GSTARS3-HTC Model Development and Evaluation as part of the Lewis and Clark Lake Sediment Management Study

Paul M. Boyd[1], Ph.D. P.E, Chih Ted Yang[2], Ph.D. P.E., Jungkyu Ahn[2], John W. Garrison[1], Daniel B. Pridal[1], P.E., John I. Remus[1], P.E., Megan A. Lien[1]

1. U.S. Army Corps Omaha District. Omaha, NB, 68102
2. Colorado State University, Department of Civil and Environmental Engineering, Hydroscience and Training Center, Fort Collins, CO 80523

Introduction

The deposition of hydraulically transported sediments occurs in all flow impoundments, whether they be naturally occurring or man-made. The natural system way of managing the deposition is to fill the impoundment with sediment until a point is reached where the flow of water finds a new path requiring less energy. This is very often caused by an impoundment completely or nearly full of sediment. If left in the current flow regime, Lewis and Clark Lake will eventually fill with deposited sediment, albeit more than 150 years in the future.

The man-made reservoir, Lewis and Clark Lake, formed by Gavins Point Dam, has existing uses that preclude merely allowing the reservoir to fill up. The lake is used for hydropower, navigation re-regulation, recreation, water supply, and flood storage. In an effort to find ways to maintain all of the interests on the lake, management of the deposited sediments in the reach is vital. While the specific management process for the reservoir is yet to be determined, the Lewis and Clark Lake Sediment Management Study aims to develop tools to evaluate a wide variety of possible management proposals.

Lewis and Clark Lake

Lewis and Clark Lake was formed by the closure of Gavins Point Dam in 1956. The dam is located at river mile 811.1 (RM 811.1), approximately five miles upstream of Yankton, South Dakota, on the Missouri River as seen in Figure 1. Gavins Point Dam is one of six mainstem dams on the upper Missouri that are operated by the US Army Corps of Engineers, primarily from the Corps offices in Omaha, NE. The dam and reservoir system provides navigation, hydropower, flood control, water supply, and recreation to the nearly 15 million people that reside in the states through which it flows.

Figure 1. Project Location Map

Lewis and Clark Lake reached its full water surface elevation of 1208-ft MSL in early 1957 and has been managed for hydropower and navigation re-regulation between 1206-ft and 1210-ft ever since. When closed, the lake extended to approximately RM 836, resulting in an open water lake approximately 25 miles long.

Since closure, the reservoir has been surveyed approximately every 10 years to determine changes in storage capacity and sediment deposition. These surveys have indicated that approximately 2,600 acre-feet of sediment per year are deposited below elevation 1210-ft in the reach between Gavins Point Dam and Fort Randall Dam at RM 880, the next impoundment structure upstream. This sediment is sourced from tributaries including the Niobrara River, Ponca Creek, and Bazile Creek, as well as from the banks and bed of the river above the reservoir. Figure 2 shows the two largest deltas in the river reach. Additional sediments are deposited in the overbanks of the river and in the Niobrara River delta at RM 844, yielding a total sediment input into the reach in excess of the volume below the 1210-ft threshold.

Figure 2. Niobrara River Delta and Lewis and Clark Lake Delta

The deposition of sediments in the lake delta has effectively shortened the length of the lake over the past 50 years. Currently, the open reach of the lake extends to near RM 828, resulting in a 17 mile long lake. The visual migration of the delta appears to be approximately 500 to 600 feet per year. The deposition rate has remained fairly constant over the past 50 years.

The migration of the delta both upriver and downriver, reduces the storage capacity of the reservoir. The initial capacity of the lake was 575,000 ac-ft below 1210-ft elevation, and the 1995 capacity was 470,000 ac-ft, approximately 18.5% of it original maximum storage. A new survey conducted in 2007 will update the current storage loss. The storage loss as of 2007 is expected to be in the range of 23-24% based on historic trends.

