some critical velocity the larger the stress on the trout population in the stream.

The equation used to calculate the stress on the trout population caused by high velocities is:

$$FSI = \Sigma((Qd - Qcrt)/ Qref$$

where FSI is the Fish Stress Index for a selected time period (usually a year), Qd is the daily discharge, Qcrt is the discharge above which the stress on the fish is significant and Qref is an arbitrary reference discharge used to make the index dimensionless. The summation is over a water year.

The velocity-habitat quality weighting function shown in Figure 3 was used to determine the critical velocity. The assumption is that a suitability of 0.1 or less introduces stress to the trout populations that could limit the size (either biomass or numbers) of trout populations. The velocity at a suitability weight of 0.1 is 3.5 feet per second (fps).

A relation between the mean channel velocity and the discharge was determined using least absolute deviation regression. The equation is:

velocity = 0.170 (discharge) ** 0.5560

From this relation the velocity at an average channel velocity of 3.5 fps was determined to be 230 cfs and is the critical discharge in the FSI equation above. The reference discharge selected for the calculations of the fish stress index was 100 cfs. The equation for FSI is then:

$$FSI = \Sigma(Q - 230.0)/100$$

The results for the period of record at the Howardsville gage are given in Figure 5. Not included in the analysis is the reduction in stress on the trout population resulting from the presence of velocity cover (usually cobbles and boulders). The velocity cover provides areas of locally low velocity where the fish are sheltered from the overall channel high velocities (see the section on links between sediment and habitat).

Little fish population data is available for the Animas River. Some data are available for the Gunnison River to the north of the Animas Basin. In the Gunnison River basin the limiting factor on the production of juvenile trout is the fry habitat during the months following the emergence of the fry from the gravels the previous year (Nehring and others, 1987). The relation between fry habitat and population of juvenile brown and rainbow trout one year later in the Upper Gunnison River in Colorado are presented in Figure 6. The figure shows that an important limiting habitat for the production of juvenile trout is the fry habitat the previous year. The lines on the figure are for average values of other variables influencing the population of juvenile trout. Rainbow trout spawn in the spring, incubate during the spring runoff, and the fry emerge towards the end of the spring runoff. The relation for rainbow trout will be discussed in this section. Because brown trout spawn in the fall and incubate during the winter the brown trout relation will be discussed in the section below on winter habitat.

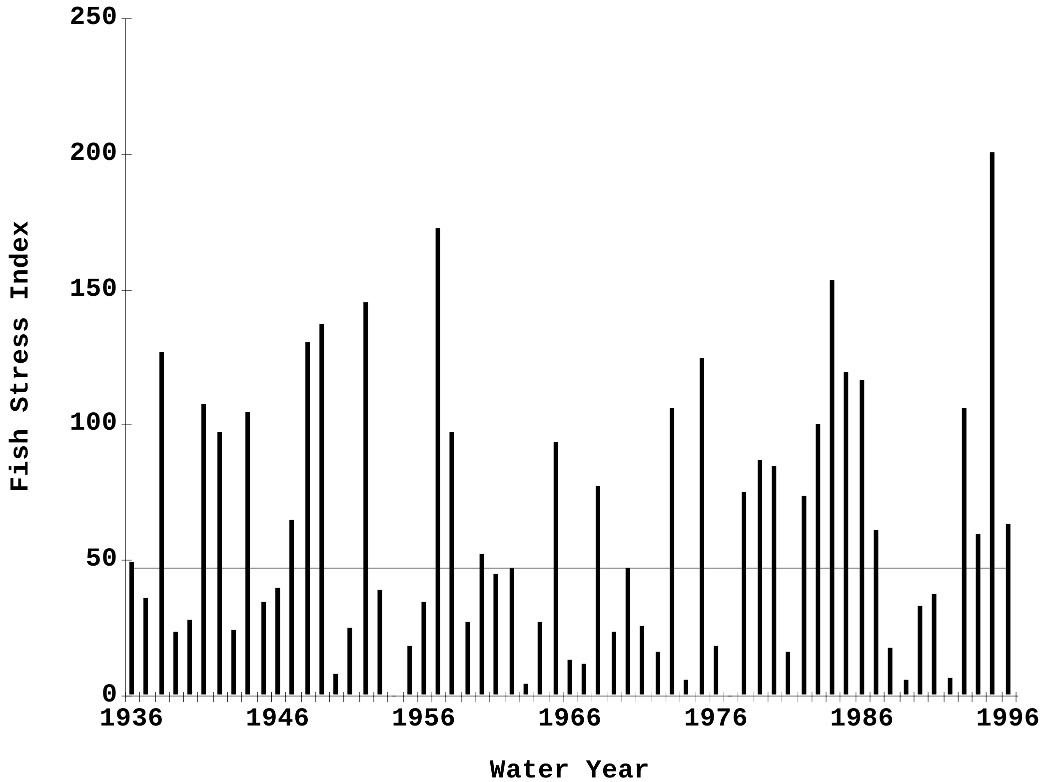

Figure 5. The variation of an annual index to the stress introduced to the trout in the Animas River, Colorado.

In the case of rainbow trout there was an additional limit. This limit is the flow conditions during the incubation period between spawning and emergence. Rainbow trout spawn in the spring during spring runoff and in some cases the redds may be scoured by high flows. The data for the Gunnison River are in Table 2.

An interesting difference shown in Table 2 and Figure 6 is in the production for the two lowest production years. In 1983 the expected production of fry (on the basis of the average line) was five juveniles per hectare; instead, the measured production was one. The reason may have been the relatively low spawning discharge followed by a relatively high incubation discharge that scoured out redds located low in the cross sections.

Analysis of fry and juvenile habitat and conditions during incubation in the Animas Basin has never been done. The conditions in the upper Animas River are sufficiently similar to the Gunnison River to warrant such an analysis.