The Lewis and Clark Lake Sediment Management Study (LCLSMS) Project Background

The LCLSMS was developed to examine the engineering viability of moving deposited sediments from behind Gavins Point Dam into the river downstream of the reservoir. In the 2003 amended Biological Opinion, the US Fish and Wildlife Service stated "*The Corps shall research and develop a way to restore the dynamic equilibrium of sediment transport and associated turbidity in river reaches downstream of Fort Peck, Garrison, Ft. Randall, and Gavins Point Dams.*

Sediment bypass around large dams is feasible (Singh and Durgunoglu 1991). Bed degradation below dams and head cutting at the mouths of tributaries might be addressed with grade control structures. Weir notches at grade control structures would allow for fish passage to the tributaries. Because of the large sediment deposition zone at the upper end of Lewis and Clark Lake and its proximity to Gavins Point Dam, Gavins Point may provide the best opportunity for a pilot study (USFWS 2003)."

Initial consideration of using flows through the reservoir to transport deposited sediment was not strongly supported. Addition research on the reservoir system in the Lewis and Clark Lake reach showed that there is the possibility of physically transporting sediments through Lewis and Clark Lake (Engineering and Hydrosystems, 2002). A number of different flow and stage scenarios have been suggested by this research.

With the recommendation for a study at Gavins Point Dam through the BiOp and proof of concept provided by the 2002 E&H study, the LCLSMS was initiated in 2005. The LCLSMS is supported by the Missouri River Recovery Program (MRRP).

Project Goals

The LCLSMS is an engineering viability study. As defined, the study will deal only with the physical processes of hydraulic flow, sediment erosion, sediment transport, and sediment deposition. Environmental, economic, political, and quality of life issues are not considered in the scope of this study. The project goals, as stated in the draft Project Management Plan (PMP) are:

- Determine the hydraulic capacity to transport sediment in and below Lewis and Clark Lake
- Develop estimated final reservoir geometries as a result of flow alternatives.
- Determine downstream sediment transport capacity and possible deposition zones
- Develop a test flow to mimic the hydraulic alternative most likely to result in the desired outcome
- Protect existing project infrastructure

Timeline

The LCLSMS project began with the development of the project plan and scope of work for modifying GSTARS3 by Colorado State University Hydroscience and Training Center (HTC) in 2005. Award of the work to develop GSTARS3-HTC signaled the beginning of the project in late 2005. The current schedule expects to see the completed project in late 2009.

The LCLSMS project has been broken down into seven phases. Those phases are:

- Phase 1: Modification of the GSTARS3 Sediment Transport Model to allow for unsteady state flow analysis.
- Phase 2: Collection of river and reservoir geometry and sediment samples between Ft. Randall Dam and Sioux City, IA. Agency workshop and public meeting to gather input on developing alternatives.
- Phase 3: Verification of the GSTARS3-HTC reservoir model by Colorado State University HTC.
- Phase 4: Development of alternatives, and analysis of alternatives using the GSTARS3-HTC reservoir model from Ft. Randall Dam to Gavins Point Dam.
- Phase 5: Development of the HEC-6T downstream computer model from Gavins Point Dam to Sioux City, IA.
- Phase 6: Analysis of GSTARS3-HTC reservoir model output by HEC-6T downstream river model.
- Phase 7: Completion of study and recommendation of an alternative for possible further testing. A public/agency meeting will be held to disseminate results during this phase, ideally in summer 2009.

Alternative Development

There is a very high level of concern associated with sedimentation issues in the Missouri River reservoir system. These concerns have been magnified in the Lewis and Clark Lake delta, where a combination of high sediment load, small reservoir, and the resultant visibly moving delta that is slowly encroaching on the open lake. With these factors comes significant interest in the future of the reservoir. In an effort to ascertain the wants and needs of local residents, and federal, state, and local agencies, the US Army Corps of Engineers held an agency meeting coupled with a public meeting on June 14th, 2007. This meeting was part of Phase 2.

At the meetings, attendees were supplied with information about the project, and asked to provide input on their ideal future state of the reservoir. Depending on what entity each person was representing, responses were widely varied. As part of Phase 4, the project will develop flow alternatives based on this input, in an effort to design scenarios to run through the models that would reach the recommended future conditions in the reservoir. Alternative development is expected to be completed by summer 2008, when they will begin to be analyzed by the GSTARS-HTC model.

LCLSMS Model Selection

To create useful modeling tools that can be used for modeling current and future scenarios, including other possible mechanisms for transporting deposited sediment, it was determined that two models should be used. One to model the reservoir, and one to model the downstream reach below Gavins Point Dam.

Reservoir Model

Through a joint effort with the Hydroscience and Training Center (HTC) at Colorado State University (CSU) and the Omaha District of the US Army Corps of Engineers, development of a quasi-2D version of the GSTARS3 (Generalized Sediment Transport Model for Alluvial River Simulation version 3) (Yang and Simões, 2002) model is underway. The effort includes merging many of the features of GSTAR-1D (Generalized Sediment Transport for Alluvial Rivers – One Dimension, Version1.0) (Yang, et al 2005) with the advanced tools of GSTARS3 to result in GSTARS3-HTC, which provides the quasi-2D flow characteristics of stream tube modeling with unsteady flow capability.

This approach to modeling the river reach between the dams was selected because GSTARS3 has the ability to simulate and predict longitudinal and lateral verification of sediment movements and channel morphologic changes under quasi-steady flow conditions. During the process of sluicing, a model applicable to truly unsteady flow conditions is required. GSTAR-1D is a truly one-dimensional model for unsteady flows. Revising GSTARS3 to include all the functions of GSTAR-1D will create a semi-two-dimensional model applicable to sediment sluicing operation under unsteady flow conditions with limited field data.

Downstream Model

The downstream river model will encompass the river reach from Gavins Point Dam to Sioux City, IA, a reach of approximately 83 miles. The first half being a river reach similar to the pre-dam/navigation river; the second half a channelized reach approximately 600 feet wide. This model will use the output of the GSTARS3-HTC model as the input boundary condition. HEC-6T by MBH Inc. has been selected as the modeling tool for this reach of the river. When completed, it will allow for the results of any flow scenario in Lewis and Clark Lake to be used as a boundary condition to evaluate that scenarios' impact on the lower reach.

Data Collection for Modeling

To provide data for accurate modeling of the river and reservoir reaches in the study area, new hydrographic surveys were required. During the summer of 2007, new surveys were collected from Sioux City, IA (RM 728) to Ft. Randall Dam (RM 880). These surveys included river/reservoir bathymetry, ADCP velocity profiles, and RTK overbanks.

In addition to the current surveys, data from the 1975, 1985, and 1995 surveys is available for evaluating the models' ability to mimic historic change. Additional data including temperature, suspended sediment, bed sediment, tributary inflows, and rating curves for gauging stations has been compiled.

Development of the GSTARS3-HTC Model

GSTARS3 has the following capabilities needed for reservoir water and sediment routing computations:

1. It can compute reservoir hydraulic parameters with fixed as well as variable width.
2. It can simulate and predict the hydraulic and sediment variations in the longitudinal and in the transverse direction in a semi-two dimensional manner based on the

stream tube concept. If only one stream tube is selected, the model becomes one-dimensional. If multiple stream tubes are selected, both the lateral and vertical bed elevation changes can be simulated.

3. It can rout sediment by size fraction. The bed sorting and armoring algorithm can provide a realistic long term simulation of the scour and deposition process in a reservoir.
4. It can simulate and predict channel geometry changes in width and depth based on minimum total stream power.
5. The channel side stability option allows simulation of channel geometry changes based on the angle of repose of bank materials and sediment continuity.
6. It can simulate non-cohesive and cohesive sediment transport.
7. Sediment particles are allowed to cross the boundaries of stream tubes due to lateral bed slope or sharp bends.
8. It can simulate equilibrium and non-equilibrium sediment transport.
9. It has 15 sediment transport formulas for users to select.

The above capabilities are adequate for most reservoir sedimentation studies. However, during sluicing, the flow is highly unsteady, GSTARS3 may not accurately simulate the sedimentation process. It is desirable to expand GSTARS3 capabilities from quasi-steady to truly unsteady flow conditions.

GSTAR-1D is a truly unsteady flow model for water and sediment routing. The stream tube and minimum total stream power concepts are not used to simulate lateral bed and width changes. The Bureau of Reclamation is in the process of improving GSTAR-1D and renaming it SRH-1D (Huang and Greimann, 2007). GSTARS3-HTC will integrate the unsteady flow capacities of GSTAR-1D or SHR-1D into GSTARS3 to form a new model GSTARS3-HTC for a semi-two-dimensional simulation and prediction of channel geometry changes under truly unsteady flow conditions.