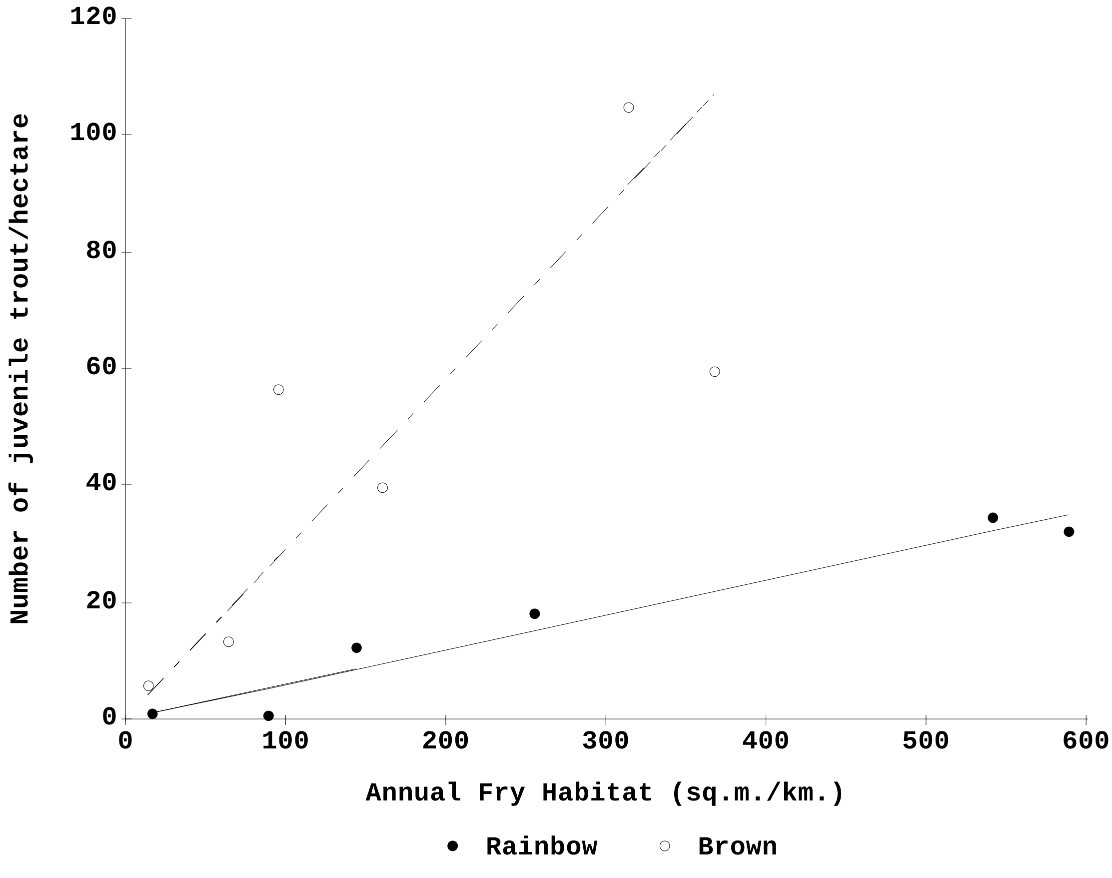

Figure 6. Effective habitat versus population density relations for juvenile brown and rainbow trout in the Upper Gunnison River Colorado. Data are from Nehring and Miller (1987).

Table 2. Spawning and incubation flows, rainbow trout fry habitat, and the juvenile rainbow trout population one year later at the Duncan/Ute Trail site on the Gunnison River. Juvenile population and weighted usable area data are from Nehring and Miller (1987).

Water year	Spawning discharge (m^3/s)	Incubation discharge (m^3/s)	Juveniles (number/ hectare)	Fry habitat (m^2/m)
1980	57	72	32	589
1981	7	8	35	542
1982	12	32	18	255
1983	45	257	1	89
1984	151	274	1	16
1985	92	135	12	144

Winter Habitat

The reduction in winter habitat shown in Table 1 is a result of the velocities being too high for trout habitat (based on winter habitat criteria). The winter conditions also limit the reproduction of brown trout in the Gunnison (see the incubation discharges in Table 3; the variation in these flows cause the scatter about the line in Figure 6). Brown trout production is further limited in the Gunnison River by the conditions of spring runoff when fry emerge from the spawning gravels. Additional limiting factors for brown trout are the winter conditions during the incubation period. There are two data points for brown trout on Figure 6 that are outliers. The likely cause of the outliers is the incubation conditions before emergence of the fry in the spring. The brown trout spawning period used in the following analysis is from 1 Oct to 15 Nov and the incubation period is from 1 Nov to 15 April. Winters in the Gunnison basin can be from cold and dry (low winter runoff); to relatively warm and wet (high winter runoff). If the streamflows during the fall are high, the fish will tend to spawn high in the cross section. If the streamflows during the incubation period are relatively high, more of the redds (nests) will produce fry. In contrast, if flows during the incubation period are low, less of the redds will yield fry. Good spawning flows followed by good incubation (high) flows should give a point to the left of the average line on Figure 6, but if the incubation flows are poor (low) the point should be to the right. The spawning and incubation flows are given in Table 3.

The outlier to the right on Figure 6 occurred in 1981 and the one to the left in 1985. The spawning flows were good in 1981 but the incubation flows were reduced. This was followed by good fry habitat but by that time the poor incubation conditions had reduced the fry that could emerge. Comparing 1981 to 1982, the incubation discharge was slightly lower but because the spawning flows were also low a reduction in fry production probably did not occur. The spawning and incubation flows in 1985 were good but the main point is that the incubation flow was not too much lower than the spawning flow. The expected result in 1985 is a larger than average production of fry which caused a larger than expected production of juveniles a year later. The difference in winter flows in the Animas Basin is not usually as large as those typical for the Gunnison, but the range is probably adequate to limit the production of fall spawning fish such as brown trout and brook trout. Winter habitat is associated with cover such as large rocks and loose gravel the fish can burrow into (Meyer and Griffith, 1977). These factors are not adequately represented in the model used to calculate the physical habitat presented in Figure 4 and Table 1; both factors are related to the sediment in the streambed. They will be discussed in the section on sediment considerations in habitat analysis.

Table 3. Spawning and incubation flows in the Gunnison River as measured below the diversion tunnel, and the juvenile brown trout population and fry habitat at the Duncan/Ute Trail site just downstream. The juvenile population was measured the following year. Juvenile population and weighted usable area data are from Nehring and Miller (1987).

Water year	Spawning discharge (m^3/s)	Incubation discharge (m^3/s)	Juveniles (number/ hectare)	Fry habitat (m^2/m)
1980	22.4	14.0	105	314
1981	34.6	4.9	59	366
1982	11.6	4.1	40	160
1983	38.1	20.4	13	63
1984	33.7	15.4	6	14
1985	47.3	38.7	57	95

At this point, it has been shown that winter habitat can limit adult trout populations and may limit the reproduction of trout that spawn in the fall. The paragraph above suggests the limits on adult habitat may not be as limiting as the winter function in Table 1 suggests. Before this possibility can be addressed, information on the bed material of the Animas River must be presented.

Bed Material

Fish use the larger particles in the armour of a gravel bed river as cover. This means that for the armour to be good winter habitat it should have particles larger than about 100 mm. Grain size distributions of the armour are presented in Figure 7. The downstream (D/S) and upstream (U/S 1) samples are from within the wetted channel at an August discharge; U/S 2 is from a bar exposed in August. The low gradient reach above Howardsville has few large particles in the armour. In contrast, the reach below Howardsville does have large particles. The substrate material from below the armour is presented in Figure 8. The specific weight and porosity for the sample from the exposed bar (U/S 2) was determined and compared to the samples from two other rivers in Table 4. The samples from both upstream sites have more fine material than the sample from below Howardsville. This may explain the lower porosity found for the Animas River in comparison to the other two rivers.