Hydrology and bed profile of the Tarbela Reservoir in Pakistan is used to test and compare simulated longitudinal bed profiles using GSTARS3 and GSTARS3-HTC model. Figure 3 is a plan view of the Tarbela Reservoir. Figure 4 shows the hydrology and dam operation for the Tarbela Reservoir. Only one stream tube is used for the simulation. Figure 5 shows the comparison between the observed and simulated longitudinal bed profiles using GSTARS3 and GSTAR3-HTC. The two models show identical results. Both models can give reasonable simulations of the delta formation process of the Tarbela Reservoir. Yang’s (1973) sediment transport formula and Han’s (1980) non-equilibrium sediment transport function are used in the simulations. To further testing the merit of using unsteady model during a sediment sluicing process, field data collected before, during, and after a sluicing process are needed. These data will be used to test, verify, and improve the GSTARS3-HTC.

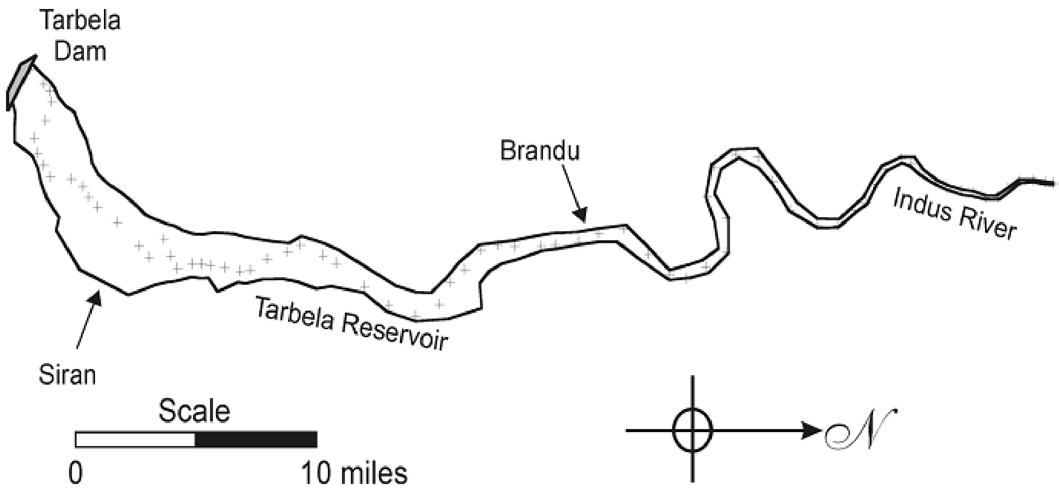

Figure 3. Tarbela Dam and Reservoir. The point (+) marks the thalweg

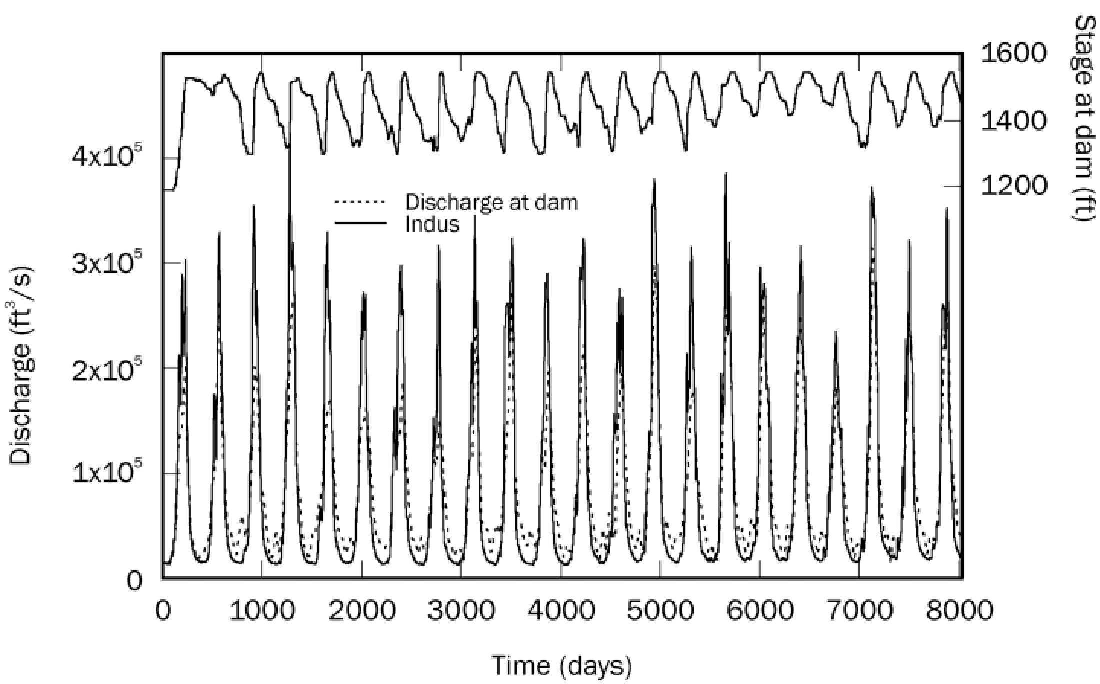

Figure 4. Hydrology and dam operation for Tarbela in the period of 1974 to 1996

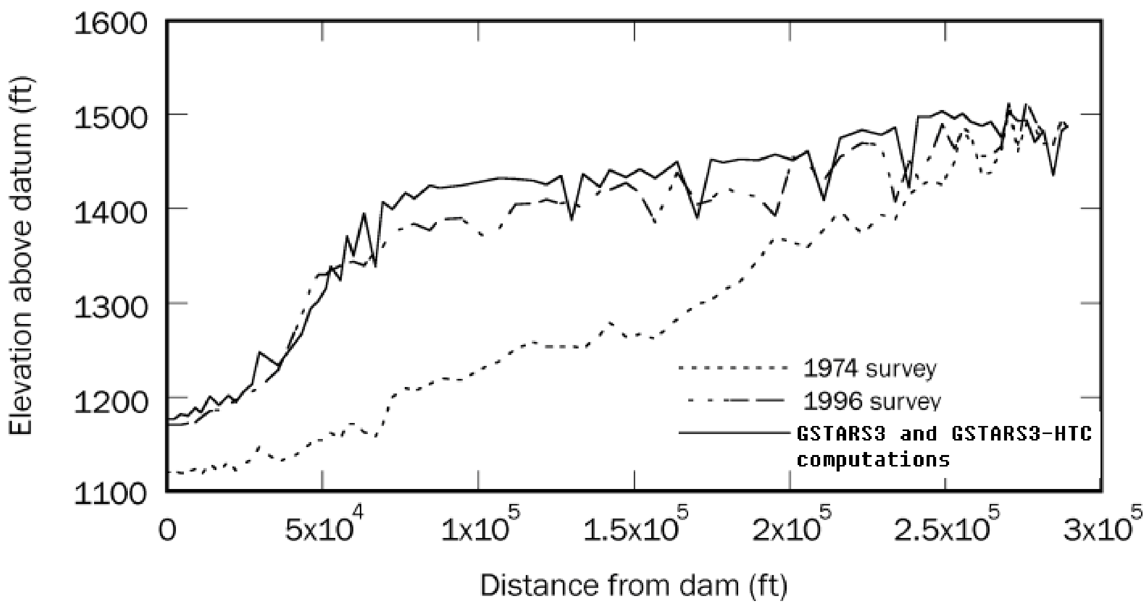

Figure 5. Result of the simulation of the Tarbela Reservoir thalweg change in 22years

Current HTC Model and Project Status

The following project status is current as of 01Feb2008.

Model data