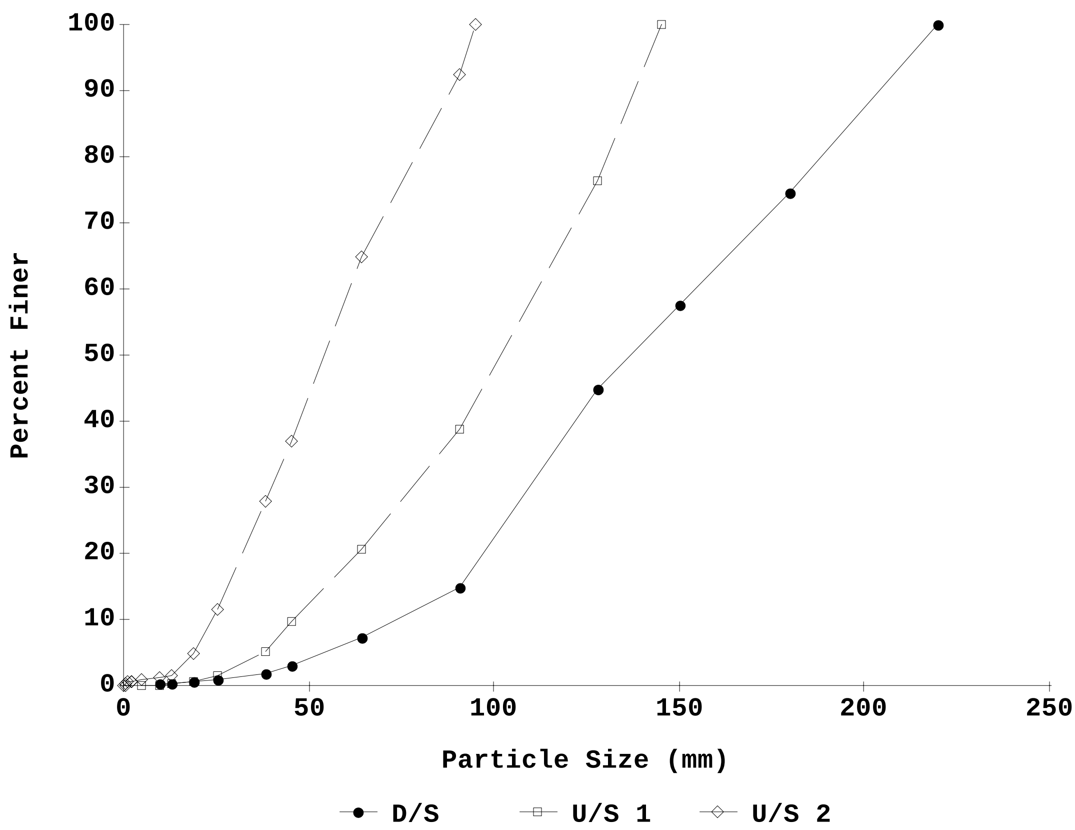

Figure 7. The particle size distribution of the armour (surface) material of the Animas River near Howardsville. D/S is downstream of Howardsville and U/S is upstream.

Table 4. Specific weight, specific gravity, and porosity for the bed material of three unregulated rivers.

Stream	Specific (lb/f^{t3})	Specific gravity	Porosity
Oak Creek, Oregon	105	2.85	0.41
Soda Butte Creek, Wyoming-Montana	106	2.65	0.36
Animas River, Colorado above Howardsville	135	2.80	0.22

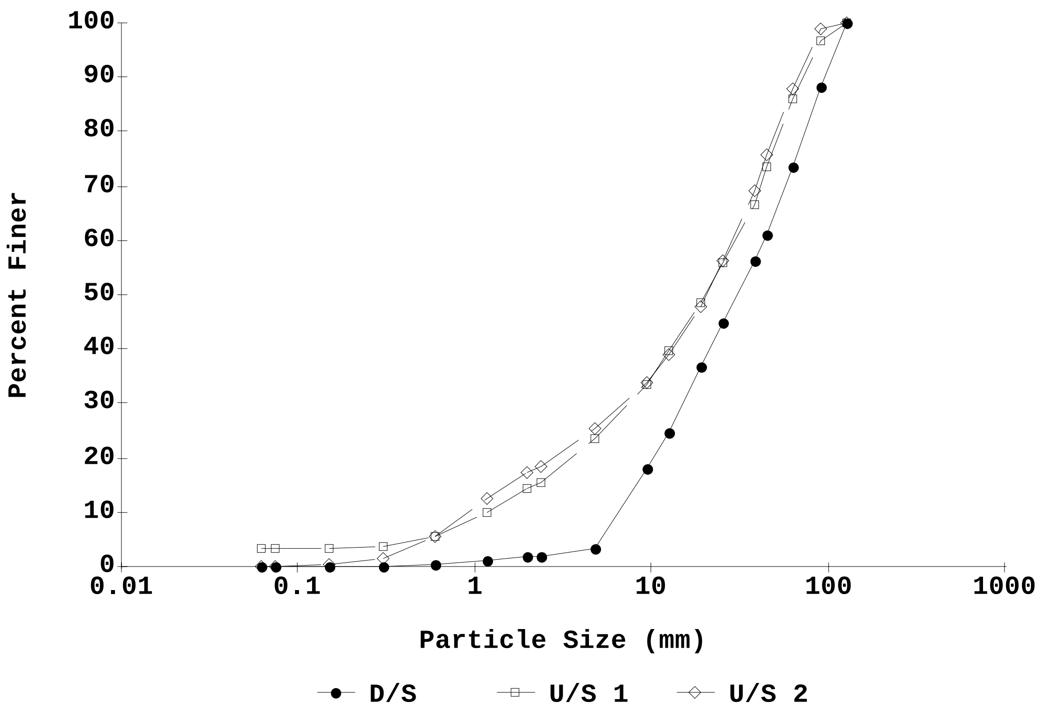

Figure 8. The particle size distribution of the subsurface material from below the armour of the Animas River near Howardsville. D/S is downstream of Howardsville and U/S is upstream.

Sediment Considerations in Habitat Analysis

Meyer and Griffith (1997) indicated a primary type of winter cover for rainbow trout is the void between and under rocks on the surface (the armour). Another type of cover used as winter habitat by rainbow trout is within the gravel substrate, provided the substrate is large enough and loose enough, for the fish to burrow into. These two factors suggest the winter trout habitat in the Animas River near Howardsville might be better than implied by Table 1. The results in Table 1 are based on velocity and depth alone.

Spring runoff also limits adult trout habitat because of high velocities. Large rocks on the surface can provide cover (shelter) for adult trout. As shown above, in most years the high velocities cause stress on the trout population unless boulders and cobbles exist to provide cover from the high velocities.

In both spring and winter, boulders and cobbles are important in providing velocity cover to trout. During the winter, loose substrate provides cover to trout. The presence of each of these cover types was investigated for part of the Animas River.

In the Animas River near Howardsville the sediment upstream appears to be reasonably dense compared to other unregulated rivers (see Table 4). The lower percentage of sands in the substrate below Howardsville (see Figure 8) suggest there may be better winter habitat conditions within the substrate below Howardsville than above because trout may be better able to burrow into the substrate.

Metals found in the interstitial waters of the substrate may be at higher concentrations than in the surface water. This is the situation for the site above Howardsville. The difference is given in Table 5. This means the substrate may not be acceptable habitat because of toxic factors even when the flowing river water is not toxic.

Table 5. The concentration of selected metals in the surface and interstitial waters of the Animas River above Howardsville. The interstitial water samples are the first and third samples removed from the substrate (see discussion in next section). All samples were acidified and then filtered through a 0.45-micron filter. The samples were obtained in August 1999.

	Surface (µg/l)	Interstitial (µg/l)	
Iron	68	4,400	1,100
Manganese	366	2,760	845
Copper	9.6	84.5	25
Zinc	276	777	395
Cadmium	1.1	3.4	1.6

The sizes of the particles in the armour are summarized in Table 6. Location U/S 1 would probably be wet in the winter. Location U/S 2 was dry in August and would be dry in the winter. The information in Table 6 shows the armour is larger downstream than upstream. The river downstream has large particles, not sampled, scattered about the surface, the upstream location does not. Also, the larger ratio between the particle size at which 90% are smaller (d90) and the median sizes suggests there may be more voids within the armour that could be used by fish as winter cover downstream than upstream.

Taken as a whole, it is expected the number and size of the fish would be larger below Howardsville than above Howardsville if velocity cover is the only factor limiting fish populations. The only trout found in the reach of the Animas River upstream of Howardsville are brook trout; in contrast, below Howardsville brook trout, rainbow trout and native trout are found (State of Colorado, 1992). Brook trout tend to be smaller than the other trout. The number of trout collected at a location near the place where the substrate samples were obtained above Howardsville was 41 brook trout in 300 feet of stream and a biomass density of 16.3 pounds per acre. Near the downstream sample site, the number of brook trout was 13 in 380 feet (6.2 lb/acre) along with 14 rainbow trout (28.1 lb/acre); the total trout biomass was 34.3 lb/acre.

Table 6. Comparison of the sizes of the armour material on the streambed of the Animas River near Howardsville. D/S is downstream of Howardsville and U/S is upstream.

Location	Median (mm)	d90 (mm)	Ratio
D/S	134.6	203.3	1.51
U/S 1	100.3	137.5	1.37
U/S 2	53.2	66.0	1.24

Pore Water Characteristics

As shown above for the reach of the Animas River above Howardsville another aspect of the sediment factors related to the physical habitat is that the metals found in the interstitial waters of the substrate may be at higher concentrations than in the surface water. Two methods have been used to sample the pore water. Nimmo and Castle (1998) dug a hole in a bar near the river and assumed the water obtained from the hole had the same concentration of metals as the interstitial water. The results they obtained for the bar just upstream of the gaging station below Silverton are presented in Table 7. The data show that the interstitial waters have higher concentrations of metals than the surface waters and can have a significant impact on the quality of the substrate for aquatic animals.