The 2007 hydrographic surveys for the reach between Gavins Point and Ft. Randall Dams were delivered to HTC in late January 2008. Surveys were filtered from thousands of points per section to between 50 and 100 points per section. In addition to the station-elevation format, the XYZ format of the data was submitted to determine overbank flow lengths in the model by GIS. Sediment data is expected to be delivered by 01Mar2008.

The survey data downstream of Gavins Point is being processed by USACE-Omaha and will be ready for HEC-6T model development by early summer 2008.

Model Progress

HTC model integrates advantages of previous versions of GSTARS models, GSTARS3 and GSTAR-1D. Each model has advantages and disadvantages.

One of the important features of GSTARS3 is the use of the stream tube concept, which is used in the sediment routing computation. The adoption of this concept allows simulation of lateral movement of sediments. In GSTARS3 model, hydraulic parameters and sediment routing are computed for each stream tube, thereby providing a transverse variation in the cross section in a semi-two-dimensional manner. Although no flow can be transported across the boundary of a stream tube, transverse bed slope and secondary flows are phenomena accounted for in GSRTARS3 that contribute to the exchange of sediments between stream tubes. The position and width of each stream tube may change after each time step of computation. The scour or deposition computed in each stream tube give the variation of channel geometry in the vertical (or lateral) direction.