The second approach was to place an air stone in the substrate with a tube to the surface that was sealed. The air stone and attached tube were left in the substrate for at least two days before sampling the pore waters. Then two samples were obtained and analyzed. Selected results from the study are given in Table 8. As was obtained from the dug hole, these results show the pore waters can be of significantly different quality than the surface waters.

Table 7. The concentration of selected metals in the surface water of the Animas River below Silverton compared to the concentrations in water obtained from a hole dug in a bar near the river (interstitial water). All samples were filtered through a 0.45-micron filter and acidified. The samples were obtained on 15 August 1997 (modified from Nimmo and Castle, 1998).

	Surface (µg/l)	Interstitial (µg/l)
Iron	20	75
Manganese	390	145
Aluminum	<100	250
Copper	3.5	235
Zinc	100	465

Table 8. Concentrations of total metals in the pore waters at two locations in the Upper Animas watershed. The samples were obtained using the air store method and were acidified and then filtered through a 0.45-micron filter. The samples were obtained in August 1999.

	Calcium (mg/l)	Copper (µg/l)	Zinc (µg/l)	Cadmium (µg/l)	Arsenic (µg/l)
South Fork Mineral Creek (few mines)					
Surface Water	20.3	1.6	17.4	0.1	0.38
Pore Water 1	25.2	23.4	994.	1.4	9.27
Pore Water 2	21.5	8.4	324.	0.49	3.64
Animas River below Silverton (many mines and mills)					
Surface Water	27.9	19.5	214.	1.3	1.11
Pore Water 1	27.0	319.	1140.	3.4	14.60
Pore Water 2	23.6	46.4	360.	1.4	5.30

The results for the two approaches are reasonably similar. The comparison of the two locations presented in Table 8 show that the impact of mining may be larger on the interstitial waters than on the surface waters.

Additional details of the pore water study may be found in Montesi (1999). The pore water study was mostly done in the Animas watershed with pore water collected at two sites in the Boulder watershed in Montana in order to obtain some idea of the impact of geology on the pore water characteristics.

Conclusions

The conclusions related to the two objectives given in the introduction are presented below. The reader should look at the papers listed in the project bibliography for additional information and specific details of the various studies undertaken as part of the project.

Physical Habitat Impacts of Sediment from Mining Operations

There are two possible impacts of sediment from mining operations on the physical habitat. The first is on the size of the sediment in the substrate and the second is on the suitability of sediment as physical habitat.

In the Animas River the impacts of the sediment from historic mining on the size of the sediment in the streams appears to be small (see Figures 7 and 8). This may be because the last discharge of sediment to the stream from mills was more than 50 years before the study.

The impact on the suitability of the substrate may not be negligible because of the impacts of metals on the waters in the substrate (see Tables 5, 7 and 8). In some locations, and at some times, the surface waters may be of adequate quality for trout but the pore waters are of poor quality. The qualities of the pore waters are most likely poor because fines from mining are in the substrate.

Usability of Reconnaissance Level Physical Habitat Studies in Understanding the Impacts of Mining on the Aquatic Ecosystem

The reconnaissance level study of the physical habitat shows the habitat is limited by winter stream flows and that fall spawning fish do not have good streamflow conditions for spawning success. The analysis also showed that high flows might limit trout populations in some years because of high velocities.

The use of reconnaissance level study of the physical habitat can be useful because the analysis shows limits on the possible quality of the fishery that may result from factors other than mining impacts.

Project Bibliography

Milhous, R.T., 1998, Aquatic physical habitat and sediment analysis in evaluating mined land remediation measures, *in* Nimick, D.A., and Von Guerard, P., eds.: The USGS abandoned mined land studies: A 1998 review: USGS Open File Report.

Milhous, R.T., 1998, Impacts of abandoned mine lands on stream ecosystems of the Upper Animas River Watershed, Colorado: U.S. Geological Survey Open File Report 98-297, Midcontinent Ecological Science Center, Fort Collins, Colorado, 15 p.

Milhous, R.T., 1998, On sediment and habitat in the upper Animas River watershed, Colorado. *in* Water Resources Engineering 98: Proceedings of the ASCE, International Water Engineering Conference '98: American Society of Civil Engineers, p. 678–683.

Milhous, R.T., 1998, Streamflows and sediment transport capacity in the Upper Animas Basin, Colorado, *in* Proceedings of American Geophysical Union, 18th Annual Hydrology Days: Atherton, California, Hydrology Days Publications, p. 177–188.

Milhous, R.T., 1998, Aquatic physical habitat and sediment analysis in evaluating mined land remediation measures: 1997 Progress Report, U.S. Geological Survey, Fort Collins, Colorado.

Milhous, R.T., 1999, Aquatic physical habitat and hydrology in abandoned mined land studies, *in* Morganwalp, D.W., and Buxton, H.T., eds., Toxic substances hydrology program, Proceedings of the Technical Meeting, Charleston, South Carolina, 8–12 March, 1999: vol. 1, p. 47–54.

Montesi, J.P., 1999, 1999, Development and testing of a method for sampling interstitial waters in gravel-bed rivers: Office report, Midcontinent Ecological Science Center, U.S. Geological Survey, Fort Collins, Colorado, October 29, 1999.

Milhous, R.T., 2000, Hydrology, metals, and aquatic physical habitat in the Upper Animas Watershed, Colorado, *in* Proceedings: Watershed Management 2000: American Society of Civil Engineers (CD-ROM).

Milhous, R.T., 2000, Changes in the substrate of rivers in historic mining districts, *in* Proceedings: Joint Conference on Water Resources Engineering and Water Resources Planning and Management: American Society of Civil Engineers (CD-ROM).

Milhous, R.T., 2001, Specific weight and median size of the bed material of gravel and cobble bed rivers, *in* Proceedings: Seventh Federal Interagency Sedimentation Conference, Reno, Nevada, March 2001.

Literature Cited

Culp, T.R., and Homa, Jr., J., 1991, Fish and macroinvertebrate habitat suitability index curves, report to Niagara Mohawk Power Corporation: Ichthyological Associates, Lansing, New York, 86 p.

Meyer, K.A., and Griffith, J.S., 1997, Effects of cobble-boulder substrate on winter residency of juvenile rainbow trout: North American Journal of Fisheries Management, vol. 17, p. 77–84.

Milhous, R.T., 1995, Changes in sediment transport capacity in the Lower Gunnison River, Colorado, USA, *in* Petts, G., ed., Man's influence on freshwater ecosystems and water use: IAHS Publication No 230, International Association of Hydrological Sciences, Wallingford, Oxfordshire, U.K., p. 275–280.

Milhous, R.T., Updike, M.A., and Schneider, D.M., 1989, Physical Habitat Simulation System Reference Manual - Version II: Instream Flow Information Paper No. 26, U.S. Fish and Wildlife Service, Biological Report 89(16), Washington, D.C. v.p.

Nehring, R. B., and Miller, D.D., 1987, The influence of spring discharge levels on rainbow and brown trout recruitment and survival, Black Canyon of the Gunnison River, Colorado: Proceedings of the Annual Conference of Western Associations of Fish and Wildlife Agencies, 13–15, July, 1987, Salt Lake City, Utah.

Nimmo, D., and Castle, C.J., 1998, Toxicological evaluation of surface and interstitial waters from headwater streams in the Animas River Basin: Presented at the meeting "Results of AML Field Studies in the Upper Animas and Boulder River Pilot Watersheds", Lakewood, Colorado.

State of Colorado, 1992, Unpublished records of a biological survey of the Animas River made in 1992.

Wright, W.G., 1997, Natural and mining-related sources of dissolved minerals during low flow in the Upper Animas River Basin, Southwestern Colorado: U.S. Geological Survey Fact Sheet FS-148-97, 6 p.