GSTARS3 uses quasi-unsteady flow concept, which assumes that water discharge hydrographs are approximated by bursts of constant discharge. Consequently, GSTARS3 is not intended to be applied to truly unsteady flow conditions. Thus GSTARS3 model may not be accurate for unsteady conditions, such as the sluicing of water and sediment at the dam and sudden water surface drawdown. Therefore, GSTARS3 has some disadvantages when applied to simulating unsteady conditions during a sudden drawdown for sediment sluicing, whereas GSTAR-1D allows the model to simulate unsteady flow characteristics more accurately than GSTARS3 which uses quasi-unsteady approximation.

GSTARS3-HTC uses stream tube concept, the advantage of GSTARS3, to simulate lateral sediment movement. Additionally, GSTARS3-HTC can simulate unsteady conditions by adopting GSTAR-1D unsteady scheme. Usually, stream flows can be simulated as quasi-unsteady flow by assuming that the flow rate changes gradually. The sluicing of water at the dam and water surface drawdown needs an unsteady flow model. Unsteady flow simulation computes more accurately than quasi-unsteady model if the flow condition is not steady. GSTARS3-HTC has several boundary options, such as weir and gate operation. Consequently, GSTARS3-HTC should be capable of simulating a dam’s operation for reservoir sedimentation and sluicing study. Other development and improvement of HTC model is still in progress.

Project Goals/Phases

Phases 1 and 2 were completed during late 2006/early 2007. Currently, Phase 3 is ongoing with the goal of completion by early summer 2008, and additional datasets are being sought to assist in testing the model. Initiation of Phase 4 began in late 2007 and will dovetail with progress on Phase 5 in late fall/winter 2008. Phases 6 and 7 will hopefully begin and conclude in 2009.

Conclusions

The initial testing of GSTARS3-HTC appears to produce results similar to the empirical survey data at the Tarbela Reservoir. Additional testing and refinement of the model will reduce uncertainty in the modeling results.

The data collection phases of the project are concluding and the project team is moving towards building the models for Lewis and Clark Lake and the reach below Gavins Point Dam. When these model geometries are completed, they will be calibrated to existing and historical data before being used to predict future conditions based on the alternatives that will be selected to run through the model.

The project is currently on schedule for completion in late 2009, with a forthcoming project update in late 2008.

References

Engineering and Hydrosystems Inc., 2002, Conceptual analysis of sedimentation issues on the Niobrara and Missouri Rivers, South Dakota and Nebraska: Omaha, NE, US Army Corps of Engineers.

Han, Q., 1980, A study on the non-equilibrium transportation of suspended load, Proceedings of the International Symposium on River Sedimentation, Beijing, China, pp. 793-802 (in Chinese).

Huang, J.V. and Greimann, B. P., 2007, User's Manual for SRH-1D (Generalized Sediment Transport for Alluvial Rivers – One-Dimensional), U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.

Singh, K. P., and A. Durgunoflu, 1991, Remedies for sediment buildup, Hydro Review: 90-95.

U.S. Fish and Wildlife Service, 2003, Amendment to the 2000 Biological Opinion on the operation of the Missouri River main stem Reservoir system, operation and maintenance of the Missouri River bank stabilization and navigation project, and operation of the Kansas River reservoir system: Minneapolis, MN. U.S. Fish and Wildlife Service, 318 p.

Yang, C. T., 1973, Incipient motion and sediment transport, ASCE Journal of the Hydraulic Division, Vol. 99, No. HY10, pp. 1679-1704.

Yang, C. T. and Simões, F. J. M., 2002, User's Manual for GSTARS3 (Generalized Sediment Transport model for Alluvial River Simulation version 3.0), U.S. Bureau of Reclamation Technical Service Center, Denver, Colorado.

Yang, C. T., Huang, J. V., and Greimann, B. P., 2005, User's Manual for GSTAR-1D 1.0 (Generalized Sediment Transport for Alluvial Rivers – One Dimension, Version 1.0), U.S. Bureau of Reclamation, Technical Service Center, Denver, Colorado.